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Doctor of Science

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Design, analysis and evaluation of dynamic spectrum allocation algorithms for quality of service provisioning in telemedicine applications based on the IEEE 802.22-2011 standard

Dissertation

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Diseño, análisis y evaluación de algoritmos de asignación dinámica del espectro para el aprovisionamiento de calidad de servicio en aplicaciones de telemedicina bajo el estándar IEEE 802.22-2011

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La reciente migración de la señal de televisión analógica a una señal digital que se ha dado en todo el mundo conlleva al desarrollo de estándares de comunicaciones que consideran el uso de los espacios blancos de televisión, por sus siglas en inglés TVWS. Uno de estos nuevos estándares es la llamada red de área regional inalámbrica IEEE 802.22 (IEEE 802.22/WRAN), que considera el uso de TVWS para lograr mejores características de propagación y distancias de transmisión más largas. Por lo tanto, esta tecnología emergente presenta una oportunidad para proporcionar conectividad y servicios de transmisión de datos desde las zonas urbanas hasta las rurales. Algunos tipos de servicios que podrían beneficiarse enormemente de la provisión de enlaces de datos desde las zonas urbanas hasta las rurales son aquellos relacionados con la telemedicina y la salud móvil. Sin embargo, el aprovisionamiento de un cierto nivel de calidad de servicio, por sus siglas en ingles QoS, es de suma importancia para permitir una apropiada prestación de servicios de telemedicina desde un punto localizado en una región urbana (por ejemplo, un hospital urbano) hasta otro punto localizado en una zona rural (por ejemplo, una clínica rural). En este contexto, el aprovisionamiento de QoS para aplicaciones de telemedicina a través de redes inalámbricas representa un desafío importante que se debe abordar con la finalidad de alcanzar el potencial que el despliegue de la telemedicina rural puede lograr a través de medios inalámbricos. En esta tesis, se presenta un enfoque Cross-layer que combina la capas de Control de Acceso al Medio (MAC) y de Aplicación (APP), con el objetivo de reducir la probabilidad de bloqueo y la probabilidad de interrupción en los servicios de telemedicina que operan sobre redes basadas en el estándar IEEE802.22 / WRAN. En la capa APP, se definen perfiles de tráfico de telemedicina basados en tasas de utilización. Por otro lado, en la capa MAC se utiliza un mecanismo de asignación dinámica del espectro basado en un algoritmo de calendarización bajo un esquema de prioridades y un mecanismo de control de admisión adaptativo para la Administración del Ancho de Banda (ABM), que realiza una clasificación basada en los requerimiento de QoS para los servicios de telemedicina para asignar dinámicamente los recursos de ancho de banda. Se consideran tres servicios de telemedicina (telediagnóstico, teleconsulta y telemonitoreo) con diferentes requisitos de ancho de banda y un caso especial para los servicios de teleconsulta que incluye diferentes niveles de servicio (es decir, teleconferencia de alta resolución, teleconferencia de media resolución y teleconferencia sólo de audio) para realizar una evaluación del desempeño de la propuesta. Los resultados de la simulación demuestran que el enfoque propuesto es capaz de reducir las probabilidades de bloqueo e interrupción mediante la implementación de un algoritmo de calendarización bajo un esquema de prioridades para tres servicios de telemedicina, junto con el mecanismo de control de admisión ABM para el caso especial de los servicios de teleconsulta.

Palabras clave: WRAN, Telemedicina, IEEE 802.22, QoS, Control de Admisión, Asignación Dinamica del Espectro, Algorítmos de Calendarización

Abstract of thesis presented by Roberto Enrique Magaña Rodríguez as a partial requirement to obtain the Doctor of Science degree in Electronics and Telecommunications with orientation in Telecommunications.

Design, Analysis and Evaluation of Dynamic Spectrum Allocation Algorithms for Quality of Service Provisioning in Telemedicine Applications based on the IEEE 802.22-2011 standard

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The recent switch from analog to digital TV broadcast around the world has led to the development of communications standards that consider the use of TV White Spaces (TVWS). One of such standards is the IEEE 802.22 wireless regional area network (WRAN), which considers the use of TVWS to achieve better propagation characteristics and longer transmission distances. Thus, this emerging technology presents an opportunity to provide connectivity and data based services from urban to rural areas. Some kind of services that could greatly benefit from the provision of data links between urban and rural areas are those related to telemedicine and m-health. Nevertheless, provisioning of a certain quality of service (QoS) level is of paramount importance to enable proper telemedicine service delivery from urban (e.g. an urban hospital) to rural locations (e.g. a rural clinic). In this context, QoS provisioning for telemedicine applications over wireless networks present a major challenge to be addressed in order to fulfill the potential that rural wireless telemedicine has to offer. In this thesis, a cross-layer approach combining Medium Access Control (MAC) and Application (APP) layers is presented, with the aim of reducing blocking probability and interruption probability in telemedicine services operating over IEEE802.22/WRANs. At the APP layer, telemedicine traffic profiles based on utilization rates are defined. On the other hand, at the MAC layer a dynamic spectrum allocation mechanism based on a priority scheduling algorithm, and an Adaptive Bandwidth Management (ABM) mechanism are used to perform a QoS-based classification of telemedicine services and then dynamically allocating the bandwidth requirements. Three telemedicine services (i.e. tele-diagnosis, tele-consulting and tele-monitoring) with different bandwidth requirements and a special case of tele-consulting services that comprises different service levels (i.e. high-resolution teleconference, medium- resolution teleconference, and audio-only teleconference) are considered when evaluating the proposed approach performance. Simulation results demonstrate that the proposed approach is able to reduce blocking and interruption probabilities by using a priority scheduling algorithm for three telemedicine services, along with the ABM admission control mechanism for special case of tele-consulting services.

Keywords: WRAN, Telemedicine, IEEE 802.22, QoS, Admission Control, Dynamic Spectrum Allocation, Scheduling Algorithms

Dedication

To the love of my life, Luz Helena. For always being the best partner in crime to achieve my craziest goals over our lifetime together. For pushing me to never back down whenever I am living a challenging situation; and for giving me a family full of love through my lovely kids, Enrique and Alba. Luz Helena, I love you like I never thought I could love someone.

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List of Acronyms

ABM	Adaptive Bandwidth Management
AC	Admission Control
AMC	Adaptive Modulation and Coding
APP	Application Layer
AQDC	Adaptive QoS-Deviation Control
ARTC	Adaptive Residual Time Control
AVC	Advanced Video Coding
BE	Best-Effort Service
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BQDF	Biggest QoS-Deviation First
BS	Base Station
BSC	Broadband Satellite Communications
BWA	Broadband Wireless Access
CBP	Coexistence Beacon Protocol
CBR	Constant Bit Rate
CDMA	Code Division Multiple Access
CPE	Customer Premise Equipment
CQICH	Codeword over Quality Indicator Channel
CR	Cognitive Radio
CRC	Cyclic Redundancy Check
CRN	Cognitive Radio Network
DCD	Downstream Channel Descriptor
DIE	Downstream Information Element
DRR	Deficit Round Robin
DS	Downstream Sub-frame
DSA	Dynamic Spectrum Allocation
ECG	Electrocardiogram
EEG	Electroencephalogram
EMS	Emergency Medical Services
ERrt	Emergency-Response Real-Time
ertPS	Extended Real-Time Polling Service
EWM	Emergency Wi-Medicine
FASTele	Focused Assessment with Sonography for Trauma using Tele-echography
FCC	Federal Communications Commission
FCFS	First-Come, First-Served
FCH	Frame Control Header
FDD	Frequency Division Duplex
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communication
HEVC	High-Efficiency Video Coding

HRR	High Rural Restricted Scenario
HRU	High Rural Unrestricted Scenario
ICT	Information and Communications Technologies
IDRP	Incumbent Detection Recovery Protocol
IEEE	Institute of Electrical and Electronics Engineers
INEGI	National Institute of Statistics and Geography
ITU	International Telecommunication Union
LAN	Local Area Networks
LOS	Line-Of-Sight
LRU	Low Rural Unrestricted scenario
LTE	Long-Term Evolution
MAC	Medium Access Control
MDBA	Medical Database Access
MIS	Medical Information System
MOS	Mean Opinion Score
MS	Mobile Station
n rtPS	Non-Real-Time Polling Service
nERnrt	Non-Emergency Response No-Real-Time
nERrt	Non-Emergency Response Real-Time
NLOS	Non Line-Of-Sight
NPU	Narrowband Primary User
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
OSA	Opportunistic Scheduling Algorithms
OSS	Overlay Spectrum Sharing
PAN	Personal Area Networks
PHI	Public Health Informatics
PHY	Physical Layer
PQ	Priority Queueing
PS	Polling Service
PSNR	Peak Signal-to-Noise Ratio
PU	Primary User
QAM	Quadrature Amplitude Modulation
QoE	Quality of Experience
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RB	Resource Block
ROI	Region of Interest
RR	Round Robin
RTA	Road Traffic Accidents
RTP	Real Time Transport Protocol
rtPS	Real-Time Polling Service
RTWN	Rural Telemedicine Wireless Network
S-OFDMA	Scalable OFDMA

SCH	Superframe Control Header
SCW	Self-Coexistence Window
SNR	Signal-to-Noise-Ratio
SP	Strict-Priority
SpO2	Peripheral Oxygen Saturation
SU	Secondary User
TDD	Time Division duplex
TelemedCLSch	Telemedicine Cross-Layer Scheduling
TVWS	TV White Spaces
UCD	Upstream Channel Descriptor
UDP	User Datagram Protocol
UGS	Unsolicited Grant Service
UHF	Ultra High Frequency
US	Upstream Sub-frame
USS	Underlay Spectrum Sharing
UWB	Ultra Wideband
VBR	Variable Bit Rate
VHF	Very High Frequency
VoIP	Voice Over IP
VSAT	Very Small Aperture Terminal
WAN	Wide Area Network
WDRR	Weighted Deficit Round Robin
WEIRD	WiMAX Extensions for Remote and Isolated Research Data
WFQ	Weighted Fair Queueing
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network
WMs	Wireless Microphones
WPAN	Wireless Personal Area Network
WRAN	Wireless Regional Area Network
WRR	Weighted Round Robin
WWAN	Wireless Wide Area Network

Chapter 1. Introduction

1.1. Background

Derived from the continuous development of wireless telecommunication technologies, and the increasing user demands for broadband services, the use of broadband wireless access (BWA) communications has become part of our daily life in last decades. BWA networks can be categorized according to their coverage ratio as short-range and long-range (Kuran & Tugcu, 2007). The short-range category comprises Personal- and Local- area networks, (PAN, LAN, e.g. IEEE 802.15.4/ZigBee, IEEE 802.15.1/Bluetooth, IEEE 802.15.6/UWB and IEEE 802.11/WiFi), which have a maximum coverage ratio of 10 meters and 100 meters, respectively. On long-range coverage, the wide and metropolitan area networks (e.g. 4G/LTE, GSM, GPRS, CMDA and IEEE 802.16) can reach up to 15 kilometers and 50 kilometers, correspondingly. Currently, the IEEE 802.22 standard is the only infrastructure network that has a maximum coverage ratio of 100 kilometers, hence it has been classified as a Wireless Regional Area Network (WRAN).

The IEEE 802.22 standard was developed by the Institute of Electrical and Electronics Engineers (IEEE) 802.22 task group (IEEE-SA Standards Board, 2011). This standard is considered as the first cognitive radio network WRAN standard, because its spectrum access is as secondary user (SU) of the TV white space (TVWS) channels ranging from 54 MHz to 698 MHz. The cognitive radio (CR) capability on the IEEE 802.22 standard takes advantage of the digital dividend, resulting from the analog switch-off (DigiTAG, 2008), by means of using those TVWS channels that have been originally licensed to primary users (i.e. digital or analog TV signals). In order to protect transmissions from primary users (PU), the IEEE 802.22 standard has established that the access to TVWS spectrum should be ruled by an overlay scheme. This means, that a customer premise equipment (CPE) subscribed to a IEEE 802.22 system, can operate over a TVWS channel only when it is not being used by a PU; otherwise, the IEEE 802.22 system must cease transmitting and abandon the operating channel, in order to avoid any interference. Therefore, the implementation of dynamic spectrum allocation (DSA) mechanisms on cognitive radio networks (CRN) has taken high relevancy.

The DSA algorithms are aimed to exploit the portions of unused spectrum of the licensed users such that it can be allocated to a secondary user, based on the opportunistic access of a time slot on a particular geographical location. This way, radio resources such as time slots and frequency bands can then be allocated according to PU occupancy channel conditions. Because radio resources are limited in CRN, the implementation of dynamic resource allocation schemes have better performance compared to an static scheme (Wang & Giannakis, 2011; Zhang, Liang, et al., 2010).

Recently, an application area of BWA technologies that has taken relevancy due to its potential impact on increasing services delivery is on the adoption of telemedicine in medical practice. Traditionally, medical practice services include patient consultation, patient diagnosis and patient follow-up. These involve several methods and specific medical instruments to treat multiple health conditions, which require the patient presence on a face-to-face consultation with a medical practitioner. Because of technological advances, new methods and instruments have been developed to assist health professionals on patient evaluation and decision making processes. In this sense, telemedicine represents a new paradigm that allows reaching and interacting with patients located in remote sites by means of using communication technologies.

The medical services offered by telemedicine can be classified as tele-diagnosis, tele-consulting, tele-monitoring, tele-education and medical database access (Vergados et al., 2006). Tele-diagnosis services are aimed to collect health information from patients located in an ambulance or a remote clinic. This way, health specialists in hospitals can use the collected data to emit recommendations, to set up pre-hospital arrangements and to deliver treatment instructions, among others. Tele-consulting considers an interaction between a local physician and a remote specialist. Generally, they are performed to discuss the patient record, to share patient health condition and to follow-up patient health status after treatment. Here, patient treatment recommendations and second opinions related to patient condition are shared between medical specialists, physicians or health professionals. In Tele-monitoring services, local biomedical data (e.g. blood pressure, ECG, EEG, etc.) is collected, sent and stored on a remote medical database to update the patient's record. In such a way, the follow-up practice can be performed without any restriction related to patient localization and patient consultation time schedule, by means of giving to medical specialist a ubiquitous access to health patient's record. Differently, tele-education and medical database access are mostly used for training physicians on new medical treatments, to inform medical community about health alarms, to discuss about particular treatment procedures, and to evaluate clinical issues with a medical board, among other subjects. Mainly, these services are oriented to discuss public health issues more than to address a patient condition particularly, or individual medical treatments.

The deployment of wireless telemedicine networks may contribute to overcome important challenges related to mobility issues from health specialists and long traveling times for patients, among others

(Siddiqua & Awal, 2012). At present, there exists an unequal distribution of medical services between urban and rural areas that results on a high constraint on medical services for isolated regions (Dussault & Franceschini, 2006) Hence, the implementation of telemedicine applications may have a higher impact on rural regions, because medical services can be extended from urban regions to underserved and sparsely populated areas. This way, telemedicine service delivery may contribute to overcome the denial of medical services and the access limitations to medical specialists by means of the deployment of rural wireless networks.

Telemedicine applications can be classified according to its emergency nature as: emergency-response real-time applications (ERrt), non-emergency response real-time applications (nERrt) and non-emergency response no-real-time applications (nERnrt) (Vergados, 2007). The ERrt applications are meant to send notifications in an urgent manner to inform medical specialists about any health changes on patient's condition. Hence, an establishment of a reliable network link for real-time data transmissions with a provisioning of quality of service (QoS) should be provided. Even more on ERrt applications, the traffic profile scheme is based on constant bit rate (CBR). Similar to ERrt, the applications classified as nERrt may require the transmission of real-time data with the QoS provisioning, but they are different on its traffic profile requirements. Because nERrt applications comprise non-emergency scenarios, its support capabilities on traffic profile support are not restricted to CBR schemes since they are also able to transmit on a variable bit rate (VBR) scheme. The nERnrt applications do not require a QoS provisioning as they are aimed to transmit delay-tolerant data streams. In order to describe a more accurate rural deployment scenario, a relationship between medical scope on telemedicine services and the emergency nature on telemedicine applications should be established. This way, the medical scope of telemedicine services can be mapped from the type of telemedicine service within an emergency scenario, to the type of network application that could better fit its QoS requirements. Consequently, a tele-diagnosis service can be mapped as an ERrt application, a tele-consulting as a nERrt and a tele-monitoring service as a nERnrt application.

Among the medical services considered on a rural telemedicine wireless network (RTWN), one of the most important services that comprise telemedicine sessions initiated by ambulances on emergency scenarios is tele-diagnosis. The tele-diagnosis service could potentially improve the survival rate of ambulance patients by means of enabling services for pre-hospital care, by remotely assisting paramedics and by providing a second opinion on patient diagnosis. For instance, a Taiwan case study based on the utilization of emergency services (EMS) over rural road traffic accidents (RTA) has shown that 5.63% of deaths were attended by post-trauma units in rural regions, and 32% of those patients died before being admitted in a hospital (Li et al., 2008). Differently, an ambulance transportation service in rural Richardson County involves elderly people that require pre-hospital EMS (Stripe & Susman, 1991). Here, 70% of EMS patients are elderly people over 64 years old. Consequently, more than 58% of EMS calls attended by an ambulance involves patients with fractures, as well as cardiorespiratory and neurologic problems.

Some telemedicine services require real-time communications capabilities to support high-resolution applications, needed for streaming medical video and audio (Vergados, 2007), therefore, the use of broadband wireless alternatives have been proposed to the deployment of RTWN. The proposals comprise long-range technologies, such as the IEEE 802.16 for Metropolitan Area Networks (Mandioma et al., 2007; Ying Su & Caballero, 2010), cellular communication systems for Wide Area Networks (Meethal & J., 2011; Mulvaney et al., 2010; Zhu & Dong, 2011) and the VSAT networks for Broadband Satellite Communications (Chorbev et al., 2008; Ibikunle, 2009; Su & Soar, 2010). The WAN alternatives tend to be used as standalone last-mile solutions, since its coverage ratio directly depends on previously deployed network infrastructure. Differently, the BSC alternative provides an unlimited coverage ratio to the deployment of network communications that are typically implemented in high budget telemedicine projects. According to the World Health Organization, the financial costs on deployment of RTWN represents an important barrier to enable telemedicine service delivery, since most of the project initiatives on rural telemedicine are limited in funding (World Health Organization, 2010b). Hence, the high-costs involved in the deployment and operation of wireless communications for rural areas, such as BSC solutions, may become a critical barrier for its broad implementation (Moffatt & Eley, 2011; Shakeel et al., 2001). This is particularly true for long-term telemedicine initiatives where funding is limited. Despite previously mentioned proposals that have been successfully deployed as RTWN, they may also be limited by the available rural infrastructure. This implies that such network architecture may not consider particularities of rural scenarios (e.g. distance between rural clinic and urban hospitals, or telemedicine traffic profiles based on rural characteristics, among others), nor a network protocol framework designed to enable telemedicine service delivery with quality of service provisioning in rural regions.

Because of telemedicine service delivery comprises health patient information, the design of a RTWN solution should guarantee the provisioning of QoS and bandwidth resource reservations for telemedicine applications. The QoS provisioning can be addressed from a network-centric approach, where the base station is required to provide QoS support to satisfy requirements requested by applications (i.e. data rate, delay, packet loss, among others) (Wu, 2005). Particularly, guarantee on QoS can be achieved by means of defining proper traffic specifications based on application’s requirements, by implementing an admission control mechanism (AC) based on QoS or by including a dynamic resource allocation scheme, among other alternatives (i.e. QoS routing, packet scheduling and wireless channel characterization).

A call admission control defines whether a connection request should be rejected or admitted, based on the availability of network resources (i.e. bandwidth, channel quality or QoS requirements). Thus, the response on network performance measured by means of blocking probability, is highly dependent of its design (Ahmed, 2005). On the other hand, a resource allocation mechanism is aimed to provide QoS guarantees by means of reserving system resources according to type of service requirements. This way, the system performance could be improved by means of maximizing the resources utilization. The sustainability on resource reservation (over all session duration) depends on the traffic congestion characteristics and the resources demand requirements, hence some applications may suffer service interruptions that in the worst case scenario may result on link's disconnection. In this context, the effects of the resource allocation mechanism can be measured through interruption probability (Li & Pan, 2006). The definition of a traffic model comprises characteristics of traffic profiles on enabled applications and traffic congestion level on users' services demand. Particularly, the traffic profile defines requirements of data bandwidth, type of traffic flow (i.e. CBR, VBR) and level of QoS (based on characteristics of delay, latency and packet loss, among others). The traffic congestion definition can be used to depict urban, suburban, or rural deployment scenarios by means of decreasing the interarrival times on access request, which results in increasing the number of admissions requests. Even more, the network response to resources' demand based on the deployment scenario can be studied by means of including session duration times on the traffic congestion definition (Bidgoli, 2008).

Most of the reported proposals for implementation of call admission control and resource allocation mechanisms have been designed for the IEEE 802.16/WiMAX and/or mobile cellular networks (AlQahtani & Mahmoud, 2006; AlQahtani & Ashraf, 2006; Bae et al., 2010; Chau et al., 2006; Dapeng Wu & Negi, 2003; Guha Roy et al., 2008; Hyang-Won Lee & Song Chong, 2006, 2006; Jirgens et al., 2005; Kalikivayi et al., 2008; Lee et al., 2006; Luo et al., 2009; Sunho Lim et al., 2002). Typically, the call admission control mechanisms are enhanced by means of including the QoS level in admittance criteria on the Medium Access Control (MAC) layer. This way, the network performance is improved by means of establishing a decision making process, based on a hierarchical structure of QoS, which is aimed to reduce call dropping probability, packet loss probability or increase throughput performance, among other parameters (AlQahtani & Mahmoud, 2006; AlQahtani & Ashraf, 2006; Bae et al., 2010; Chau et al., 2006; Jirgens et al., 2005; Kalikivayi et al., 2008; Luo et al., 2009). On a different perspective, some proposals combine call admission control and resource allocation mechanisms into an integral solution that is capable to improve the admission probability, while delivering QoS provisioning by means of reserving and scheduling system resources (Dapeng Wu & Negi, 2003; Guha Roy et al., 2008; Hyang-Won Lee & Song Chong, 2006, 2006; Lee et al., 2006; Sunho Lim et al., 2002). In telemedicine service delivery, most proposals that are aimed to address the QoS provisioning in BWA networks, comprise a resource allocation mechanism to establish a priority scheme among network applications. For instance, several proposals based on OFDM networks (i.e. IEEE802.16/WiMAX) include a scheduling priority algorithm that is capable to allocate system resources by considering the QoS type of service associated to the telemedicine service. This way, tele-diagnosis services can have a higher priority on resources reservation than any other telemedicine service (Chorbev et al., 2008, 2008; Husni & Waworundeng, 2011; Niyato et al., 2007a; Sorwar & Ali, 2010; Vergados et al., 2006; Zhang, Ansari, et al., 2010a).

Regarding cognitive radio networks, the QoS provisioning must consider two of the system's main characteristics: the spectrum access scheme (overlay or underlay) to implement a dynamic spectrum allocation mechanism (i.e. resource allocation); and the bandwidth constraints, given by the presence of primary users on the operating channel, for QoS provisioning. The overlay spectrum access scheme dictates that no secondary user can operate on a channel that is on use by a primary user, while the underlay scheme allows a coexistence between primary and secondary users on a non-interference basis (Qing Zhao & Sadler, 2007; Zhao & Swami, 2007). In cognitive radio networks, the establishment of channel availability comprises spectrum sensing techniques that are aimed to improve the detection probability of primary users, as an approach to provide QoS guarantee by means of improving throughput (Ariananda et al., 2009; Sansoy & Buttar, 2015; Suseela & Sivakumar, 2015; Ying-Chang Liang et al., 2008; Yucek & Arslan, 2009). Once the secondary user has been enabled to use an available channel, the network has to establish system resource availability to provide a QoS guarantee among the users of the cognitive radio network. In this context, the throughput performance can be improved by means of establishing a priority scheme among all active links, such that it can be used as a network policy for admission control and resource allocation. This is not an easy task if we consider that all users on cognitive radio networks are limited to access the spectrum as secondary users, which results on throughput drops or a forced termination of its transmission. One way to address this issue is by implementing a cross-layer architecture in the network design.

The cross-layer architecture allows to include an alternative network design, where two layers (which are typically disjoint) can exchange information through an abstraction parameters process. This way, an objective function based on previously designed objectives can be evaluated to modify specific parameters on one or both layers (Foukalas et al., 2008; Fu et al., 2014). In fact, it has been shown that a performance improvement can be reached by including a cross-layer architecture on the design of cognitive radio networks (Umamaheswari et al., 2012). For instance, authors in (Chen et al., 2011; Danobeitia & Femenias, 2011; Han et al., 2006; Jia Tang & Xi Zhang, 2007; Matalgah et al., 2013; Wang et al., 2007) have proposed the design of resource allocation mechanisms based on cross-layer architecture to improve throughput performance, while guaranteeing QoS provisioning. On short-range CR networks (e.g. WPAN and WLAN), the deployment of m-Health and telemedicine applications have been mainly proposed for wireless sensor networks in a hospital environment (Chavez-Santiago & Balasingham, 2011; Mamoon et al., 2015; Naeem et al., 2015; Phunchongharn et al., 2010; Syed & Yau, 2013). Regarding telemedicine service delivery on CR networks, it has been shown that QoS guarantee can be provided by means of implementing dynamic spectrum allocation techniques (Feng et al., 2010a). However, at best of our knowledge, no proposal has been presented to enable telemedicine service delivery on the IEEE 802.22/WRAN standard.

1.2. Problem Statement

As it was mentioned in above section, the deployment of telemedicine wireless networks for rural regions is one of the most important scenarios, where the capacity of extending specialist medical services to underserved regions can have a high impact. Furthermore, because of the telecommunications infrastructure in rural regions is poor or null, the deployment of telemedicine networks in this type of scenarios represents a high challenge that goes from choosing a suitable technology to go farther, to offering an adequate QoS level for rural telemedicine services. By considering that medical services comprises patient's health information, the guarantee on QoS provisioning for telemedicine applications in BWA rural networks has become a major issue.

Typically, the IEEE 802.16/WiMAX standard has represented the deployment of BWA technology on rural regions. However, some isolated regions in rural environments may be located at distances longer than the maximum transmission distance offered by WiMAX. In consequence, the underserved rural populations can experience an access restriction to medical specialist services. This means that both, the hospital and patients have to incur on additional costs related to transportation, in order to receive or provide medical specialist services. In this context, a patient that requires a specialized medical treatment of consultation, diagnosis or follow-up could be unnecessarily exposed to painful or long travel times, from its local community to an urban hospital, in order to receive medical attention. Even more, in worst case scenario, all traveling costs would have to be covered by the patient, which for people coming from rural populations under extreme poverty conditions may become a major issue. Therefore, the consideration of emerging BWA technologies with a coverage ratio of up to 100 km, such as the IEEE 802.22/WRAN may become an alternative solution to extend telemedicine services to isolated and underserved regions, by means of the deployment of rural telemedicine wireless networks.

Because the IEEE 802.22/WRAN is a cognitive radio standard, its spectrum access is opportunistic and all subscribed users are limited to operate as secondary users of the channel bandwidth. Consequently, all secondary users are exposed to experience throughput drops, service interruptions, forced service termination, or a denial of network services. Thus, since telemedicine service delivery involves emergency scenarios, such as tele-diagnosis sessions for ambulances, the QoS provisioning on cognitive radio networks has become a major challenge. Particularly, on dynamic spectrum allocation mechanisms and on bandwidth availability that results from the presence of primary users on its operating channel. These two factors affect the provisioning of a QoS guarantee on cognitive radio telemedicine networks, which also impact the performance of dynamic spectrum allocation mechanisms on rural scenarios.

The QoS provisioning on cognitive radio networks, by means of resource allocation mechanisms and channel bandwidth availability, have been proposed on multiple research works (Ariananda et al., 2009; Chen et al., 2011; Danobeitia & Femenias, 2011; Han et al., 2006; Jia Tang & Xi Zhang, 2007; Matalgah et al., 2013; Sansoy & Buttar, 2015; Suseela & Sivakumar, 2015; Wang et al., 2007; Ying-Chang Liang et al., 2008; Yucek & Arslan, 2009). Additionally, several proposals have studied the impact of these two factors on the performance of health applications. For instance, authors in (Feng et al., 2010a) have established that resource allocation algorithms have a main role on performance of wireless telemedicine networks based on cognitive radio technologies. Furthermore, it has been shown that performance of resource allocation mechanism on cognitive radio networks, depend on bandwidth availability given by presence of primary users on the operating channel (Doost-Mohammady et al., 2014). From here, it can be inferred that it is highly important to consider these two factors on the design of resource allocation mechanisms for cognitive radio based telemedicine networks. However, despite that several proposals on cognitive radio networks have considered the effects of resource allocation mechanisms on the guarantee of QoS level for telemedicine applications, most of them omit the impact of bandwidth availability constraints given by the presence of primary users, based on the assumption of an ideal scenario where a secondary user has unrestricted access to spectrum usage.

On the other hand, the availability of a rural telemedicine model will allow to obtain and share information related to the network traffic profiles, the hierarchical structure among telemedicine services and utilization characteristics of network services, in a simple manner. The periodic exchange of this type of information could be used by base station to characterize telemedicine applications and determine their QoS requirements. This way, the base station could use this information to take the best decision on resource allocation, by means of reserving them based on particular priority characteristics of the telemedicine network. Therefore, from a design perspective of a resource allocation mechanism, the definition of a rural telemedicine model is the best way to characterize the priority scheme among services of tele-diagnosis, tele-monitoring and tele-consulting. Typically, the policy management on resource allocation is based on the QoS type of service (defined on MAC layer) that is associated with a specific type of telemedicine service. In fact, this technique has been widely adopted to provide a guarantee for QoS provisioning on the design of resource allocation mechanisms, both in telemedicine services (Feng et al., 2010a; Phunchongharn et al., 2010) as in any other type of network service (Chen et al., 2011; Matalgah et al., 2013). However, this simplistic perspective does not addresses two important issues: it does not consider a priority scheme based on the deployment scenario of telemedicine services, such as emergency or non-emergency; nor the bandwidth availability constraints given by presence of primary users. There are some proposals that address the issue of establishing a priority scheme for resource allocation in telemedicine service delivery; as in (Niyato et al., 2007a), where the highest resource reservation is for tele-diagnosis services, while availability on bandwidth resources for tele-consulting services is limited by a predetermined threshold. From a different perspective (Skorin-Kapov & Matijasevic, 2010), have provided a QoS guarantee for tele-consulting services, by means of mapping from QoS requirements for health services, to existing QoS types of services on network. Regarding mechanisms for resource allocation on cognitive radio networks that do not consider bandwidth availability constraints given by presence of primary users, the proposals presented in (Naeem et al., 2015; Phunchongharn et al., 2010), have shown a system performance improvement on the network capacity and QoS provisioning (i.e., transmission delay and loss probability), for health services. However, these proposals have been evaluated under an ideal deployment scenario where the base station performs a resource allocation based on the previous geo-location knowledge of primary users, or by assuming that health services can be considered as primary users since they have a higher priority on a telemedicine network. Even if these assumptions and considerations can be valid in a hospital environment, they cannot be applied on rural telemedicine networks where narrowband primary users (i.e., wireless microphones) can have unrestricted access to radio spectrum, without reporting its geo-location to the base station. Therefore, the results obtained on these proposals are not conclusive.

Most of cognitive radio telemedicine networks consider a design of dynamic resource allocation that is based only on existing QoS type of services. This means that even if two telemedicine users require the same type of service level, it does not imply that they are on same priority classification. In this context, a tele-diagnosis service on an emergency scenario would have to contend for system resources with other lower priority services that require the same type of service level. Because these proposals are evaluated on ideal deployment scenarios, the negative effects that result from this bandwidth contention issue are apparently not affecting the network performance. However, under a realistic deployment scenario there are different factors that importantly affect the telemedicine service delivery on rural regions, mainly, the traffic profile characteristics and the priority scheme for rural telemedicine services (Vergados, 2007; Vergados et al., 2006). Therefore, a resource allocation mechanism for telemedicine service delivery on rural regions that is only ruled by existing QoS type of services, could result on an erroneous restriction of resource allocation for higher priority services, such as tele-diagnosis. This issue can affect the telemedicine service delivery, from transmission disruptions and forced terminations of ongoing sessions, to a denial of service given by a rejection on admission requests. Even more, an erroneous resource allocation that occurs in a homogeneous traffic scenario, where telemedicine services that are not on highest priority and all of them require the same level of QoS, can affect significantly the telemedicine network performance. Thus, by including rural region characteristics on the design of resource allocation mechanisms, the resource reservation for telemedicine service delivery could fit better particularities on QoS requirements, which contributes positively to reduce the blocking probability, and interruption probability of telemedicine services.

It is important to notice that the design of resource allocation mechanisms for QoS provisioning on cognitive radio networks has been widely studied (Chen et al., 2011; Han et al., 2006; Jia Tang & Xi Zhang, 2007; Matalgah et al., 2013). Since secondary users on cognitive radio networks are limited to access spectrum usage in opportunistic manner, most of the designs of dynamic allocation spectrum algorithms propose a cross-layer architecture. In fact, several proposal have shown that the use of cross-layer architecture in the design of resource allocation mechanisms contribute to improve network performance while guaranteeing QoS provisioning (Danobeitia & Femenias, 2011; Wang et al., 2007). In rural telemedicine deployments, the constraints on channel bandwidth can be determined on lower network layers, such as PHY and MAC; and telemedicine service delivery characteristics related to data bandwidth requirements, utilization rates of telemedicine services, traffic profiles and rural telemedicine service particularities can be abstracted from upper layers, such as the APP layer. In this context, the design of a resource allocation algorithm that includes a cross-layer architecture could improve telemedicine network performance, by means of coupling the MAC and APP layers. Although several proposals have adopted the cross-layer architecture on the design of dynamic spectrum allocation mechanism for telemedicine applications (Feng et al., 2010a; Naeem et al., 2015; Phunchongharn et al., 2010), the presented results on characterization of telemedicine service delivery does not reflect the particularities of deployment scenario on the design of resource allocation mechanisms for rural regions.

1.3. Objectives

1.3.1. General Objective

The main objective on the presented research work is to study the effects of a priority scheme for QoS provisioning and the bandwidth constraints resulting from the presence of primary users, on the design of resource allocation mechanisms for rural telemedicine wireless networks based on the IEEE 802.22/WRAN standard. This way, new alternatives on the design of resource allocation algorithms can be proposed to improve telemedicine network performance in comparison with previously presented solutions for telemedicine service delivery.

1.3.2. Particular Objectives

In order to pursue the general objective presented on this research work, the following particular objectives are defined:

The design of a rural telemedicine model that considers the particular characteristics related to underserved and isolated regions, in order to establish a more realistic rural deployment scenario that defines the interaction scheme between patient and medics, the traffic profile of telemedicine applications and the types of telemedicine services, among others.

The design an admission control mechanism for rural telemedicine networks that consider various levels of service for telemedicine applications based on videoconference systems, in order to improve its system blocking probability.

The design of a dynamic spectrum allocation algorithm based on the IEEE 802.22/WRAN standard that considers a priority scheme among telemedicine services on rural deployment scenarios, in order to improve its interruption probability.

To evaluate and compare the performance of proposed algorithms by means of considering the IEEE 802.22/WRAN standard and realistic conditions on the deployment of rural telemedicine wireless networks.

1.4. Methodology

This research work is based on the methodology described in the following paragraphs:

Research on state of the art about telemedicine network deployments that includes QoS protocols for wireless communication networks and types of telemedicine services on rural region scenarios in order to implement a testbed that reflects the actual particular characteristics of rural telemedicine service delivery.

Literature review of dynamic spectrum access algorithms for telemedicine applications, with or without a priority scheme consideration. Choose the most relevant algorithms for telemedicine services and evaluate them on a rural deployment scenario. This way, the opportunity areas on the design of dynamic spectrum access algorithms for rural telemedicine networks can be detected.

By considering the opportunity areas detected, an initial design of a dynamic spectrum access algorithm is proposed. Here, a comparative performance evaluation with previously reported solutions is implemented, on rural deployment scenario conditions.

Based on observations about the results of comparative performance evaluation, an alternative admission control mechanism for tele-consulting services is included on the final design.

The final design is evaluated on rural deployment conditions for telemedicine service delivery, in order to establish a comparative with previous reported solutions, by considering the metrics of blocking probability and interruption probability.

1.5. Thesis outline

Chapter 2 presents in detail the telemedicine service delivery framework and the rural deployment scenarios characteristics. Furthermore, a review of the IEEE 802.22/WRAN standard is included in this chapter.

Chapter 3 presents a discussion about state of art on dynamic spectrum access algorithms, in order to determine the factors that should be considered on its design and evaluation. Additionally, this chapter includes a review of admission control mechanisms and scheduling algorithms oriented to telemedicine service delivery. This way, several important aspects can be identified as relevant to the design and evaluation of proposed algorithms.

Chapter 4 presents the design of proposed adaptive bandwidth management mechanism for admission control on rural telemedicine networks based on the IEEE 802.22/WRAN standard, for videoconference tele-consulting applications.

Chapter 5 presents the design, evaluation and performance results of the proposed scheduling algorithm for rural telemedicine service delivery based on IEEE 802.22/WRAN standard, for tele-diagnosis, tele-consulting and tele-monitoring applications.

Chapter 6 presents the conclusions about the design of scheduling algorithms and admission control mechanisms for telemedicine service delivery on rural deployment scenarios.

Finally, a list of the references that support this research work is presented.

1.6. Outcomes

The work on capacity analysis of rural broadband wireless access technologies proposed contributed to the following book chapter:

Magana-Rodriguez, R., Villarreal-Reyes, S., Galaviz-Mosqueda, A., Rivera-Rodriguez, R., & Conte-Galvan, R. 2015. Telemedicine Services over Rural Broadband Wireless Access Technologies: IEEE 802.22/WRAN and IEEE 802.16 WiMAX. In S. Adibi (Ed.), Mobile Health. Cham: Springer International Publishing, Vol. 5, pp. 743–769. Retrieved from http://link.springer.com/10.1007/978-3-319-12817-7_32

The work on Adaptive Bandwidth Management (ABM) admission control mechanism proposed contributed to the following paper:

Magana-Rodriguez, R., Villarreal-Reyes, S., Galaviz-Mosqueda, A., Rivera-Rodriguez, R., & Conte-Galvan, R. 2017. An Adaptive Cross-layer Admission Control Mechanism for Telemedicine Services over the IEEE 802.22 standard. IEICE Transactions on Communications, Vol. E101-B, No. 4, April, 2018.

Chapter 2. Wireless Telemedicine Service Delivery over BWA Technologies

2.1. Overview of Telemedicine

The use of technology to facilitate public health services is included in a discipline named public health informatics (PHI). The PHI comprises the application of information, computer science and technology to public health practice (Yasnoff et al., 2000). One of the many applications of PHI includes telehealth to enforce public health infrastructure by delivering medical services to underserved populations worldwide (Singh et al., 2010). According to (Institute of Medicine (U.S.), 2012), telehealth is defined as "the use of electronic information and telecommunications to support long-distance clinical care, patient and professional health-related education, public health and health administration technologies". By the above definition, telemedicine is commonly used as a synonym of telehealth (Lievens & Jordanova, 2007). However, the use of telemedicine services differs from telehealth because the first one refers exclusively to physicians or health specialists (e.g. nurses, pharmacists) (World Health Organization, 2010b).

A typical medical practice comprises: patient consultation, diagnosis, treatment and follow-up, where the patient's presence represents a necessary condition to treat multiple health conditions. Contrarily, the new medical paradigm delivers medical information remotely by merging information and communications technologies (ICT) with health services (Malindi, 2011). Thus, telemedicine tends to extend medical services through the use of telecommunications technologies (World Health Organization, 2010a).

The use of ICT for clinical activities includes the deployment of large bandwidth applications (i.e. voice over IP, video streaming, digital imaging, etc.) to provide telemedicine services that can be classified as: tele-consulting, tele-monitoring, tele-diagnosis, tele-education and medical database access (Vergados et al., 2006). Additionally, they may also include: initial patient evaluations, triage decisions, second opinion consultation, medical imaging and preventive medicine, among others (Grigsby, J. et al., 1994). In this way, rural regions with sparse technological infrastructure may have a limited offer of telemedicine services (Martinez et al., 2004a). Consequently, there is a health services gap where urban deployments tend to cover a wider gamma of telemedicine services, than those offered in rural areas with low population densities. Hence, rural telemedicine could contribute to close that gap by contributing to reduce travel times; costs of treatments and consultations, among others (Athavale & Zodpey, 2010; Dussault & Franceschini, 2006; Siddiqua & Awal, 2012).

Telemedicine comprises the use of information and communications technologies to deliver medical information oriented to health services from one location to another. Namely, telemedicine represents the distribution of medical services, traditionally offered by health specialists, through the use of telecommunications technologies. The use of communications technologies to improve health care delivery services has been growing in last decade, as a consequence to the rapid development shown by ICT technologies. By considering its advantages to support high-consumption network-resource applications (i.e. Voice over IP, Video Streaming, Digital Imaging, etc.) the people's demand of this kind of high data rate services has been also being growing. Consequently, network infrastructure connectivity and quality of service guaranteeing requirements, have become a major challenge in this matter.

Traditionally the medical practice is based on a face-to-face interaction to offer basic services of consultation, diagnosing and follow-up. These services comprise several methods and particular medical instruments over multiple health conditions and treatments. However, the use of communication technologies in the medical practice has shown its potential to extend the medical specialist evaluation capabilities over distance locations. For instance the use of remote robotic assisted surgery interventions has been used to assist medical specialists in the decision making process. In this context, the use of communication technologies as a tool capable to extend the medical service delivery over distance locations is called telemedicine services.

According to (Grigsby, J. et al., 1994) telemedicine applications comprise: initial patient evaluations, triage decisions, surgical follow-up, routine consultation or second opinion (primary care encounters), medical imaging, public health, preventive medicine and patient education among others. From a general perspective, telemedicine services include: tele-diagnosis, tele-education, tele-monitoring, tele-consultation and medical information databases. However, a large list of technological applications available to the implementation of telemedicine can be found in the literature. In this context two main factors should be considered in the deployment of any given telemedicine application, the first one is the medical application scenario and the second one is the medical service requirements.

The deployment scenario restricts the access to telemedicine services and applications due to the technological infrastructure availability to operate ICT. Therefore, health care services offered in urban areas tend to cover a wide range of telemedicine services compared to the rural areas with a low population density. In this context, rural telemedicine can be defined as the deployment of telemedicine services in underserved areas where the health specialist mobility is limited by transportation availability, large travelling times and the natural geographical barriers. In this matter, the broadband wireless access technology represents a feasible solution to implement telemedicine services by delivering medical services for isolated sparsely populated areas from a wide range of health specialists regardless of their location.

2.2. Telemedicine Service Delivery over BWA technologies

BWA networks can be categorized according to their maximum coverage area into Wireless Local Area Networks (WLAN), Wireless Wide Area Networks (WWAN), Wireless Metropolitan Area Networks (WMAN) and Wireless Regional Area Networks (WRAN) (Kuran & Tugcu, 2007). The most popular technologies capable to deliver high data rates up to 100 Mbps and 270 Mbps are WWAN and WLAN, respectively. The categories designed to cover large areas up to 50 or 100 kilometers are the WMAN and WRAN correspondingly.

The Institute of Electrical and Electronics Engineers 802.16 task group developed a family of standards for WMAN since 2001, which resulted in the IEEE 802.16 standards family (IEEE Computer Society et al., 2009). Similar to the WiFi Alliance certification based on IEEE 802.11 standards, the Worldwide Interoperability for Microwave Access (WiMAX) forum released a certification based on the IEEE 802.16 standard for WMAN. The certification aim is to guarantee technological interoperability between different IEEE 802.16 equipment vendors. With the release of the IEEE 802.16m standard in 2011 (known as mobile WiMAX release 2), the IEEE 802.16 family of standards included both fixed and high-speed mobile wireless services. The IEEE 802.16/WiMAX standard provides coverage ranges of up to 50 kilometers for line-of-sight (LOS) and up to 24 kilometers for non-line-of-sight (NLOS) transmissions. Therefore, it is considered a suitable technology to cover rural areas and a feasible solution to serve as a backbone network over a backhaul infrastructure. In contrast to fixed WiMAX, the IEEE 802.16m standard supports mobility and is fully capable of serving dense urban areas with a coverage ranging from 5 to 15 kilometers for NLOS transmissions. This version of the standard provides peak data rates of up to 70 Mbps (So-In et al., 2009). Through the adoption of quality of service (QoS) and scheduling mechanisms, WiMAX is able to support time constrained transmissions such as: multimedia streaming, real time surveillance, Voice over IP (VoIP), and multimedia conferencing (Li et al., 2007). Both technologies, IEEE 802.16/WiMAX and IEEE 802.22/WRAN, aim to offer wireless data services for fixed and mobile users comparable to those offered by wireline networks. Thus, both standards can be considered as emerging long range BWA technologies (Siddiqua & Awal, 2012).

The development of BWA technology has been growing not only to increase network connectivity, but also to provide higher data bandwidth. Lately, the use of wireless technology to support telemedicine applications are ranging, from transmission of biomedical signals for follow-up purposes, to transmission of high-definition ultrasound video for diagnosis purposes. Although, a network design methodology for rural telemedicine has been proposed in (Mendez-Rangel & Lozano-Garzon, 2012), the medical requirements based on the patient's condition may become an issue to define accurate traffic profiles for QoS provisioning.

Basic telemedicine deployments generally involve data acquisition from patients, transmission, processing and, depending on the offered services, remote storage. To be effective, any telemedicine solution must consider the QoS and bandwidth requirements for the different telemedicine services included within the deployment. Thus, in order to be a suitable alternative for the implementation of rural telemedicine networks, a particular BWA technology must be able to satisfy the QoS, bandwidth, and transmission range requirements of the network.

It has been shown that the IEEE 802.16/WiMAX standard presents a viable solution for the deployment of telemedicine and m-Health services (Alinejad et al., 2011, 2012; Chorbev et al., 2008; Chorbev & Mihajlov, 2009; Debono et al., 2012; Feng et al., 2010b; Ibikunle, 2009; Ito et al., 2011; Komnakos et al., 2008; Lam et al., 2009; Mignanti et al., 2008; Neves et al., 2007; Niyato et al., 2007b; Panayides et al., 2012, 2013; Pawar et al., 2012; Yun-Sheng Yen et al., 2011; Zhang, Ansari, et al., 2010b). The proposed m-Health applications cover different scenarios and can be categorized as: accident, clinical care, and home care (Komnakos et al., 2008; Niyato et al., 2007b). In (Chorbev & Mihajlov, 2009) and (Chorbev et al., 2008) the authors implemented a telecommunications backbone from a local clinic to a hospital using a WiMAX network aimed to support a medical information system (MIS). The MIS provided remote locations with telemedicine services such as: expertise sharing between physicians; remote consultations; access to laboratory analysis and tests results for physicians; access to a medical scientific website; and an appointment scheduling application for patients. An integrated system using a heterogeneous network architecture with WiMAX and WLAN was proposed in (Zhang, Ansari, et al., 2010b) with the aim to deliver m-Health services such as patient monitoring, medical data access, emergency and pre-hospital care. In a different perspective (Alinejad et al., 2011), introduces a mapping from multiple parameters of m-Health services to mobile QoS variables in WiMAX. In contrast (Alinejad et al., 2012), proposes a particular WiMAX dynamic subframe allocation for the support of m-Health services. Both proposals aim to enable telemedicine services under clinical care, home care, and emergency scenarios.

The development of tele-diagnosis services for ambulances has received particular attention due to its potential for improving the survival rate of patients in emergency situations. Typically, an emergency scenario requires providing real-time communication capabilities in order to support the transmission of biomedical signals, voice and/or video, all of them in a real time basis. Providing these capabilities will enable the provisioning of services such as pre-hospital care, remote assistance, and second opinion to paramedics. Different telemedicine and m-Health emergency systems such as WiMAX extensions for remote and isolated research data networks (WEIRD), (Mignanti et al., 2008; Neves et al., 2007), Emergency Wi-Medicine (EWM), (Lam et al., 2009), and Focused Assessment with Sonography for Trauma using Tele-echography (FASTele), (Ito et al., 2011), have been developed as integral systems based on WiMAX technologies. The WEIRD project includes applications for remote diagnosis, monitoring and follow-up in general telemedicine scenarios. EWM tries to improve hospital admission times through enhanced videoconferencing services. This is achieved by modifying the maximum video bit rates over a WiMAX platform (Lam et al., 2009). The FASTele project uses WiMAX technology to provide a wireless link between an ambulance and a hospital. This link is used by a physician located in the hospital to remotely control a portable and attachable tele-echography robot system (Ito et al., 2011). Other proposals focus on modifications to the IEEE 802.16/WiMAX standard in order to transmit high quality video images from ultrasound devices in emergency situations (Debono et al., 2012; Panayides et al., 2012, 2013). In (Debono et al., 2012), a cross-layer approach based on region of interest (ROI) algorithms and resource allocation mechanisms are used to guarantee QoS parameters in the transmission of ultrasound video data. Other approaches consider the use of H.264/advanced video coding (AVC), (Panayides et al., 2012, p. 264), or high-efficiency video coding (HEVC) standards, (Panayides et al., 2013), to enable the transmission of high resolution ultrasound video, resulting in quality comparable to that of in-hospital examination standards.

Another telemedicine and m-Health area that has drawn much attention is the development of tele-monitoring systems for home care scenarios. These systems transmit the patient’s biomedical signals, enabling health specialists to remotely evaluate their health status. In this context, WiMAX and IEEE 802.22 can fulfill the requirements specified in (Pawar et al., 2012) to enable extra-BAN communication for m-Health applications. For example, in (Yun-Sheng Yen et al., 2011) a tele-monitoring system framework based on WiMAX technology for chronic hypertension patients is proposed.

Although all the previously mentioned projects show that WiMAX is a viable technology to implement telemedicine and m-Health services, its coverage range below 50 kilometers can represent a drawback for its deployment in certain rural scenarios. In fact, deployment of telemedicine services in scarcely populated areas with urban centers separated by long distances may require the use of broadband satellite communications (BSC), leaving the use of WiMAX as a wireless last mile solution (Ibikunle, 2009), and furthermore, a drawback of a using BSC solution is its operational cost.

2.2.1. Rural Telemedicine Service Delivery

Currently there exists an unequal distribution of medical services between urban and rural areas (Dussault & Franceschini, 2006). In fact, providing medical services for rural regions faces several challenges such as: health specialists mobility issues, poor technological infrastructure, large travelling times, and natural geographical barriers among others (Siddiqua & Awal, 2012). In this context, telemedicine has been considered a fundamental tool to provide medical services for remote rural communities (Malindi, 2011).

One of the main challenges in rural telemedicine is mobility (Wickramasinghe et al., 2010). Since health specialists are often concentrated in main urban centers, rural patients may be exposed to long traveling times in order to be attended. This condition may represent a major effort for post-operative, re-convalescing and elderly patients (Sudhahar et al., 2010). Wireless rural telemedicine presents an alternative solution not only to reduce travel time issues, but also to extend health services by offering health care specialist consultation in situ.

From a rural telemedicine perspective, the health issues prevalent among rural regions and their particular needs must be taken into account. Thus, the telemedicine services offered should focus in attending critical health issues prevalent in rural regions, which may be different to those found in large urban centers. Another aspect that must be considered is the technological infrastructure found in the place where the rural telemedicine solution will be implemented. For example, (Whitacre et al., 2007) present a study of the economic impact of rural hospitals in the United States, where it was assumed that the telemedicine sites had wired connectivity. Such assumption may not be used to perform a similar study for developing countries, as most rural clinics may not have wired connectivity. Indeed, there are several examples in the literature (Ali et al., 2010; Bravo et al., 2013; Fong & Pecht, 2010; Foster, 2010; Husni & Waworundeng, 2011; Kachieng'a, 2011; Lu et al., 2010; Luo Kun & Wen Hao, 2010; Meethal & J., 2011; Mulvaney et al., 2010; Polze et al., 2010; Sharma & Kunwar Singh Vaisla, 2012; Sudhahar et al., 2010; Whitacre et al., 2007; Wickramasinghe et al., 2010; Zambrano et al., 2012; Zhu & Dong, 2011), that propose the deployment of wireless rural telemedicine solutions in order to offer medical services to rural populations in developing countries.

Although a large variety of telemedicine services have been implemented worldwide, there is not a standard guideline that establishes the characteristics that should be considered for rural telemedicine deployments (Kapoor L et al., 2005; Meethal & J., 2011; Mulvaney et al., 2010; Sharma & Kunwar Singh Vaisla, 2012; Wickramasinghe et al., 2010; Zhu & Dong, 2011). To this end, a review of relevant rural telemedicine projects of different world regions has been performed, specifically cases of rural regions in Italy (Zanaboni et al., 2009), Mexico (Pacheco-López et al., 2011), Somalia (Zachariah et al., 2012), and Bolivia (Vargas et al., 2014) were considered. These projects are briefly discussed in the following paragraphs.

A pilot project named TELEMACO was deployed in the Lombardy region of Italy. It was operational for more than 4 years (2006-2010). This project was aimed to provide telemedicine services such as tele-consulting and tele-education for 30 rural areas. During the last two years of the project, a total of 5,350 tele-consulting sessions were established to provide second-opinion support for general practitioners. By considering a typical 5 days working week, it can be assumed that the TELEMACO project received an average of 10 tele-consulting requests per day, which means that on a typical 8 hours working day an average of one session per hour should be considered.

As reported in (Zachariah et al., 2012), within one year a total of 527 tele-consulting services were provided between clinicians located in the pediatric ward of the Guri'el district hospital in Somalia and a specialist pediatrician located in Nairobi, Kenya. By considering a typical 40 hours working week, it can be assumed that the average arrival rate of tele-consulting sessions is one request every four hours.

In the case of Bolivia there is a telemedicine network deployed called RAFT-Altiplano, (Vargas et al., 2014). More than 20 health institutions distributed in the broad area of the Bolivian's Altiplano are part of this telemedicine network. The project includes tele-consulting services between physicians from three departments of Bolivia i.e., La Paz, Oruro and Potosí. The RAFT-Altiplano project comprises up to 15 medical specialties that are provided by the Arco Iris Hospital, located in La Paz. According to the authors, an average of 700 tele-consultations originate from rural regions every year. By considering similar working week conditions as in Italy and Somalia examples, it can be assumed that the RAFT-Altiplano project has been attending an average of one tele-consulting session every three hours.

2.2.2. Telemedicine Service Delivery: Mexico

The definition of rural environments differs from one country to another, which makes very difficult to obtain appropriate statistical data to construct a general model for a case study. For instance, the National Institute of Statistics and Geography (INEGI) in Mexico states that up to 51% of Chiapas's population is classified rural, because they have less than 2,500 inhabitants. Moreover, up to a 99% of the municipalities that comprises the Chiapas state have a population density under 500 inhabitants per square kilometer, which turns it on a suitable region for the deployment of the IEEE 802.22 standard. In this context, one BS located in the urban city of Tuxtla Gutierrez may cover up to 25 rural populations, in a cell radius of up to 34 kilometers. According to Mexico's Ministry of Health, in the Chiapas state a maximum density of 0.14 health care centers per square kilometer is considered, because of its large territorial extension. This means, that in best case scenario the minimum distance between two health care centers is approximately 7 kilometers, but in worst case scenario (that represents approximately 65% of municipalities) the distances are ranging from 25 to 100 kilometers among them. Consequently, the travel times from rural populations to urban cities could be very long, to patients that require specialized medical treatment for consultation, diagnosis or follow-up. In addition to long travel times, the covering of travel costs is considered a difficulty for patients enrolled into a specialized treatment, since it has been established the extreme poverty issue that characterizes rural populations in the Chiapas state.

Regarding other telemedicine deployments In México, it has been found that in Nuevo Leon state a telemedicine public program has been operating since 2002. This network includes 6 rural hospitals and 4 rural clinics located in 9 municipalities, and during the year 2014, a total of 3,985 tele-consulting sessions were performed (Ramos-Contreras, 2016). This Mexican initiative has been operating as part of a public health program supported by the ministry of health. In this project, satellite communications systems are used to connect rural facilities in the Nuevo Leon municipalities of Galeana, Linares, Montemorelos, Santiago and Allende, as well as the Metropolitan hospital in the city of Monterrey. Thus, it can be assumed that on a typical working day, the Monterrey telemedicine center receives on average 15 tele-consulting session requests, which results on an average arrival rate of two tele-consulting sessions every hour.

2.3. Challenges and Opportunities of Telemedicine Service Delivery

Enabling effective telemedicine services allows saving time and reducing costs for both, patients and healthcare institutions (Kailas & Ingram, 2009). Thus, telemedicine services are particularly valuable in communities where transportation issues and the lack of medical specialists pose major difficulties for the provisioning of health services, as in the case of rural communities located outside major urban areas (Martinez et al., 2004b). In this context, the deployment of Broadband Wireless Access (BWA) networks is considered a key enabler that could radically increase the access of medical services for isolated and underserved rural regions (Bravo et al., 2013; Chorbev et al., 2008; Ibikunle, 2009; Mandioma et al., 2007; Su & Soar, 2010; Ying Su & Caballero, 2010).

Currently there is a growing interest for the development of BWA-based technological solutions to enable remote monitoring of patients in rural areas (Kas et al., 2010; Meethal & J., 2011; Mulvaney et al., 2010; Niyato et al., 2007a; So-In et al., 2009; Zhu & Dong, 2011). Telemedicine services that could be offered over such networks include: medical second opinion, post-operatory follow-up sessions, and primary care on chronic diseases among others (Hadjidj et al., 2013; Hamdi et al., 2014; Kulkarni & Ozturk, 2011; McGregor et al., 2007). As an example, the use of IEEE 802.16/WiMAX has been previously proposed in (Bravo et al., 2013; Mandioma et al., 2007; Ying Su & Caballero, 2010), to support web-based telemedicine applications (e.g. medical information systems). The IEEE 802.16/WiMAX standard and the solutions introduced in these works state maximum transmission distances of 25 km and 50 km in non-line-of-sight and line-of-sight conditions, respectively. Particularly, a BWA network based on IEEE 802.16/WiMAX can offer peak data rates up to 22.44, 14.96 and 7.48 Mbps with 64-QAM, 16-QAM and QPSK modulations respectively. Regarding transmission ranges from the base station (BS), in NLOS conditions the IEEE 802.16/WiMAX standard can cover up to 6 km with 64-QAM, 11 km with 16-QAM, and 25 km with QPSK (Tarhini & Chahed, 2007). Consequently its use for telemedicine service delivery from urban centers towards distant rural areas is limited (Barjis et al., 2013; Mattson, 2011). Thus, in order to fulfill the potential that BWA-based rural telemedicine provisioning has to offer, there is the need of extending the coverage ratios beyond those offered by IEEE 802.16/WiMAX-based solutions. Thus, the recent switch-off of analog terrestrial TV networks presents an opportunity to provide long-distance high data rate wireless connectivity by using the freed spectrum.

In order to clearly identify similarities and differences between the IEEE 802.22/WRAN standard and the IEEE 802.16/WiMAX standard an overview of both is presented in next subsection. This way, the reader can obtain a better understanding about the challenges that should be considered when deploying rural telemedicine networks based on the IEEE 802.22/WRAN standard, in comparison with implementations based on the IEEE 802.16/WiMAX standard.

2.4. Overview of The IEEE 802.22/WRAN Standard

In the final quarter of 2011, the IEEE 802.22 standard was released as the first cognitive radio wireless regional area network technology (IEEE-SA Standards Board, 2011). From a general perspective, the cognitive radio technology considers a hierarchical dynamic spectrum access by classifying primary and secondary users, where the first type of users are entitled to operate on a channel frequency, and the secondary ones are allowed to operate on the same channel by providing a protection to primary users with non-interference constraint. Two DSA schemes are defined on cognitive radio networks, the overlay access and the underlay access. The overlay access states that SUs are allowed to transmit on a channel frequency, only when non-presence of PUs has been detected on it, while the underlay access scheme allows simultaneous transmissions of both types of users on the same channel frequency only if the secondary user does not cause interference to the primary user transmission. In this context, the IEEE 802.22/WRAN standard establishes a mandatory overlay DSA scheme as a condition to operate over channel's frequencies allocated in the VHF/UHF bands, named TV white space channels.

The TVWS channels result from the analog TV switch-off process. This means that several digital TV signals have been reallocated to a single TV channel bandwidth, which once was occupied by only one analog TV signal. This highlights the importance of cognitive radio technology to modify the operation of the IEEE 802.22 standard, by protecting licensed PUs, through a spectrum sensing function to detect their presence in the operation channel. Hence, the system can operate as a SU of the TVWS channel, limited only by the presence of three defined PUs: Analog or Digital TV signals, and auxiliary broadcast devices (i.e. wireless microphones). At present, the United States has regulated the access to TVWS channels as unlicensed frequency bands. Other countries such as Mexico, European Community Countries, South Africa and China, among others, may also consider to follow the same regulation scheme, but they concerned about its coexistence with other technology standards already deployed (i.e. cellular network technologies).

Due to the propagation characteristics of TVWS channel frequencies, the maximum transmission distance of the IEEE 802.22 standard is beyond 60 miles, therefore its design is focused to cover rural environments. The deployment of telemedicine networks requires quality of service provisioning, by means of parameters such as transmission delay, packet loss rate and system throughput, among others. Thus, the restriction to operate as a SU by using cognitive radio technology represents a major challenge in the deployment of telemedicine networks. Nevertheless, it has been shown in (Feng et al., 2010a), that CRNs are fully capable to guarantee QoS parameters for wireless telemedicine applications, by designing resource allocation methods, for urgent and periodic traffic profiles.

Thus, the recent switch-off of analog terrestrial TV networks presents an opportunity to deliver high data rates in rural and suburban areas through TV white spaces technology. In fact, the TV broadcast bands in the high-VHF/low-UHF range are ideal for covering large areas in scarcely populated rural environments because of its propagation characteristics. Hence, the IEEE 802.22/WRAN standard offers an alternative to provide wireless broadband access over large areas as observed in the comparative chart shown in Fig. 1.

Because of its coverage area and provided data rates, the use of IEEE 802.22/WRAN based networks presents an opportunity for the deployment of rural telemedicine services over rural areas where the IEEE 802.16/WiMAX coverage is too short and the deployment of BSC is unviable because of its cost. In other words, the deployment of IEEE 802.22 based telemedicine solutions will enable to provide coverage beyond 50 km without the need of recurring to the deployment of high cost broadband connectivity solutions. Nevertheless, before being able to deploy an IEEE 802.22 telemedicine solution there exist several issues that must be addressed.

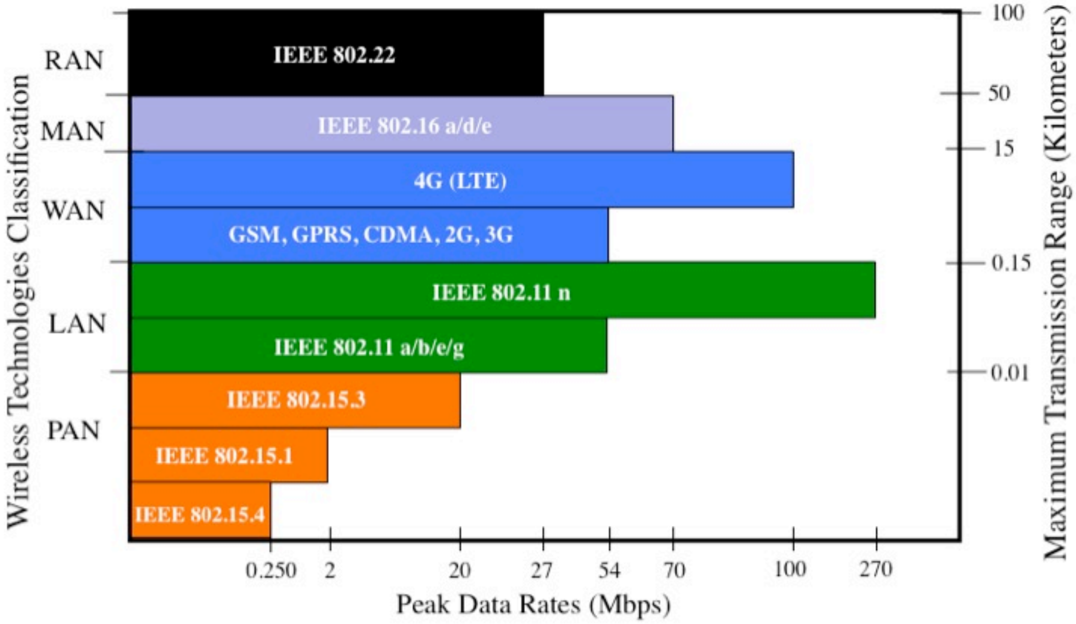


Fig. 1. Wireless technologies classifications comparison between data rates and coverage area.

The IEEE 802.22 standard defines a point to multipoint WRAN implementation over TVWS. Its basic network topology considers the deployment of a base station and several customer premises equipment. Before using a particular TVWS channel, the BS and the CPE must verify that it is not being occupied by transmissions from primary users. The IEEE 802.22 physical layer (PHY) requires the use of an orthogonal frequency-division multiple access (OFDMA) scheme where each user is assigned a set of resource blocks for downstream and upstream connections. Additionally, the IEEE 802.22 multiple access procedure includes a quality of service mechanism that considers four different types of service for different traffic profiles. However, the standard leaves to the implementer how to assign the priorities depending on the application scenario.

One of the main issues to overcome for the implementation of effective telemedicine services over IEEE 802.22, is the spectrum allocation restriction caused by the protection of primary users. In fact, this restriction may cause a drop in the throughput because of the requirement of stopping transmissions in the frequency bands where the primary users are found (Fitch et al., 2011; Gao et al., 2012; Shellhammer et al., 2009). Thus, before deploying telemedicine services over IEEE 802.22, the design of mechanisms aimed at guaranteeing the availability of enough bandwidth resources for telemedicine applications, even in the presence of primary users, is needed. Even though the standard considers four different levels of QoS, the solution to this problem is not trivial, as none of the QoS levels guarantees availability of resources when a primary user is found. One way to overcome this issue is by means of resource allocation mechanisms that enable a dynamic reservation of resources according to the bandwidth requirements of telemedicine services. As IEEE 802.22 uses OFDMA, a natural way of reserving resources is by means of a scheduling algorithm. Therefore, a properly designed scheduling algorithm should enable the implementation of telemedicine services over IEEE 802.22, by providing the required resources without violating the spectrum restriction constraint of protecting the primary users.

2.4.1. Overview of PHY and MAC Layers

The IEEE 802.22 air interface includes 50 channels with 6 MHz of bandwidth, ranging from 54 to 698 MHz for countries of US and Canada. In Western Europe and many other countries in Asia, Africa and the Pacific, the channel bandwidth could be of 7 MHz or 8 MHz for frequencies ranging from 50 MHz to 227 MHz, or ranging from 474 MHz to 858 MHz, respectively. A single air interface based on 2048 carriers using orthogonal frequency-division multiple access is used to provide a reliable link for NLOS operation in a single time-domain duplex mode. Because different channel delays must be supported, four different lengths of cyclic prefix defined as 1/4, 1/8, 1/16, and 1/32 are considered. The standard includes an adaptive modulation and coding (AMC) scheme defined by the PHY layer description. The AMC considers the quality variations in the wireless link (caused by fading, interference, etc.) to provide enhanced data rates between a base station and a customer premise equipment. Therefore, the use of quaternary phase shift keying (QPSK), 16-quadrature amplitude modulation (16-QAM), and 64-quadrature amplitude modulation (64-QAM), with four coding rates (1/2, 2/3, 3/4, 5/6) for each OFDMA subcarrier are considered in IEEE 802.22 to provide robustness over time-variable wireless links.

The MAC layer includes cognitive capabilities for a reliable protection of primary users in TVWS frequency bands and for enabling self-coexistence between IEEE 802.22 networks located nearby. The frequency bands used by an IEEE 802.22 cell will depend on the availability of TV channels, which is inherent to the geolocation of both the BS and CPE. Additionally, the use of frequency bands by the BS and the CPE will be restricted by an U.S.-FCC Part 74 device broadcast transmissions (i.e. narrowband primary users -NPU- like wireless microphones). Therefore, the cognitive capabilities of IEEE 802.22 networks rely on their capacity to detect the primary users (PUs – TV transmissions and NPUs) over all the possible operational channels. Thus, the CPE and the BS will be forced to stop any transmission in channels where PUs are detected. In case a CPE detects a PU it will notify the BS via an urgent coexistence situation message. Then, an incumbent detection recovery protocol (IDRP) will be performed such that the BS will reallocate the CPE transmissions to a backup channel. In case the BS detects a PU, it will run the IDRP to reallocate all the transmissions from the CPEs that were using the channel where the PU was found.

The IEEE 802.22 standard includes a normal operational mode, where one WRAN cell transmits over an entire channel using all the available frames merged into a superframe. Additionally, a self-coexistence operational mode is considered in the standard. This operational mode aims to coordinate transmissions from multiple WRAN cells by assigning one or several frames to one particular WRAN. The self-coexistence mode uses a coexistence beacon protocol (CBP) operated by BSs detecting concurrent transmissions from other WRANs. The CBP protocol requires broadcasting a packet containing BS identifiers through a dedicated self-coexistence window (SCW). This facilitates network discovery, coordination and spectrum sharing.

The IEEE 802.22 systems use a connection-oriented protocol to exchange information between the BS and the CPEs. This protocol allows the CPEs to request particular bandwidth allocations from the BS in a dynamic fashion. However, as granting all the bandwidth allocations requests from different CPEs may consume all the available system resources, the BSs must decide how to assign resources to a particular

CPE. There is not a pre-defined way to perform this, leaving the resource allocation scheduling as an open issue. Commonly, the scheduling algorithms look to provide a certain degree of fairness regarding resource allocation to CPEs. However, in the case of telemedicine networks an "unfair" scheduling algorithm that prioritizes the traffic generated by telemedicine and m-Health applications may be required.

In addition to cognitive radio capabilities, the IEEE 802.22 MAC layer includes geolocation operations, channel database access and spectrum sensing initialization. These functionalities are needed for synchronization, ranging, capacity negotiation, registration, and connection setup authorization processes. The BSs and the CPEs use satellite-based geolocation technology to perform two main tasks: synchronization with other WRAN networks through a global time source, and verification of unused TV channels on the region by referring to an up-to-date database. Nevertheless, regardless of the channel status (used or unused) registered in the database, the spectrum sensing function must be performed by both the CPEs and BSs.

The IEEE 802.22 MAC frame structure comprises two parts: the downstream (DS) sub-frame, and the upstream (US) sub-frame. The MAC frame structure is formed horizontally by time symbols and vertically by OFDM subchannels. The total frame duration is 10 ms divided in 26 to 41 time symbols. For example, if the TV channel bandwidth is 6 MHz the maximum number of time symbols per frame is 31 (by considering a 1/32 cyclic prefix). The standard allows to allocate symmetric or asymmetric data bandwidths for the DS and US. This allocation is not restricted to be fixed, thus it can be dynamically adjusted according to data bandwidth requests by the CPEs. The DS sub-frame includes: frame preamble, frame control header (FCH), Downstream/Upstream Map (DS/US MAP), downstream channel descriptor (DCD), upstream channel descriptor (UCD), and downstream payload. The US sub-frame includes: the upstream payload, optional signaling contention intervals (for notifications, bandwidth requests, and ranging protocols), and an optional self-coexistence window. When two or more WRAN networks are nearby, the SCW is allocated at the end of the sub-frame as defined by the IEEE 802.22 opportunistic coexistence beacon protocol. An example of an IEEE 802.22 MAC frame time/frequency structure is shown in Fig. 2.

The IEEE 802.22 standard provides three types of QoS schemes: unsolicited grant service (UGS), polling service (PS), and best-effort service (BE). These schemes support constant bit rate and variable bit rate traffic to enable real and non-real time transmissions. The UGS service is designed to carry CBR traffic where fixed-size data packets are transmitted periodically. Thus, the BS will reserve the required resources (if available) to support CBR traffic transmissions from the CPE with the aim of reducing the negative effects of delay and jitter. The PS service offers two subtypes supporting two kinds of VBR traffic: real-time and no real-time. These service subtypes are called real-time polling service (rtPS) and non-real-time polling service (nrtPS). The rtPS service supports the transmission of real-time data streams by dynamically assigning system resources based on the QoS requirements. Contrary to rtPS, the nrtPS service just assigns a minimum bandwidth that can be used for the transmission of no real-time data streams. Lastly, the BE service does not guarantee any QoS, since its bandwidth allocation depends on the policies used for the other service types.

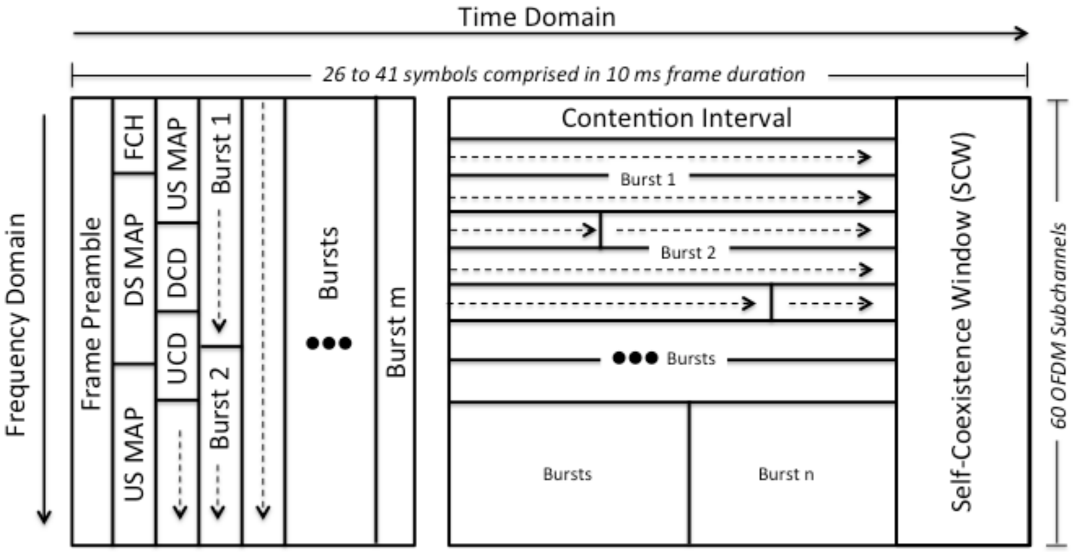


Fig. 2. Example of the IEEE 802.22 standard MAC frame (time/frequency structure).

Because of the QoS schemes included in the IEEE 802.22/WRAN standard, it seems to be a viable technology for the deployment of wireless telemedicine networks. Nevertheless, an open research issue for the implementation of IEEE 802.22/WRAN telemedicine network concerns how to deal with possible throughput drops caused by sporadic PU transmissions (detected by either the BS or the CPEs).

2.5. Overview of The IEEE 802.16/WiMAX standard

The air interface of IEEE 802.16/WiMAX operates at unlicensed spectrum between the 2-11 GHz frequency range or licensed spectrum between the 10-66 GHz frequency range. For NLOS scenarios, IEEE

802.16/WiMAX supports two different air interfaces at the PHY layer: OFDM and OFDMA (Kumar et al., 2011; Prasad, 2010). Furthermore, the IEEE 802.16e includes a scalable OFDMA (S-OFDMA) air interface. The standard supports channel bandwidths ranging from 1.5 MHz to 20 MHz. Additionally, it considers the use of adaptive modulation and coding. Thus, the modulation and coding schemes employed in each OFDM subcarrier are set based on a link quality indicator. The standard includes a connection oriented MAC layer definition to support different types of QoS. Hence, the MAC protocol considers an unidirectional connection for all transmissions between BS and mobile station (MS) (Chahed et al., 2009). The standard defines two medium access schemes: time division duplex (TDD) and frequency division duplex (FDD). In both cases, bandwidth for QoS connections can be requested.

As the BS manage the network, it assigns the bandwidth reservation and transmission opportunities for each MS. However, each MS can dynamically request bandwidth from the BS by using a bandwidth-request protocol data unit in a contention or contention-free mode (e.g. polling). Additionally, IEEE 802.16e defines different bandwidth-request protocols such as: unsolicited request, poll-me bit, piggybacking, bandwidth stealing, codeword over quality indicator channel (CQICH) and code division multiple access (CDMA) code-based on bandwidth-request protocols.

Similar to the IEEE 802.22/WRAN standard, there are different scheduling service types in IEEE 802.16/WiMAX, namely: unsolicited grant service (UGS), extended real-time polling service (ertPS), real-time polling service, non real-time polling service, and best-effort service. Each of these service types has its own QoS parameters like minimum throughput requirement and delay/jitter constraints.

2.6. IEEE 802.22/WRAN and IEEE 802.16/WiMAX Main Characteristics Comparison

A comparison between the main characteristics of the IEEE 802.22/WRAN and IEEE 802.16/WiMAX standards is presented in Table 1. Although both standards show some similarities at the PHY and MAC layers (e.g. the use of OFDMA, ACM, QoS types of services), the bandwidth allocations, transmission ranges, and MAC frame sizes are different.

As previously mentioned, IEEE 802.22/WRAN networks operate as secondary users in TVWS frequency bands. Operation in these bands within the United States is unlicensed as far as there is not interference to PUs. The rules to use TVWS channels are still under review worldwide. However, Mexico, the European Community, South Africa, and China, among other countries, are considering following the United States TVWS regulation model. Therefore, it is fair to assume that IEEE 802.22/WRAN networks potentially have 60 unlicensed channels to operate worldwide. In contrast, most of the operating frequencies considered in the IEEE 802.16/WiMAX standard are licensed, except by the 2.4 GHz and 5.8 GHz frequency bands, which are already used by other wireless technologies (e.g. WiFi, ZigBee, Bluetooth).

Because IEEE 802.16/WiMAX operates at frequencies above 2 GHz, propagation characteristics limit its maximum transmission range to 50 kilometers for LOS and to approximately 24 kilometers for NLOS. In comparison, the IEEE 802.22/WRAN standard operating bands are allocated below 900 MHz. Therefore, the maximum transmission range of IEEE 802.22/WRAN doubles the range offered by IEEE 802.16/WiMAX, reaching up to 100 kilometers for LOS and up to 33 kilometers for NLOS transmissions.

Another difference between the IEEE 802.16/WiMAX and IEEE 802.22/WRAN standards relies on their maximum data rates. The IEEE 802.16e standard is fully capable of achieving a maximum data rate of up to 40 Mbps. In comparison the IEEE 802.22 standard supports up to 31 Mbps using a 64-QAM modulation scheme (802.22-2011, 2011, p. 22; Chakraborty & Bhattacharyya, 2010). However, IEEE 802.22 achieves this data rate using a bandwidth channel of only 8 MHz instead of the 20 MHz required by the IEEE 802.16e standard.

Table 1. Comparison between IEEE 802.16 and IEEE 802.22

System parameters	IEEE 802.16/WiMAX	IEEE 802.22/WRAN
Frequency band	2-10 GHz	54-862 MHz
Channel bandwidth	≥ 5 MHz	6, 7, 8 MHz
Transmission rate	10-40 Mbps	23-31 Mbps
Cell radius	Up to 50 kms.	Up to 100 kms.
Multiple access	TDMA or OFDMA	OFDMA
MAC frame size	5 ms	10 ms

Another difference between the IEEE 802.16/WiMAX and IEEE 802.22/WRAN standards relies on their maximum data rates. The IEEE 802.16e standard is fully capable of achieving a maximum data rate of up

to 40 Mbps. In comparison the IEEE 802.22 standard supports up to 31 Mbps using a 64-QAM modulation scheme (802.22-2011, 2011, p. 22; Chakraborty & Bhattacharyya, 2010). However, IEEE 802.22 achieves this data rate using a bandwidth channel of only 8 MHz instead of the 20 MHz required by the IEEE 802.16e standard.

Maximum data rate is only achieved when the distance between the BS and the user (MS in WiMAX and CPE in IEEE 802.22/WRAN) is relatively short, such that 64-QAM can be used without incurring in an unacceptable bit error rate (BER). In order to compare the capabilities offered by the IEEE 802.22/WRAN and IEEE 802.16/WiMAX standards, Fig. 3 shows a graphical representation of the modulation scheme used for a given coverage area in a typical deployment scenario.

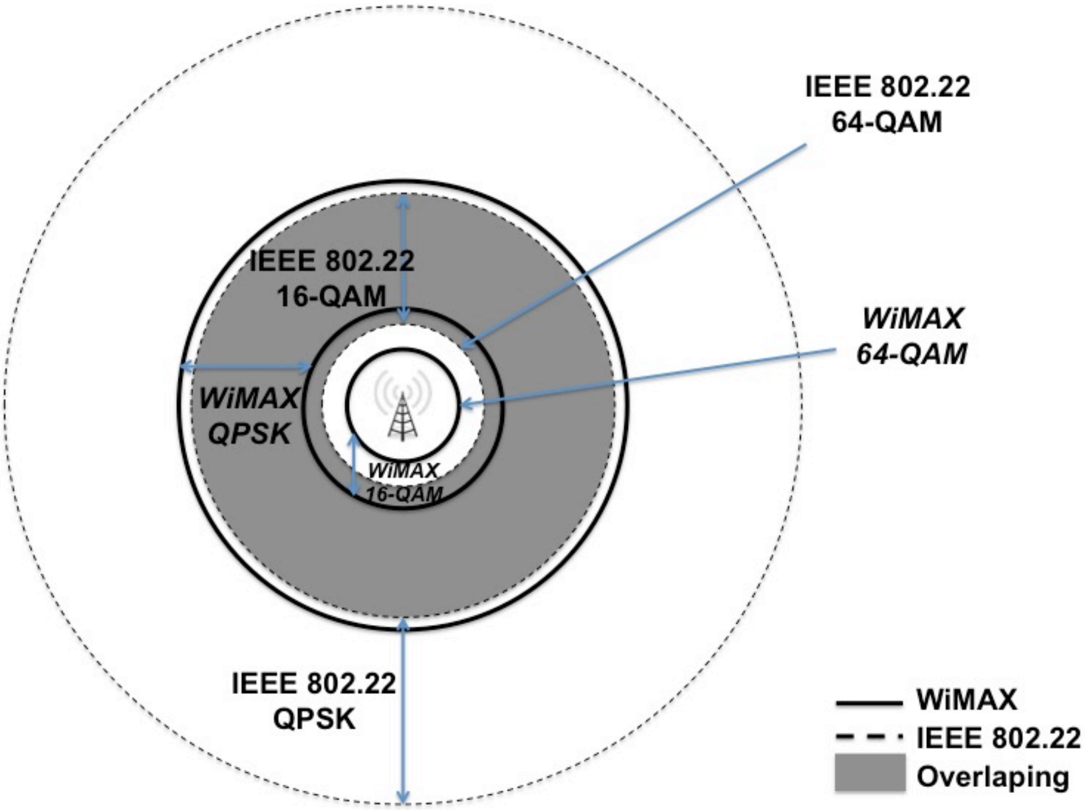


Fig. 3. Modulation schemes used for a given coverage range for typical IEEE 802.22/WRAN and IEEE 802.16/WiMAX deployments.

Since the coverage range of IEEE 802.22 is larger than that of IEEE 802.16, the overlapping between IEEE 802.22 QPSK and IEEE 802.16 is minimal. In contrast, it can be seen that the areas covered by IEEE 802.22 16-QAM and IEEE 802.16 QPSK are similar (they are almost completely overlapped). Furthermore, the area corresponding to IEEE 802.22 64-QAM completely covers the area corresponding to IEEE 802.16 64-QAM and a significant portion of the area corresponding to IEEE 802.16 16-QAM. This means that the range achieved with IEEE 802.22 for QPSK, 16-QAM, and 64-QAM is larger than that achieved with WiMAX.

2.7. Chapter Summary

Telemedicine services represent restrictive applications mostly related to patient's consultation, diagnosis and monitoring through their biomedical signals by health specialists. Since wireless telemedicine services depend on technological infrastructure, rural area coverage has been considered an important challenge, and the Institute of Electrical and Electronics Engineers 802.16/WiMAX standard has been used to provide broadband wireless access because of its MAC and PHY characteristics.

However, the switch-off of the analog terrestrial network presents the opportunity of delivering high data rates over large coverage areas by means of TV white spaces technology using cognitive radio capabilities. Hence, at the end of 2011 the IEEE Working Group for Wireless Regional Area Networks released the first TVWS standard named IEEE 802.22. Within this standard, bandwidth availability depends on the geographical location of the base station and the customer premise equipment. Thus, a model to evaluate the suitability of IEEE 802.22 and WiMAX for the deployment of rural telemedicine networks is required. The model should consider specific traffic profiles based on the telemedicine services that will be offered over the rural wireless telemedicine network. Therefore, in the following Chapter a telemedicine framework of telemedicine traffic profiles requirements and its importance on the design of resource allocation mechanisms based on bandwidth availability is presented.

Chapter 3. Dynamic Spectrum Allocation in Wireless Telemedicine Networks

3.1. Overview of TVWS and Cognitive Radio Networks

The European Community initiated the analog switch-off process to migrate TV terrestrial signals from analog to digital since 2000. This process is part of the revision about frequency allocation planning made by the International Telecommunication Union (ITU), which is based on the international Stockholm's agreements of 1961. The main goal of the frequency allocation revision was to develop a new frequency-planning map that includes digital signals. This way, the new frequency allocation scheme that results of the TV analog switch-off process will contribute to improve usage efficiency of radio spectrum resources, by means of re-assigning the new available frequency bands (named TV White Spaces) to innovative wireless emerging technologies and services. In 2006, The Geneva meeting agreements established a common platform to build the new digital frequency-planning scheme. These settlements comprise the guidelines about interference protection for primary users and spectrum access schemes for secondary users. Currently, the United States of America, Canada and Mexico have concluded with the analog switch-off process. The Latin American countries of Brazil, Colombia, Chile, Argentina, Costa Rica, El Salvador, Venezuela, Peru and Bolivia are scheduled to finish this process at most in 2020.

In a worldwide context, the United States of America was the first country to issue the legislation via the Federal Communications Commission that contemplates the access and usage policies of TVWS (FCC, 2008b). In 2011, the Federal Communications Commission (FCC) released a regulation that established the requirements that should be observed by secondary users of TVWS (FCC, 2011). This regulation includes the mandatory implementation of cognitive radio capabilities for secondary users allowed to access TVWS. Here, analog/digital TV signals and FCC Part 74 auxiliary wireless devices (i.e. wireless microphones) are defined as primary users. Hence, these primary users are protected of any interference resulting from the presence of secondary users. According to FCC regulation, this cognitive radio capability should be assisted by a geo-location database that includes previous registration of analog/digital TV signals coverage ratio. This way a secondary user can determine TVWS channel availability. Differently, on case of auxiliary wireless devices there is not a geo-location database that includes its geo-location since these devices are not fixed to a specific geo-location. For instance, the wireless microphones (WMs) are considered as primary users and must be protected from any potential interference caused by the presence of secondary users. However, its geo-location and spectrum usage are not fixed. Therefore, TVWS secondary users can determine the presence of WMs based only on its spectrum sensing function by measuring signal-to-noise-ratio (SNR) levels. In this context, detection of narrowband primary users (i.e. WMs) has become a major challenge, since its detection SNR levels are ranging from -20dB to -18dB, which is lower in comparison with a typical detection SNR level of up to -15dB for TV analog/digital signals (Chen & Gao, 2011; Shellhammer et al., 2009).

The cognitive radio technology is proposed as part of a dynamic spectrum access technique that contributes to reduce underutilization of the licensed wireless spectrum that could be inefficiently used. This way, the wireless channel can be shared with secondary users that can have access to radio spectrum in an opportunistic manner. According to (FCC, 2003), a formal definition of cognitive radio is: “a radio that changes its transmitter parameters based on interaction with its environment”. Thus, spectrum-sharing challenges on cognitive radio networks involve coexistence with licensed users over a wide range of available radio frequency channels. Here, spectrum access schemes for wireless channel sharing can be classified as overlay spectrum sharing (OSS) and underlay spectrum sharing (USS). In OSS, the secondary users can access the network on coexistence with licensed users by using an unused portion of spectrum. Differently, the USS scheme establishes that spectrum access availability depends on presence of primary users such that if a licensed user is detected, the secondary user cannot use spectrum. Even more, if a primary user is detected within a spectrum band occupied by a cognitive radio user, it should vacate that spectrum band (Menon et al., 2005).

Regarding access of secondary users to TVWS channels, the FCC regulated an underlay spectrum sharing access scheme to avoid interference to licensed users (FCC, 2008a). This regulatory mandate is suitable to protect wideband primary users (i.e. TV analog/digital signals). However, this regulation does not contribute to improve an efficient use of shared wireless spectrum because narrowband primary users such as WMs occupy a bandwidth of only 200 KHz over a 6, 7 or 8 MHz TVWS channel (Shellhammer et al., 2009). Consequently, authors in (Gronsund et al., 2014; Park et al., 2012) have shown that by using DSA schemes in TVWS cognitive radio networks, a secondary user can avoid interference to narrowband primary users within an underlay spectrum sharing scheme. This way, unused channel bandwidth portions can be allocated to cognitive radio users whenever a narrowband primary user is detected on a TVWS channel.

Several DSA functions such as spectrum mobility, channel sensing, spectrum sharing and resource allocation are based on network MAC layer (Akyildiz et al., 2006). Spectrum mobility allows secondary users to switch between channels on case of primary user detection. Channel sensing is used to determine channel availability by means of collecting spectrum usage information. Spectrum sharing is in charge of avoiding harmful interference with primary users. Resource allocation assigns available network resources in opportunistic manner for QoS provisioning on users demand. It is important to note that DSA schemes operate in a slotted basis. In other words, it is assumed that within a slot time duration the primary user activity status (idle/busy) remains constant (Tumuluru et al., 2011). Thus, there are many ways to implement a DSA scheme on cognitive radio networks (Vamsi Krishna & Das, 2009). In last decade, two implementation approaches have become relevant on the design of DSA schemes for cognitive radio networks: The MAC protocol design for radio resources allocation and the scheduling algorithm design for QoS purposes (Ahmad et al., 2015; Akyildiz et al., 2006; De Domenico et al., 2012).

A DSA scheme based on the MAC protocol includes a contention phase and a data transmission phase. On the first phase, all secondary users contend for available channels on licensed spectrum by using a common signal control channel. Once the channel is assigned, the cognitive radio user proceeds to the data transmission phase (Jun Zhao et al., 2005; Su & Zhang, 2008). Differently, A DSA scheme based on scheduling algorithms can collect information about the data bandwidth requirements from cognitive radio users in order to define a time slot allocation schedule for data transmission. Thus, the scheduling approach is also known as an slot-based DSA scheduling scheme (Tumuluru et al., 2011). According to (Hind et al., 2016), an slot-based MAC protocol strategy achieves the best network performance in comparison with a contention-based approach because overhead load on contention is higher than a slot-based resource allocation scheme. Therefore, a DSA scheme based on scheduling algorithms may contribute positively to an efficient use of bandwidth.

Currently, emerging BWA technologies (e.g. IEEE 802.16/WiMAX and IEEE 802.22/WRAN) include multiple-access methods such as OFDMA, which comprises multiple subcarriers for network resource allocation. In this context, a scheduling algorithm for OFDMA networks that operates on licensed spectrum can alternatively use channel information to perform scheduling. However, a DSA scheduling approach for OFDMA networks based on cognitive radio technology must include channel awareness features in order to perform an opportunistic scheduling (Knopp & Humblet, 1995). The opportunistic scheduling algorithms (OSA) for cognitive radio networks are mainly focused to enhance the total capacity of the network by means of scheduling resource allocation among secondary users based on partial channel information (Asadi & Mancuso, 2013). For instance, authors in (Luo et al., 2011) maximize the throughput of cognitive radio network by implementing flow control and resource allocation policies. Additionally, by using a distributed greedy scheduling algorithm they have shown that their solution is capable to maintain a defined average congestion while delivering almost all the traffic. Differently, authors in (Khalil et al., 2011) proposed a cooperative scheduling scheme where data from primary users is transmitted through secondary users such that transmission time is extended to include data from both primary and secondary users.

Regarding scheduling algorithms for QoS provisioning on cognitive radio networks, the main concern is on delay and average throughput performance. These requirements have become more relevant on Voice over IP and videoconference applications. Some examples of such scheduling algorithms are shown in (Beidokhti et al., 2011; Kae Won Choi et al., 2009; Kim & de Veciana, 2007). In (Beidokhti et al., 2011), authors propose three schedulers: biggest QoS-deviation first (BQDF), adaptive QoS-deviation control (AQDC), and adaptive residual time control (ARTC). Here, network users are defined as QoS type flows based on throughput, delay and packet drop requirements. The first scheduler is only based on QoS flows, which results in throughput degradation. Hence, AQDC scheduler is proposed to reduce the throughput degradation resulting from BQDF by means of including channel information in order to schedule first those users with maximum transmission rate. The ARTC scheduling algorithm is proposed as an alternative option to adjust trade-off between QoS provisioning and throughput. On a different perspective, the proposed algorithm depicted in (Kae Won Choi et al., 2009), is based on the average transmission rate metric. Here, the schedule of network resources is performed on every MAC layer the OFDMA frame, in order to guarantee an average throughput. This way, the algorithm can select users by considering the channel information and the average transmission rate on each MAC frame. By pursuing the goal of reducing starvation of network resources in long term period basis, the authors in (Kim & de Veciana, 2007) have proposed a scheduling algorithm that allocates a fixed average throughput to every QoS flow on each time slot.

In this context, opportunistic scheduling can be an alternative solution to wireless channel bandwidth limitations. According to (Asadi & Mancuso, 2013), opportunistic schedulers focused on capacity can provide up to 37% capacity gain and 70% delay reduction. QoS oriented proposals offered throughput improvement up to 30% throughput gain and delay improvement up to 80%. However, the performance evaluation of proposals under more realistic scenarios should be considered on the design of opportunistic scheduling, in order to observe the system performance in a real-world scenario.

3.2. Scheduling Algorithms

Radio channel on wireless links are typically variable and unpredictable, both on a time-dependent basis and a location-dependent basis. For BWA technologies that transmit on long distances, multipath and fading effects are also important factors that should be considered for QoS provisioning. By considering that QoS requirements for voice and video applications are highly sensitive to variations on delay and jitter, the proper allocation of network resources among users has become more relevant. However, BWA standards such as the IEEE 802.16/WiMAX and the IEEE 802.22/WRAN do not specify any resource allocation or admission control mechanism for QoS provisioning purposes.

According to (Dhrona et al., 2008), scheduling algorithms can be classified as: homogeneous, hybrids and opportunistic. The homogenous algorithm class does not include channel information to perform scheduling. The hybrid category combines two or more homogeneous algorithms in order to satisfy QoS requirements. Differently, the opportunistic scheduling algorithm is a channel-aware mechanism that performs resource allocation based on channel conditions.

3.2.1. Homogeneous and Hybrid Scheduling Algorithms

Typically, the choice of a scheduling algorithm for QoS provisioning is based on the target application and it pursues the achievement of a specific Qos metric. For instance, one of the most basic scheduling algorithms that shows the best performance in terms of jitter on WiMAX networks is Round Robin (RR) (Belghith & Nuaymi, 2008). Basically, the RR scheduler organizes traffic in queues such that, on first time-slot the resources are scheduled for first queue, on second time-slot for second queue, and so on. This process is repeated in a circular manner, until all queues are empty. It is important to note that on RR scheduling all queues are equally treated, which means that the resource allocation is scheduled on a fair manner. In order to include a priority scheme among queues that require different QoS type of services (i.e. UGS, rtPS, nrtPS, BE), an adaptation of the RR algorithm named Weighted Round Robin (WRR) has been proposed (Guesmi & Maaloul, 2013). The WRR algorithm guarantees that all type of QoS services can get access to networks resources in a fair RR scheme, while the amount of allocated bandwidth resources on a given queue are defined by a weight value according to its QoS requirements.

By considering that different types of QoS may require a minimum guarantee of network resources, a Weighted Fair Queueing (WFQ) scheduling algorithm has been proposed in (Al-Howaide et al., 2011). Similar to the WRR scheme, on WFQ scheduling each queue is assigned with a different weight in order to avoid bandwidth monopolization by providing a fair scheduling. Different to WRR, on WFQ scheduling a queue does not have to wait a slot-time turn to transmit data, because a minimum amount of network resources is guaranteed on every slot-time. In order to provide a minimum guarantee of network resources for QoS purposes, a deficit counter has been introduced in the design of a scheduling algorithm named Deficit Round Robin (DRR) (Belghith & Nuaymi, 2009). Here, all queues are served within a RR scheme and a minimum of bandwidth resources is guaranteed for each one of them. On this algorithm, a deficit counter defines the maximum of network resources that can be allocated for each queue on each slot-time turn. This way, the monopolization of bandwidth resources is avoided.

Other priority scheduling approaches based on weighted queues are Priority Queueing (PQ) and the Strict-Priority (SP) algorithms. On PQ scheme all queues are assigned with a weight value according to its priority, based on QoS requirements. In this scheme, only the highest priority queue receives resources allocation on each time-slot turn. Differently, the SP scheduling algorithm categorizes the data packets depending on its QoS type of service and then allocates them into different priority queues. This means that allocated resources for highest priority queue are not released until the queue empties, which may result in monopolization of network resources.

It was previously mentioned that QoS requirements are different depending on target applications. This condition constitutes a challenge for scheduling design since it has to consider a trade-off among network capacity, fairness on resource allocation and achieving minimum QoS requirements for each network service. In this context, a scheduling process based on the combination of two or more homogeneous scheduling algorithms is known as hybrid scheduling algorithm. This type of scheduling algorithm can be explained on a simple way as a serial process, where the output of the first homogeneous scheduler is the input of the second one, and so on. For instance, WRR and PQ scheduling algorithms have been combined to provide fairness between different real-time and non-real-time traffic profiles on WiMAX networks (Guy Pujolle & Nadjib Achir, 2012). Differently, authors in (Lakkakorpi et al., 2008), propose a hybrid scheduler that includes Weighted DRR (WDRR) and SP algorithms. Here, in order to improve network throughput performance, the UGS traffic is scheduled under an SP scheme, while other QoS types of service are served within a WDRR approach.

3.2.2. Opportunistc Scheduling Algorithms

By considering that access to network resources on cognitive radio networks depend on the presence of primary users, it is necessary to define a dynamic resource allocation mechanism by means of designing an opportunistic scheduling algorithm. These scheduling schemes comprise different algorithms to handle several QoS types of service. In this context, the fairness issue for the users in the same QoS type of service has become an important challenge to be considered. Therefore, the implementation of a cross-layer architecture on the design of this type of scheduler has been widely adopted.

The cross-layer scheduling algorithms are aimed to improve throughput efficiency, satisfaction user level, route paths on multi-hop networks, etc. Particularly, a cross-layer scheduling design can be classified as air interface-centric, user-centric and route-centric (Shariat et al., 2009). The air interface-centric design is based on throughput efficiency, fairness and QoS provisioning. The user-centric approach is concerned on keeping a certain level of user satisfaction, by observing end-to-end throughput, delay and power consumption metrics. Finally, the route-centric design objective is based on selecting the best route in multi-hop wireless networks.

By using a cross-layer approach, an opportunistic scheduling algorithm is able to allocate system resources by means of evaluating an objective function that considers information abstracted from two disjoint network layers. For instance, an air-centric cross-layer scheduler for throughput efficiency optimization may require exchange information regarding channel variations (i.e. channel quality) and queue lengths from the PHY and DATA LINK layers, respectively. This way, the scheduler could perform a radio resource allocation according to channel conditions (Matalgah et al., 2013). Differently, a route-centric cross-layer scheduler could assume an error-free channel to establish resource allocation policies for QoS provisioning by means of optimizing channel capacity on multi-hop networks (Jia Tang & Xi Zhang, 2007). In this sense, cross-layer schedulers can include characteristics of channel-aware or channel-unawareness (So-In et al., 2009).

Regarding scheduler designs for telemedicine service delivery based on BWA technologies, an air interface-centric algorithm that maximizes utilization of radio resources for the IEEE 802.16/WiMAX has been proposed in (Niyato et al., 2007a). Here, system resources are allocated primarily for tele-diagnosis services from ambulances (on emergency scenarios), and secondly for tele-consulting services from clinics (on non-emergency scenarios) for follow-up purposes. This way, the telemedicine network can guarantee QoS provisioning to those services with highest priority, while maintaining a minimum bandwidth resource reservation for lower priority services, such as tele-consulting. On the other hand, a scheduling algorithm for transmission-time reservation based on a priority scheme between telemedicine services for cognitive radio networks has been proposed in (Feng et al., 2010a). Here, transmission-time requires channel reservation to transmit messages from higher priority telemedicine services, while periodic traffic from telemedicine services with lower priority includes a scheduling packet algorithm based on periodic channel reservation.

It is important to notice that these proposals are similar on the adoption of priority schemes for resource allocation design for telemedicine services, but they differ on its channel-aware characteristics. For instance, scheduling algorithm for telemedicine applications based on the IEEE 802.16 standard assumes that all network subscribers have unrestricted access to spectrum usage, however on cognitive radio networks such as IEEE 802.22, the reserved resources can become unavailable due to primary transmissions.

3.3. Telemedicine Service Delivery and Dynamic Spectrum Allocation

In Chapter 2, a MAC layer description of the IEEE 802.22/WRAN standard has been provided. Here, reservation priority of system resources for network users mostly depends on four types of services for QoS guarantees (i.e. UGS, rtPS, nrtPS and BE). Furthermore, it was previously mentioned that priority on telemedicine services might depend of the deployment scenario. This means that, when two telemedicine users require the same type of service level, it may not imply that they are on same priority classification. In this context, a tele-diagnosis service on an emergency scenario would have to contend for system resources with other lower priority service that requires the same type of service level. An alternate way to solve this issue is through the implementation of a scheduling algorithm for resource allocation that contemplates the priority level associated to different telemedicine applications. Unfortunately, the IEEE 802.22/WRAN standard do not include a dynamic spectrum allocation mechanism for resource reservation that can be used to resolve this controversy.

On cognitive radio networks (CRN), the telemedicine applications are restricted to access spectrum in an opportunistic manner as secondary users, only if a non-interference guarantee is protecting primary users transmissions. Here, telemedicine applications are exposed to issues of bandwidth constraints, network service denials, and a forced termination of transmissions, among others. Therefore, the QoS provisioning for telemedicine service delivery on the IEEE 802.22 standard represents a major challenge. Nevertheless, it has been shown that CRN can provide QoS guarantees to health applications, by means of including a dynamic spectrum allocation mechanism (Feng et al., 2010a). In CRN, the QoS can be achieved by designing adequate resource allocation methods for priority and periodic traffic profiles in an underlay cognitive radio scheme. As opposed to overlay schemes, the underlay approach does not require leaving the entire channel when a PU is detected. Instead, the underlay scheme requires the generation of notches in the transmission spectrum such that no interference over the PU is caused. It has been shown that the underlay spectrum access scheme contributes to maximize the spectral efficiency (Leem et al., 2008). Currently, the IEEE 802.22 standard defines that when a PU is detected in the operation channel, the BS and the CPEs must abandon it and stop any transmissions (overlay spectrum access scheme). Thus, considering that narrowband primary users, such as WMs, may use only 200KHz of a 6MHz channel bandwidth, an underlay access scheme can contribute positively to make a more efficient use of the available spectrum. In this sense, the dynamic allocation of radio resources for secondary users, based on available channel bandwidth given by the presence of primary users, is still an open issue on CRN, even if we assume a perfect detection of narrowband primary users towards the implementation of an underlay access scheme.

Regarding the density of wireless microphones that can be present on some specific usage scenarios and geographical locations, there are some reports that can be considered for traffic modeling. For instance, up to 50 WMs can be operating steadily for up to 3 hours on sports and cultural events, such as super bowl games and music concerts, which represents the highest density scenario of WMs that results on the highest constraint scenario for bandwidth allocation, to any secondary user of a CRN (European Commission & Directorate-General for the Information Society and Media, 2013; Microsoft Corporation, 2013; The Coalition of Wireless Microphone Users, 2009). Another case where a high density of WMs can be found is on theater play events, where microphone-using hours can be expected, and their operating locations can be estimated. For instance, in Broadway Avenue at New York City, up to 20 simultaneous WMs may be operating continuously on any regular scheduled play throughout the day and eve hours, every single day. Besides, during the length of this research work, authors could not found a valid and usable traffic pattern for WMs reported in the literature. It can be inferred that the lack of a traffic model of narrowband primary users for rural regions may represent a drawback for the implementation of the underlay access scheme over the IEEE 802.22/WRAN standard. Even more, this issue hinders the design of resource allocation mechanisms that can be used to provide QoS guarantee for telemedicine services on this type of scenarios.

As an starting point to address this issue, the authors in (Park et al., 2012), have proposed a traffic model for narrowband primary users based on queuing theory, in order to evaluate network performance under several congestion scenarios. Here, a cross-layer architecture has been implemented to maximize the system throughput performance for the IEEE 802.22 standard in the presence of primary users. The presented results were based on dynamic spectrum access techniques such as subchannel notching and subchannel bonding. These techniques are used with the aim of guaranteeing spectrum allocation over generic constant bit rate and variable bit rate traffic flows even in the presence of primary users. Nevertheless, this approach does not characterize traffic modeling of primary users on rural regions with low population density.

In this context, a scheduling algorithm in OFDMA systems assigns resource blocks (RB), which represent a specific number of data subcarriers allocated to each user to be transmitted on a time interval. Specifically, a RB on the IEEE 802.22 standard is represented as an OFDM symbol, formed by one time symbol and one OFDM subchannel. In telemedicine networks, scheduling algorithms are used to give telemedicine users a bandwidth allocation priority among others types of traffic e.g., web surfing. In long range BWA communication systems (e.g. IEEE 802.22-based networks), the Weighted Round Robin algorithm has been proposed as a resource allocation mechanism for transmission scheduling (Jianfeng Chen et al., 2005; Markarian et al., 2010, 2012). The aim of implementing a Round Robin algorithm is to schedule the packet transmission in a circular manner to provide fairness among all users requesting system resources. On the other hand, the associated weight to each traffic flow allows including a priority on allocation of available bandwidth. In other words, the WRR scheduling algorithm is able to provide a fair access to resource reservation, while providing a priority scheme where the amount of system resources that can be reserved for each traffic flow depends on its associated weight. For instance, in telemedicine video distribution a WRR algorithm has been proposed for video packet scheduling (Markarian et al., 2012). Even if the WRR scheduling algorithm may be used to establish a priority scheme among telemedicine traffic flows (to provide QoS guarantee), it does not solve the controversy of scheduling resources between two telemedicine traffic flows, which may have the same weight but different priority classification according to its telemedicine deployment scenario. Accordingly, it is required a telemedicine model that defines the telemedicine applications on its characteristics of traffic profiles, data bandwidth requirements, utilization rates and time sustaining rates, among others. In (Gallego et al., 2005; Vergados, 2007), it has been shown that establishing a priority scheme among medical services connections, is considered a better approach for telemedicine service delivery while an adequate QoS level is provided. Thus, the relationship between radio resources reservation and a priority scheme on telemedicine applications may affect the blocking probability. For instance, the blocking probability from ambulance services is highly-reduced, at the cost of increasing blocking probability of other telemedicine services (i.e. tele-consulting and tele-monitoring) which is addressed by defining a bandwidth threshold (Niyato et al., 2007a; Zvikhachevskaya et al., 2009).

However, this bandwidth threshold approach affects all telemedicine services within a lower priority scheme, which may compromise the QoS provisioning for these applications.

In other words, the definition of a telemedicine model contributes to improve the blocking and interruption probabilities for high-priority services, by means of managing all available data bandwidth. Therefore, it is necessary to define a rural telemedicine model that describes a deployment scenario by means of including the rural/urban infrastructure network characteristics, and traffic profiles based on telemedicine services offered for rural regions, among others.

3.4. Rural Telemedicine Framework

Telemedicine is considered a fundamental tool to provide medical services to remote rural communities (Malindi, 2011). Unfortunately, to the best of our knowledge, there is not a guideline regarding which telemedicine applications should be considered for rural telemedicine deployments. Typically, the telemedicine services have been classified as: access to medical databases, tele-education, tele-monitoring, tele-consulting and tele-diagnosis (Skorin-Kapov & Matijasevic, 2010; Vergados et al., 2006; Vouyioukas et al., 2007; Zvikhachevskaya et al., 2009). As such, a significant number of rural telemedicine deployments reported in the literature include at least one of the following services: tele-diagnosis, tele-consulting and tele-monitoring (Bravo et al., 2013; Fong & Pecht, 2010; Foster, 2010; Husni & Waworundeng, 2011; Kachieng'a, 2011; Luo Kun & Wen Hao, 2010; Meethal & J., 2011; Mulvaney et al., 2010; Sharma & Kunwar Singh Vaisla, 2012; Sudhahar et al., 2010; Wickramasinghe et al., 2010; Zambrano et al., 2012; Zhu & Dong, 2011).

As mentioned before, from a general perspective telemedicine services comprise tele-consulting, tele-diagnosis, tele-monitoring, medical database access (MDBA) and tele-education, (Vergados et al., 2006), and the inclusion of one or all services in a telemedicine model depends on the application scenario. For instance, because of the large technological and health infrastructure available in countries like Germany and the United States, rural telemedicine services focusing on home monitoring have been proposed (Lu et al., 2010; Polze et al., 2010). In contrast with developing countries, (e.g. Malaysia and Bangladesh), rural telemedicine is mainly focused on interconnecting rural clinics with main hospitals, in order to assist local physicians remotely by extending health specialist services through tele-diagnosis and tele-consulting (Ali et al., 2010; Bravo et al., 2013). Hence, the number of fixed and mobile wireless connections needed in a rural wireless telemedicine deployment varies with the proximity of the population to the local clinics. In this sense, when there are relatively large numbers of rural settlements in a given area, the number of required services may also be large

For instance, in Mexico more than 37% of states have over 30% of rural population. The most drastic case is the State of Chiapas, with a rural population of 51%, (INEGI, 2011) which, incidentally, has the highest poverty rate in Mexico with over 74% of the population living in poverty (CONEVAL, 2012). Therefore, Chiapas is a representative example where people need primary and extended medical services, including consultation by health specialists. At least 30 municipalities are located within a radius of 50 km from Tuxtla Gutierrez, Chiapas's capital (including the popular tourist city of San Cristobal de la Casas), and 15 of them can be classified as rural. Based on these conditions, a generic rural wireless telemedicine network for the IEEE 802.16/WiMAX and IEEE 802.22/WRAN architectures can be defined (Fig. 4). Here, the network includes a 50 km backhaul link between points A and B. Additionally, other link distances are: 22 km (A to C), 17 km (A to D), 18 km (A to E), 24 km (A to F), 14 km (A to G), and 60 km (A to H).

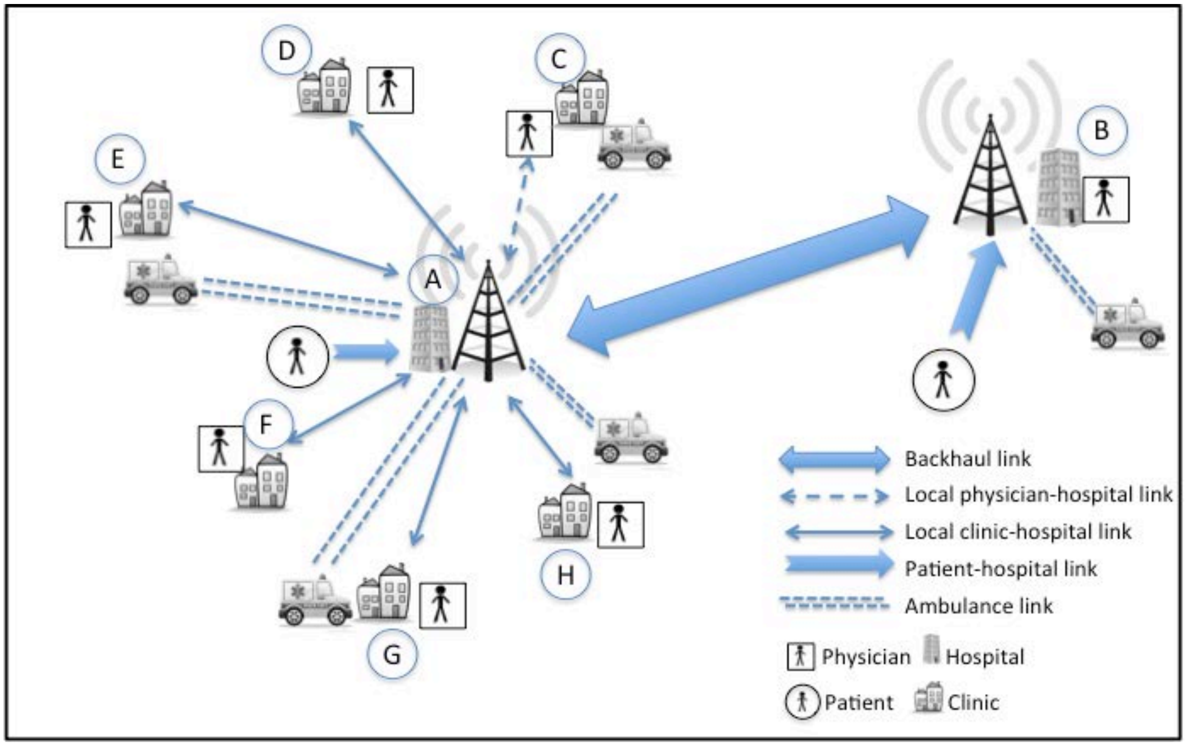


Fig. 4 Generic rural wireless telemedicine network architecture

In this context, it is important to define those telemedicine applications that can support a wide range of QoS levels (e.g. application involving video and audio connections), depending on its medical purpose. This way, those telemedicine services that could adapt their data bandwidth requirements (e.g. video conference) may be capable to respond dynamically to bandwidth allocation in accordance to network resources availability.

Thus, the rural telemedicine model presented in this section considers the provisioning of basic medical services from urban to rural regions by enabling tele-diagnosis, tele-consulting and tele-monitoring services. As each one of these services corresponds to a particular telemedicine scenario, the telemedicine network should serve them in a hierarchical manner. For instance, an urgent scenario in an ambulance service, where tele-diagnosis for an injured patient is required, should have a higher service priority than a follow up tele-consulting service. Hence, emergency and non-emergency scenarios must be considered within the rural telemedicine model, which will lead to define different priorities and traffic profiles for each service.

3.4.1. Telemedicine based on Tele-diagnosis, Tele-consulting and Tele-Monitoring Services

A general telemedicine model that includes a prioritized scheme to provide admission control in wireless healthcare information systems has been proposed in (Vergados, 2007). The policy management included in the general model defines three classes of telemedicine applications: emergency-response-real-time with highest priority; non-emergency-real-time with medium priority; and non-emergency-no-real-time with low priority. This way, the admission of a telemedicine application is evaluated by the policy management strategy, to accept or reject its connection link to the system. This general model system does not include a resource block allocation mechanism to provide data bandwidth allocation to telemedicine applications. However, the classification based on the emergency nature of the telemedicine applications is useful to establish a hierarchy. Thus, the rural telemedicine model proposed in this thesis adopts the ERrt, nERrt and nERnrt classification for the offered services.

The model considers three different telemedicine scenarios based on the patient health condition: chronic condition, medical control condition, and emergency condition (Fig 5). The chronic condition scenario involves patients with a chronic condition (e.g. diabetes, hypertension, etc.) where the health specialist requires a tele-monitoring service to observe any unusual changes in the patient health status (examples of this kind of scenario are provided in (Bai & K, 2008; Saponara et al., 2012)). Because the medical purpose of this telemedicine service is follow-up, it will be assumed that the tele-monitoring service will be provided within the rural clinic and the collected information will be transmitted to an urban hospital for its analysis, processing, and storage. Therefore, this service is not considered an emergency and does not require real-time transmission. Thus, the traffic profile of the tele-monitoring service within the chronic scenario will be considered as a nERnrt transmission for QoS provisioning. Additionally, it will be assumed that the telemedicine service (assisted by a local physician) will be organized by the rural clinic, based on scheduled appointments to provide follow-up consultations.

The medical control condition represents a patient that requires a tele-consulting service from a health specialist for medical evaluation purposes. Video and audio streaming in a teleconference system is enough to perform a basic tele-consulting service (see examples in (Kim et al., 2009)). Similar to the chronic scenario, it will be assumed that the tele-consulting service provision will be based on scheduled appointments within the local clinic. This way, the local physician and the patient will be connected with the health specialist through a teleconference system to perform the medical evaluation consultation. Because this tele-consulting service is not considered an emergency, but requires a real-time transmission, it will be classified as a nERrt transmission for QoS provisioning.

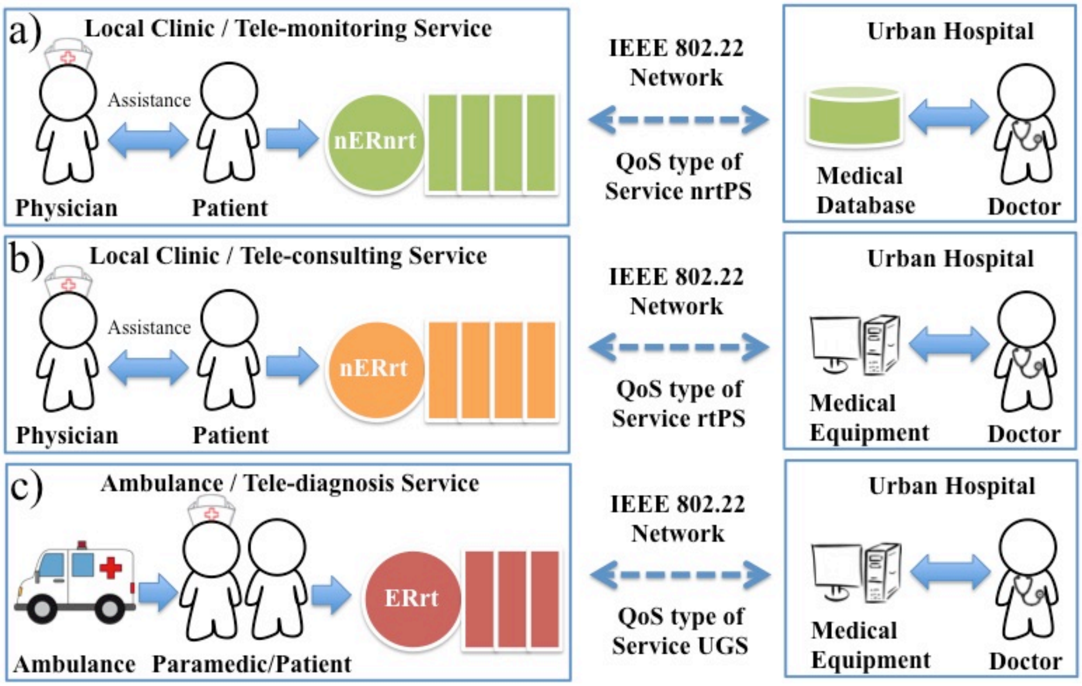


Fig. 5. Telemedicine scenarios based on the rural telemedicine model: a) chronic, b) medical control, c) emergency.

Finally, the emergency condition scenario represents patients that require tele-diagnosis services from a health specialist (assisted by paramedics) within an ambulance, located outside the hospital and the local clinic, for emergency purposes (examples of this emergency scenarios are provided in (Gallego et al., 2005; Niyato et al., 2007a)). Because this telemedicine service involves emergency consultation prior ambulance transportation, it will be assumed that the tele-diagnosis service will be provided on the emergency-site. This way, the transmission of the patient vital signs can be used for pre-hospitalization arrangements, patient health stabilization and/or second opinion consultation via a teleconference session. Because this tele-diagnosis service is considered an emergency the transmission of real-time data is required. Thus, this emergency condition scenario will be classified as an ERrt transmission with the highest priority for QoS provisioning.

Based on previously mentioned scenarios, a list of minimum data rates (per sensor) for each telemedicine service is shown in Table 2. The data in this table was obtained from (Bai & K, 2008; Chan et al., 1999; Gallego et al., 2005; Kim et al., 2009; Niyato et al., 2007a; Rao et al., 2009; Saponara et al., 2012; Tsapatsoulis et al., 2007). Note that the overall data bandwidth required for tele-monitoring, tele-consulting and tele-diagnosis services are 18.4 kbps, 400 kbps and 968 kbps, respectively.

Here, a teleconference system for tele-consulting service includes three basic operating modes: a High-resolution teleconference (with a resolution of 320x240 pixels running at 25 frames per seconds), a Medium-resolution teleconference (with a resolution of 160x120 pixels running at 25 frames per seconds), and audio-only teleconference (with a quality audio bit rate of 128Kbps that is also included within high, and medium resolution modes). Different to tele-consulting service, the tele-diagnosis video has a highest resolution of 432x240 pixels running at 30 frames per second. Additionally, tele-diagnosis service includes a high quality audio bit rate of 192 Kbps. In this context, both telemedicine services (tele-consulting and tele-diagnosis) data bandwidth requirements assumes a H.264/AVC coding format for compression purposes (Panayides et al., 2012; Stockhammer et al., 2003). From Table I, it can be seen that the tele-diagnosis systems not only requires highest QoS priority, and it also has the highest requirements in terms of bandwidth. Thus the scheduler must consider both, the QoS required by each service, and the resources needed to attend these services.

Table 2. Telemedicine scenarios and minimum data rates per sensor

Telemedicine scenario	Sensor description	Minimum data rate (Kbps)
Chronic Condition Tele-monitoring nERnrt/nrtPS	ECG (3 leads)	18
	SpO^2	.03
	Blood pressure	.064
	Weight	.032
	Chest Impedance	.25
	3 axes posture	.024
Medical Control Condition Tele-consulting nERrt/rtPS	High Resolution	404
	Medium Resolution	198
	Audio-only	128
Emergency Condition Tele-diagnosis ERrt/UGS	ECG (12 leads)	288
	High quality video	640
	Blood pressure	36
	Diagnostic sound and voice	2
	Heart bit rate	2

In this context, it is important to notice that the definition of telemedicine model should consider those applications that can support a wide range of QoS levels (e.g. application involving video and audio connections), depending on its medical purpose. This way, those telemedicine services (i.e. tele-consulting) that could adapt their data bandwidth requirements (e.g. video conference) may be capable to respond dynamically to bandwidth allocation in accordance to network resources availability. Hence, the following subsection presents a description of tele-consulting telemedicine services, as an special case on the rural telemedicine model.

3.4.2. Telemedicine based on Special Case of Tele-consulting

In Mexico, only the telemedicine network deployed in Nuevo Leon provides information about the location of the considered rural facilities, in this case tele-consulting as reported by (Ramos-Contreras, 2016). Here, rural regions in Nuevo Leon involve a complex orography that includes a mountain range named the Sierra Madre Oriental. This means that the deployment of infrastructure to achieve LOS conditions is not feasible. Thus, in the case of Nuevo Leon rural regions NLOS conditions were considered. Hence, considering the maximum radio range of 50 km on NLOS condition of IEEE 802.22/WRAN and the geographic distribution rural telemedicine facilities in Nuevo Leon, it can be concluded that a BS located on Montemorelos could provide telemedicine services for most of the other rural telemedicine hubs previously mentioned (Galeana, Linares, Santiago and Allende). Specifically, the

Euclidian distances between the Montemorelos rural hospital and other rural facilities are as follows: Galeana 47 km, Linares 45 km, Santiago 40 km and Allende 21 km. This means that a BS located in Montemorelos could provide telemedicine services to the Allende rural hospital with the data rates supported within the IEEE 802.22/WRAN 16-QAM coverage range. On the other hand, the same BS could provide data rates within the IEEE 802.22/WRAN QPSK coverage range for local clinics located on Galeana, Santiago and Linares. This way, practitioners of Montemorelos hospital could provide specialty assistance to other rural health professionals located nearby as an alternative option to wait for a personal appointment in Monterrey city.

Regarding data traffic connections generated by telemedicine services, they will be characterized by a negative exponential distribution, with average interarrival and departure times given by $1/\lambda$ and $1/\mu$ respectively (Van Mieghem, 2009). Thus, the average number of active users in the system will be affected by these two parameters. Considering the rural telemedicine projects reported in (Kapoor L et al., 2005; Meethal & J., 2011; Mulvaney et al., 2010; Sharma & Kunwar Singh Vaisla, 2012; Wickramasinghe et al., 2010; Zhu & Dong, 2011), currently a rural telemedicine center can have an average arrival rate of one to two tele-consulting session requests per hour. According to (Vargas et al., 2014), the average time duration of a tele-consulting session is 30 minutes per telemedicine session.

The implementation of a telemedicine network enables the access to medical services for rural populations. Thus, its successful deployment involves several challenges that range from time-reservation of medical resources to the mobility of patients. In this context, a rural tele-consulting appointment represents a coordinate effort that involves highly valuable resources from a technical, medical and human perspective. Thus, the cancellation of a rural telemedicine service results in a sub-utilization of human resources and a major inconvenience for patients. In order to reduce cancellation of rural tele-consulting sessions, a telemedicine system based on videoconference applications could reduce the required bandwidth per session by adjusting the video or audio quality when the networks resources become scarce. With this in mind, a tele-consulting service with high-resolution video might be set to a default value when there is enough bandwidth. However, as the number of simultaneous active tele-consulting sessions increases and the available bandwidth left is reduced, services with medium-resolution video or even audio only could be offered instead of completely cancelling the telemedicine appointment.

Unfortunately, specific technical details about the architecture, configuration and technology of the videoconference system used for tele-consulting were not provided in (Kapoor L et al., 2005; Pacheco-

López et al., 2011; Vargas et al., 2014; Zanaboni et al., 2009). Regarding the Nuevo Leon tele-consulting service, it is reported in (Mariscal-Aviles et al., 2014) that bandwidths above 2 Mbps between the telemedicine facility and the rural clinic are desirable. Contrastingly, the solution reported in (Vargas et al., 2014) states that its aim is to enable telemedicine services over data networks with limited bandwidths. It is important to note that these works report results from tele-consulting services provided with telemedicine networks that used the videoconferencing technology available at the time of deployment. As the technology has evolved it is fair to assume that new telemedicine deployments will use new codecs and will require lower data rates than those reported in (Mariscal-Aviles et al., 2014). Therefore, the rural telemedicine model presented in this thesis considers using the H.264/AVC coding format, which has been widely adopted as a typical standard for videoconference systems (Wiegand et al., 2003). Moreover, H.264/AVC has been specially considered for videoconference systems working over wireless networks, as it can support different video resolutions levels (Stockhammer et al., 2003). Without loss of generality, in this work it will be assumed that a tele-consulting service for rural regions based on the H.264/AVC coding format can include the following options: a high-resolution videoconference with video of 320x240 pixels (25 frames per seconds), a medium-resolution videoconference with video of 160x120 pixels (25 frames per seconds) and audio-only conference with 404.3 kbps, 198.6 kbps and 128 kbps bandwidth, correspondingly

Once defined the codec and video quality options, upper layer overhead from Real Time Transport Protocol (RTP) over User Datagram Protocol (UDP) must be considered in the analysis. The RTP and UDP header payloads formats for H.264 are 12 and 8 bytes per packet respectively (Eggert & Fairhurst, 2008; Wang et al., 2011). Therefore, the data bandwidth requirements considered to enable a tele-consulting session are: 408.8 Kbps for high-resolution videoconference, 202.8 Kbps for medium-resolution videoconference and 132.8 Kbps for audio-only enabled tele-consulting.

3.5. Chapter Summary

Through the use of TV white spaces, wireless high data rate connectivity could be provided to rural and suburban areas because of low propagation losses in TVWS spectrum (Molisch et al., 2009). At the end of 2011, the IEEE Working Group for Wireless Regional Area Networks released the IEEE 802.22 standard (IEEE-SA Standards Board, 2011), which was the first standard considering TVWS use. The IEEE 802.22/WRAN standard defines a basic architecture for WRANs implementations using cognitive radio capabilities over TVWS frequency bands. The IEEE 802.22/WRAN standard aims to provide wireless data connectivity within a coverage ratio of up to 50 km on NLOS conditions and a maximum transmission distance of 100 km in LOS conditions for a single IEEE 802.22/WRAN base station, with peak data rates of up to 22.69 Mbps on a single channel.

Therefore, an alternative solution could be the deployment of wireless telemedicine networks based on the IEEE 802.22 standard. Theoretically, this standard could double the coverage range offered by the IEEE 802.16/WiMAX standard. The IEEE 802.22 standard defines a CRN technology that uses an opportunistic spectrum access scheme. Consequently, QoS provisioning as required by telemedicine and m-Health networks may present a major challenge. Nevertheless, in (Feng et al., 2010b) it was shown that by designing resource allocation methods both the urgent and periodic traffic profiles, the CRNs standard is a suitable technology for wireless telemedicine implementations.

Despite its potential, before planning and deploying telemedicine services over an IEEE 802.22/WRAN network, the CR radio approach adopted by the standard must be considered. The IEEE 802.22/WRAN CR capabilities are used to avoid interfering legacy narrowband primary users of the TVWS spectrum, as is the case of wireless microphones (Deb et al., 2009; IEEE-SA Standards Board, 2011). This implies that on a NPU detection the physical layer of an IEEE 802.22/WRAN BS must release the wireless channel resources, which in turn may lead to either dropping an active connection or rejecting new connection requests. In the case of telemedicine networks, this could have a direct impact on the number telemedicine services that can be offered, as one or several services might have to be dropped in order to allocate resources for primary users. Hence, before implementing telemedicine services delivery over IEEE 802.22/WRAN, it is necessary to consider mechanisms aimed at maximizing the use of available wireless radio spectrum resources. Particularly, a scheduler mechanism to guarantee quality of service provisioning for telemedicine services by means of reserving network resources is required. In addition, an access control mechanism is also required in order to decide whether to accept or reject new resource allocation requests based on current radio resources availability.

Chapter 4. An Adaptive Cross-layer Admission Control Mechanism for Telemedicine

4.1. Introduction

Commonly, AC mechanisms in telemedicine networks define different quality of service levels for different telemedicine services (Chen et al., 2011; Feng et al., 2010a; Matalgah et al., 2013; Phunchongharn et al., 2010). In the context of telemedicine service delivery over BWA technology, two AC mechanisms with a priority scheme for IEEE 802.16/WiMAX were previously proposed in (Niyato et al., 2007a; Zvikhachevskaya et al., 2009). In these works, telemedicine services with heterogeneous telemedicine traffic were considered, i.e., tele-diagnosis, tele-consulting and tele-monitoring. The proposed AC mechanism introduced on these works accepts or rejects an admission request based on the type of QoS assigned and the bandwidth resource availability. For example, tele-diagnosis services have the highest priority and are provided with IEEE 802.16/WiMAX unsolicited grant service type of service, whereas tele-consulting services have a medium priority and are provided with real-time polling service type of service. This way the AC mechanism allocates more radio spectrum resources to critical telemedicine services. Note that the AC mechanism proposed in (Niyato et al., 2007a; Zvikhachevskaya et al., 2009) might not be straightforward used for IEEE 802.22/WRAN-based rural telemedicine delivery, because of the bandwidth availability constraints imposed by the random appearance of primary users.

On rural telemedicine deployments the sessions are mainly performed between a local clinic and a hospital. In this case, the patient interacts with a health specialist through a local physician (or health professional) that is always assisting on session. In fact, according to several studies, (Sachpazidis et al., 2005; Smith et al., 2005; Vargas et al., 2014; Zanaboni et al., 2009), rural tele-consulting services usually follow an appointment schedule, as these sessions involve aspects like reservation-time of medical resources. Moreover, the appointment schedule scheme on rural telemedicine service delivery also responds to the number of patients that require a second opinion to evaluate their health status, which in some cases could potentially reach the quantity of 50 tele-consulting sessions per day (Sachpazidis et al., 2005). Thus, in the described context, it can be assumed that most of the telemedicine traffic from a clinic on rural deployment scenarios consists of tele-consulting sessions that have the same priority. Therefore, in rural scenarios, the priority AC scheme proposed in (Niyato et al., 2007a; Zvikhachevskaya et al., 2009), could have low or even null impact because most of the traffic has the same priority. In fact, under such traffic assumption, this AC mechanism is reduced to a first-come, first-served (FCFS) scheme.

A typical AC mechanism mainly considers the currently available resources as an admittance criterion. In the homogeneous telemedicine services scenario, using an AC mechanism based on a simple FCFS scheme will reject new connections if there are not enough resources available. Even worst, for IEEE 802.22/WRAN networks an active connection might be dropped because of a random primary user transmission. Nevertheless, several telemedicine services (e.g. tele-consulting) are able to support different data bandwidths depending on its medical purpose and operation mode (Gallego et al., 2005; Meethal & J., 2011; Sharma & Kunwar Singh Vaisla, 2012; Sudhahar et al., 2010; Vergados, 2007; Wickramasinghe et al., 2010). Thus, if different data bandwidths are supported at the application layer (e.g. for a tele-consulting videoconference), the use of an AC mechanism like the one proposed in (Niyato et al., 2007a; Zvikhachevskaya et al., 2009), might result on dropping or rejecting telemedicine sessions that could be otherwise serviced by making adjustments at the application layer and properly reassigning network resources. In the case of rural telemedicine deployments, dropping or cancelling a telemedicine session represents a major drawback for patients and medics, as patients would have to reschedule their appointments and the medic resources would be underutilized. From a patient point of view, an appointment rescheduling may involve disruptions from productive activities related to the patient financial support. Furthermore, a rescheduling may lead to long time delays in receiving medical attention, which in turns may lead to financial losses and health-threatening situations. Therefore, in the homogeneous rural telemedicine service scenario, it would be preferable to make adjustments at the application layer (if possible) rather than rejecting or dropping a session. Thus, reducing the blocking and dropping probabilities in rural telemedicine networks represent a major issue for the deployment of this kind of networks. It is important to note that reducing these probabilities is particularly relevant for patients with limited mobility such as post-operatory patients (on follow-up consultations) or patients with chronic diseases (requiring specialized medical treatments). In this sense, to the best of our knowledge, the design of an AC mechanism for IEEE 802.22/WRAN-based telemedicine networks that evaluates if a new connection can be established based on both, the amount of existing resources and the possibility of making adjustments at the application layer (APP), has not been previously proposed.

The design of an AC mechanism aimed at decreasing the blocking probability by means of allocating available bandwidth while considering the particular characteristics of telemedicine applications is not a trivial task. The lack of awareness at the application layer about system resources availability is a major issue for the design of such AC mechanism. Therefore, a cross-layer strategy must be considered in order to exchange information between the application and the system lower layers. In this work a cross-layer AC mechanism that adapts tele-consulting service levels (on video and audio resolutions) to available system resources is proposed. The cross-layer AC mechanism considers that telemedicine services can support different levels of video and audio resolutions for tele-consulting services.

The novelty of the proposed AC mechanism is based on providing new admission alternatives for telemedicine services that support different data bandwidths at the APP. Such alternatives can be offered by enabling the interaction between the APP and the medium access control layers. This way the system can use more than one criterion to determine admission/rejection of a new connection. Such criteria can include traffic profile information abstracted from the APP and network resources availability abstracted from the MAC. This way the system will be capable of evaluating a new connection admission based on MAC layer resources availability and data bandwidth requirements from the APP (without affecting previously admitted connections).

The proposed approach assumes that initially all tele-consulting services request high-resolution video service, but that they can support medium-resolution video sessions and even audio-only sessions as well. As previously mentioned, rural tele-consulting sessions are usually programmed in accordance to medical resource availability, thus the cancellation of a telemedicine session due to an AC rejection represents a major drawback for patients and medics.

To demonstrate the proposed AC mechanism applicability for rural telemedicine network deployments, a proper rural telemedicine model is proposed considering a survey of different rural telemedicine deployments around the world. Assuming the scenario conditions (e.g. traffic profile) imposed by the proposed telemedicine model, the performance of the proposed AC mechanism is evaluated using a Markovian model. The proposed AC mechanism is further evaluated using a simulation scenario implemented in MATLAB.

4.2. Tele-consulting over IEEE 802.22/WRAN System Model

Once the rural telemedicine framework has been introduced in the previous Chapter 3, the proposed IEEE 802.22/WRAN system model for tele-consulting applications is introduced in the following paragraphs. This system model aims to capture the characteristics of a rural tele-consulting service deployment based on the IEEE 802.22/WRAN standard. The telemedicine network characteristics related to deployment scenarios and traffic profiles considered are based on (Magana-Rodriguez et al., 2015).

As this work focuses on rural tele-consulting scenarios, the system model considers that all of the resource allocation requests have the same priority. It is further assumed that each tele-consulting session is initially requested as a videoconference service with high-resolution video. Nevertheless it is also considered that medium-resolution video or audio-only tele-consulting services can be offered instead of cancelling the appointment. As previously mentioned, for the analysis it is assumed that interarrival and service times follow a negative exponential distribution with parameters λ and μ respectively. In order to obtain a holistic evaluation of the proposed AC mechanism over different traffic congestion scenarios, the average interarrival times will be varied from 60 to 2 minutes in the evaluation scenario. This variation will enable the assessment of the proposal capabilities to accommodate more sessions, as the demand of telemedicine services increases over time (as it has been happening in recent years, e.g. see (Mariscal-Aviles et al., 2014; Ramos-Contreras, 2016)). Regarding average time duration, the tele-consulting session will be set to 30 minutes (Vargas et al., 2014). Thus, it will be considered that the average interarrival, 1/λ, time varies from 60 to 2 minutes and that the average service time, 1/μ, for each tele-consulting session is 30 min. This corresponds to an average of $\lambda = \{1,2,\dots,30\}$ arrivals and $\mu = 2$ services per hour. This way, the system performance based on blocking probability can be used to evaluate the proposed cross-layer AC mechanism suitability under low and high loads of telemedicine services requests.

As previously mentioned, the CR approach considered in IEEE 802.22/WRAN may lead to either dropping an active connection or rejecting new connection requests. Particularly, when detecting the presence of a narrowband primary user, the IEEE 802.22/WRAN standard considers that the BS and associated customer premise equipment stop transmitting and abandon the channel (overlay spectrum access scheme). Considering that NPUs like WMs only use 200 KHz while the total channel bandwidth is 6 MHz, the overlay spectrum access scheme translates to a significant underutilization of available spectrum. Therefore, an underlay access scheme can contribute positively to make a more efficient use of the available spectrum (Park et al., 2012). This way, an IEEE 802.22/WRAN customer premise equipment does not have to stop transmitting and abandon the operating channel to protect NPU transmissions. Instead, an IEEE 802.22/WRAN network can protect NPU transmissions by isolating particular portions of channel spectrum, while the remaining spectrum is re-allocated to enable secondary users (SUs) transmissions. Thus, the proposed model considers the use of subchannel notching and subchannel bonding for the provisioning of tele-consulting services over IEEE 802.22/WRAN networks.

The IEEE 802.22/WRAN wireless data link is based on single 6 MHz bandwidth channels, which includes 60 orthogonal frequency-division multiple subchannels and 18 time symbols on the downstream. It is fair to assume that an IEEE 802.22/WRAN deployment for rural tele-consulting services provisioning will rarely use the 64-QAM modulation scheme, because of the coverage range of up to 9 km in NLOS conditions considered for this modulation format. Therefore, without loss of generality, it will be assumed that the IEEE 802.22/WRAN deployment will offer tele-consulting services to rural clinics located beyond a ratio of 10 km from the BS. Thus, only the data rates offered by the 16-QAM and QPSK modulation schemes will be considered for performance analysis purposes. For example, consider an IEEE 802.22/WRAN PHY configuration of 18 time symbols and 60 subchannels, which results in 1080 resource blocks available for system allocation. Additionally, assume a 16-QAM modulation scheme with 1/2 coding rate that offers a peak data rate of 144 Kbps per subchannel. Then this configuration will offer an equivalent peak data rate of 4.8 Kbps per resource block.

To calculate the capacity of an IEEE 802.22/WRAN deployment it is not enough to consider the peak data rates achieved with each modulation scheme. Particularly, any capacity analysis must consider the overhead introduced by the PHY and MAC layers. In this sense, the overhead introduced by the IEEE 802.22/WRAN standard comprises a fixed and a variable part (IEEE-SA Standards Board, 2011). The variable part of the overhead factor increases with the number of active users, (So-In et al., 2010), which in turn will decrease the capacity of accepting new connections. Thus, an overview of the overhead introduced by IEEE 802.22/WRAN will be provided next.

4.2.1. PHY and MAC Overhead

Commonly, overhead analysis only considers a fixed factor corresponding to two channel descriptors: downstream and upstream, (e.g. see (Park et al., 2012)). However, a variable data bit load from DCD and UCD channel descriptors is neglected when a fixed overhead factor is considered. Because information elements (IE) included on DCD and UCD are related to the mapping of OFDM burst for each active user, the data bit load varies depending on the number of active users registered in the IEEE 802.22/WRAN network. Thus, a more accurate MAC and PHY overhead calculation can be achieved by including a variable part on DCD and UCD, compared to the use of a fixed overhead factor. The overhead calculation method introduced in (So-In et al., 2010) includes a variable part on DCD and UCD channel descriptors, and therefore has been adapted in this work to compute the overhead in IEEE 802.22/WRAN. In the following paragraphs a detailed description of such adapted method is presented.

For IEEE 802.22/WRAN the fixed part of MAC overhead comprises: downstream mapping (DS-MAP) messages, upstream mapping (US-MAP) messages, and an optional 4-byte header load resulting from cyclic redundancy check (CRC). Therefore, the fixed overhead load per frame based on DCD and UCD descriptors is 26 bytes. On the other hand, for the variable part a downstream overhead calculation can be obtained by using Eq. (1):

$$\#DS_{RB=}\left\lceil\frac{DS_{MAP}+CRC+(\#DS_{users}*DIE)}{S}\right\rceil*r+$$

$$\left\lceil\frac{US_{MAP}+CRC+(\#US_{users}*UIE)}{S}\right\rceil*r+$$

$$\#DS_{users}*\left(\frac{MAC_{header}+Subheader}{S}\right) \qquad (1)$$

where DS-MAP is the header load (bytes) given by the fixed part of the DS-MAP and the DCD messages. The downstream information element (DIE) represents the variable part of the DS-MAP message format. Subheaders include the fragmentation and packing subheaders. The repetition factor, *r*, is associated to the QPSK operation mode used for the transmission of coexistence beacon protocol (CBP), superframe control header (SCH) or FCH packets. The variable *S* represents the resource block capacity (bytes) given by the modulation and coding scheme. Similarly, an upstream overhead calculation can be obtained by using Eq. (2):

$$\#US_{RB}=\#US_{users}*\left(\frac{MAC_{header}+Subheader}{S}\right) \qquad (2)$$

In order to clarify the overhead calculation, consider the following example: assume 29 time symbols per frame, a repetition factor of 2, and a QPSK-1/2 modulation. This results in a fixed header load (including CRC) of 16 and 18 bytes from DS-MAP and US-MAP, respectively. Additionally, the DIE and UIE header sizes are 56 and 32 bits, respectively. Substituting in Eq. (1) and Eq. (2) a total of 34 and 3 RBs are required for header transmission. Hence, the overhead size in US and DS requires 0.56 and 0.05 of a time symbol respectively. This results in an overhead factor of 2.1% (per frame) with one active user. As a comparative example, following the same procedure, an overhead factor of 12% is calculated for 15 active users. According to the IEEE 802.22/WRAN standard, binary phase shift keying (BPSK) modulation is strictly used to transmit information messages about network management and control. This results in an overhead load of 15 RBs per active user regardless of its service level or its modulation scheme.

As an example consider an IEEE 802.22/WRAN tele-consulting service deployment with two rural hospitals located at 21 km and 45 km from the BS. The first hospital can be provided with peak data rates of up to 7.2 Kbps per RB (16-QAM 3/4 coding), whereas the second hospital can be provided with peak data rates of up to 2.4 Kbps per RB (QPSK 1/2 coding). For these modulation schemes Table 3 provides the number of RBs required, with and without overhead, for each tele-consulting service level considered.

Table 3. RB requirements per tele-consulting session

Service Level	No-Overhead		Overhead	
	QPSK	16-QAM	QPSK	16-QAM
High-Res	171	57	186	72
Mid-Res	85	29	100	44
Audio	56	19	71	34

4.3. Proposed Cross-layer Architecture for Resource Allocation

When considering applications able to adapt their data bandwidth requirements (e.g. teleconference), a traditional access control mechanism approach in homogeneous traffic scenarios could lead network resources underutilization. In a telemedicine context, this approach could potentially lead to medical resources sub-utilization resulting from cancelled sessions.

For a better utilization of network resources, the AC mechanism has to take advantage of data bandwidth adaption characteristics available at the application layer. Thus, a joint cooperation between different layers of the system is required. The use of cross-layer architectures in the design of resource allocation mechanisms for wireless networks has been previously proposed in the literature (Chen et al., 2011; Danobeitia & Femenias, 2011; Han et al., 2006; Jia Tang & Xi Zhang, 2007; Matalgah et al., 2013; Wang et al., 2007). Authors in (Han et al., 2006; Jia Tang & Xi Zhang, 2007) have shown that by coupling the PHY and data link layers, resource allocation policies and packet scheduling can be adapted to improve the system performance in terms of throughput. In (Chen et al., 2011; Danobeitia & Femenias, 2011; Matalgah et al., 2013; Wang et al., 2007), authors propose abstracting parameters related to channel conditions (PHY layer) and queue lengths (at MAC layer) from active users in order to improve the system throughput. The authors in (Khan et al., 2006; Yang Peng et al., 2005), introduce a resource allocation mechanism to maintain a desired level of video quality. Such mechanisms consider coupling three different layers, namely: the APP, the data link layer and the MAC. Both application-driven proposals use a rate distortion factor, which is expressed as a peak signal-to-noise ratio (PSNR) parameter to represent user-perceived video quality. However, these proposals do not include an admission control mechanism aimed at reducing the blocking probability, which for instance could help in minimizing cancellation of telemedicine sessions. It is important to note that the implementation of the previously mentioned proposals on IEEE 802.22/WRANs-based rural telemedicine deployments is not straightforward, as they do not consider particular characteristics the application scenario.

The AC mechanism introduced in this paper takes advantage of the data bandwidth adaptation capabilities of tele-consulting applications in order to reduce the blocking probability of the system. Particularly, by implementing the cross-layer architecture shown in Fig.6, resource allocation requests at the MAC layer are negotiated with the APP layer considering the available network resources.

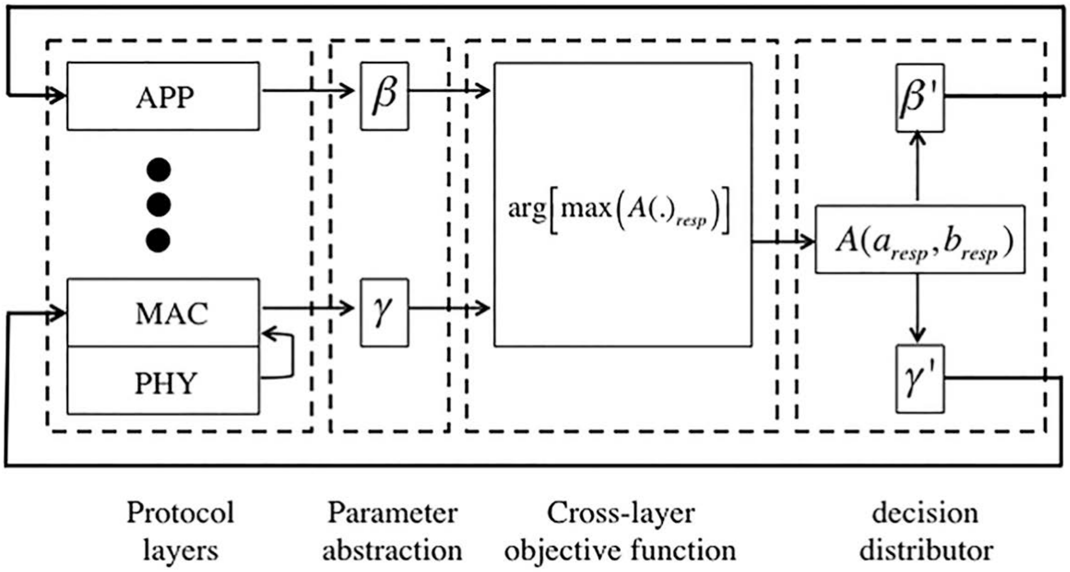


Fig.6. Cross-layer architecture for coupling MAC and APP layers.

4.3.1. Proposed Cross-layer Architecture

As it can be seen from Fig. 6, several parameters from the MAC and PHY layers are abstracted in the β and γ vectors. Specifically, the $\beta = \{\beta_1, \beta_2, \cdots, \beta_n\}$vector contains the bandwidth requirements of the *n* tele-consulting applications at the APP layer. On the other hand, vector $\gamma = \{\theta, \tau, \omega, \psi, M\}$ contains information of available bandwidth resources at the MAC layer, such as: number of subchannels per frame (θ), modulation and code rates for tele-consulting connections (ω). Details from the abstracted parameters are provided in Table 4.

Table 4 Abstracted parameters from APP and MAC layers

parameter	Description
$\boldsymbol{\beta}$	Data bandwidth requirements for all tele-consulting applications.
$\boldsymbol{\theta}$	Number of subchannels per frame
$\boldsymbol{\tau}$	Number of time symbols on downstream link
$\boldsymbol{\omega}$	Modulation and Code rates for all tele-consulting connections
$\boldsymbol{M}$	Number of active users in system
$\boldsymbol{\psi}(\boldsymbol{M})$	Overhead factor based on M

Vectors β and γ are provided by the APP and MAC layers respectively, and are fed into the AC mechanism of a base station (BS) which performs the admission decision (a_{resp}) based on the cross-layer objective function (see Section 4.4). The BS can make three possible decisions at this stage: service rejection, full-service admission, and restricted-service admission. If admission (full or restricted-service) is granted, the AC mechanism also provides the data bandwidth granted, b_{resp} by the MAC layer. By using b_{resp}, the corresponding telemedicine application is informed that bandwidth requirements should be adjusted as: High Video Resolution (β^{high}), Medium Video Resolution (β^{med}), or Audio-only (β^{low}). The specific values of the configuration parameters, β‘ and γ’, which fulfill the restrictions of a_{resp} and b_{resp} are delivered to the APP and MAC layers by means of the decision distributor process.

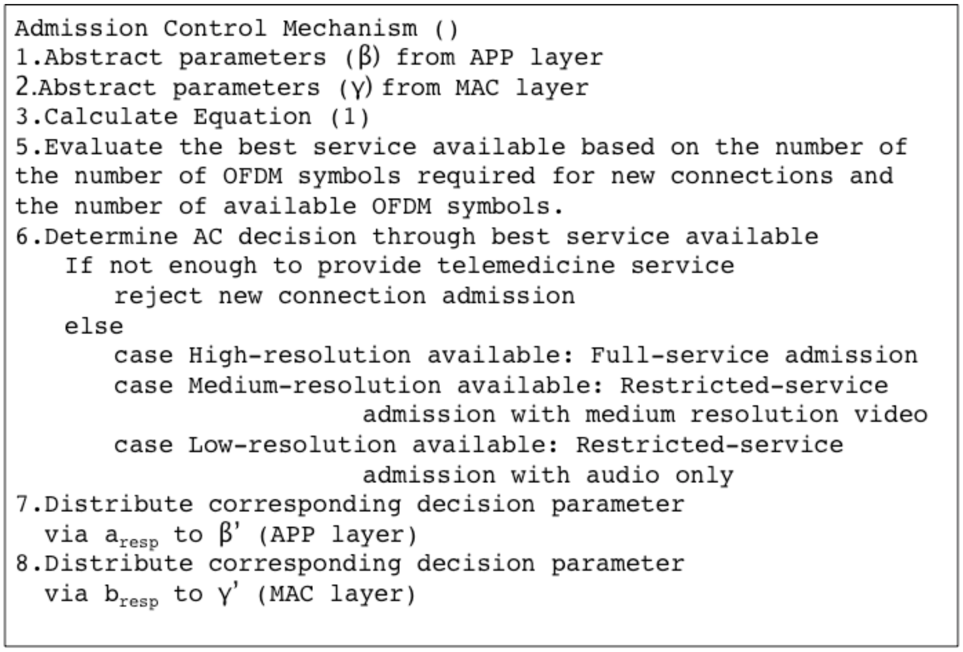
The main goal of the objective function is to assign a particular set of parameters (β and γ) for the APP and MAC layers, such that blocking probability can be reduced. To this end the maximum amount of resources that can be granted to satisfy the new connection bandwidth request is established by computing the number of OFDM symbols required for new connections and the number of available OFDM symbols. Thus, the number of OFDM symbols required for new connections is obtained by calculating $\alpha_{M+1}(\beta_{M+1}^{n}, \omega_{M+1}, \psi_{M+1})$ for an n defined as high, medium and low resolutions. Differently, the number of available OFDM symbols that could be allocated for new connections is obtained through calculation of $\delta(\beta, \omega, M)$ as shown in Eq. (3):

$$\delta(\beta,\omega,M) = \theta * \tau - \sum_{i=1}^{M} \lceil \alpha_i(\beta_i,\omega_i,\psi_M) \rceil$$

$$where\ \alpha_i(\beta_i,\omega_i,\psi_M) = \frac{\beta_i}{C(\omega_i,\psi_M)} \qquad (3)$$

In Eq. (3), resources from active users are reserved through the calculation of $\alpha_i(\beta_i,\omega_i,\psi_M)$, which is based on $C(\omega_i,\psi_M)$ that returns the data bandwidth capacity per OFDM symbol.

Therefore, the best available service level that the system can offer is chosen based on resource availability, which is computed using the Eq. (3). Afterwards, the available service level should be evaluated by calculating the number of OFDM symbols required for new connections. This way, the available service level will be represented by “High” in case the system can offer a full-service admission; “Medium” if restricted-service admission with medium resolution video is available; or “Audio” for restricted-service admission with audio-only. If there are not enough resources to provide one of the previously mentioned service levels, the new admission request is rejected. The proposed AC algorithm is shown in Fig. 7.



```
Admission Control Mechanism ()
1.Abstract parameters ($\beta$) from APP layer
2.Abstract parameters ($\gamma$) from MAC layer
3.Calculate Equation (1)
5.Evaluate the best service available based on the number of
the number of OFDM symbols required for new connections and
the number of available OFDM symbols.
6.Determine AC decision through best service available
   If not enough to provide telemedicine service
      reject new connection admission
   else
      case High-resolution available: Full-service admission
      case Medium-resolution available: Restricted-service
                      admission with medium resolution video
      case Low-resolution available: Restricted-service
                      admission with audio only
7.Distribute corresponding decision parameter
  via $a_{resp}$ to $\beta'$ (APP layer)
8.Distribute corresponding decision parameter
  via $b_{resp}$ to $\gamma'$ (MAC layer)
```

Fig. 7. Adaptive bandwidth cross-layer admission control algorithm.

4.4. Analytical Model for the Proposed ABM

As it was mentioned in Section 4.3, the main goal of the proposed ABM mechanism is minimizing the sub-utilization of network resources. This, by means of enabling new decision levels for the AC mechanism. As such, the performance of the proposed ABM mechanism is evaluated in terms of the blocking probability. To this end, a Markov chain model based on the queuing model shown in (Takagi & Walke, 2008) is proposed. The proposed analytical model is detailed in the following subsections.

4.4.1. General Assumptions

As mentioned in Section 4.3, for evaluation purposes it is assumed that the IEEE 802.22/WRAN deployment for tele-consulting services provisioning uses QPSK and/or 16-QAM modulation schemes. This way the resource block requirements can be characterized in terms of two classes (c_1 and c_2) of users requesting different amount of resources. In addition, for the proposed ABM model it is considered that the system allocates high-resolution services while there is enough available data bandwidth. Afterwards, the admission request for high-resolution service could be admitted as a teleconference with medium-resolution or audio-only before rejection. Consequently, the blocking probability will be given by the state where the system cannot admit new tele-conference sessions in any of the three possible resolutions.

It has been shown that traffic of medical services, such as Emergency Medical Services, can be characterized as a typical Poisson process on arrival times. Similarly, departure times correspond to an exponential distribution (Channouf et al., 2007; Matteson et al., 2011). Hence, the state of the system can be modeled as a birth and death process where the transitions from state *i* to *i+1* will be given by a λ parameter. Likewise, the transition from *i* to *i-1* will depend on a μ parameter, where λ/μ is the offered traffic per each type of teleconference service. It is considered that the resolution of the tele-conference is modified at the BS upon the arriving of the request, i.e., users always request high-resolution tele-conference. Thus, it can be stated that users from each modulation scheme arrive in independent Poisson processes where the λ and μ parameters are the same, regardless of the granted type of service.

4.4.2. Non-ABM Blocking Probability

Let Rb_t be the total number of available RBs on the system. Additionally, let $Rb^{c_1,H}$ and $Rb^{c_2,H}$ be the number of RBs required by users of class c_1 and c_2, respectively. Thus, the maximum number of users that can be allocated in the system per class can be defined as $S_{max}^{c_1,H}(Rb_t, Rb^{c_1,H}) = \lfloor Rb_t/Rb^{c_1,H} \rfloor$ and $S_{max}^{c_2,H}(Rb_t, Rb^{c_2,H}) = \lfloor Rb_t/Rb^{c_2,H} \rfloor$. Hence, the number i of c_1 users and number j of c_2 users being served in the system is finite and defined as state space $\Omega \coloneqq \{(i,j) :\ i * Rb^{c_1,H} + j * Rb^{c_2,H} \leq Rb_t, 0 \leq i \leq S_{max}^{c_1,H}, 0 \leq j \leq S_{max}^{c_2,H}\}$.

Here, the system rejects a connection when a new request arrives and the remaining capacity $\xi(i,j)$ of the system is lower than $Rb^{c_1,H}$ or $Rb^{c_2,H}$, according to the class of the arriving request. Thus, a c_1 request is rejected for the states belonging to the subset $\Omega_{\xi(i,j)}^{c_1,H} \coloneqq \{(i,j) \colon [Rb_t - (i * Rb^{c_1,H} + j * Rb^{c_2,H}) = \xi(i,j)] < Rb^{c_1,H}, i \geq 0, j \geq 0\}$. Similarly, a c_2 request is rejected for the states belonging to the subset $\Omega_{\xi(i,j)}^{c_2,H} \coloneqq \{(i,j) \colon [Rb_t - (i * Rb^{c_1,H} + j * Rb^{c_2,H}) = \xi(i,j)] < Rb^{2,H};\ i \geq 0, j \geq 0\}$. Hence, the blocking probability for c_1 and c_2 request is $P\left\{(i,j) \in \Omega_{\xi(i,j)}^{c_1,H}\right\}$ and $P\left\{(i,j) \in \Omega_{\xi(i,j)}^{c_2,H}\right\}$ respectively. It is important to noted that the state subset $\Omega_{\xi(i,j)}^{c_1,H}$is conditioned to $Rb^{c_2,H} \leq \xi(i,j) < Rb^{c_1,H}$ when $Rb^{c_1,H} > Rb^{c_2,H}$. When $Rb^{c_2,H} > Rb^{c_1,H}$, the state subset $\Omega_{\xi(i,j)}^{c_2,H}$is conditioned to $Rb^{c_1,H} \leq \xi(i,j) < Rb^{c_2,H}$.Therefore, the blocking probability without ABM for high resolution users based on two different classes of users is given by$P\left\{(i,j) \in \Omega_{\xi(i,j)}^{c_1,H} \cup \Omega_{\xi(i,j)}^{c_2,H}\right\} = \sum_{(i,j) \in \Omega_{\xi(i,j)}^{c_1,H}} (p_{i,j}) + \sum_{(i,j) \in \Omega_{\xi(i,j)}^{c_2,H}} (p_{i,j})$. In Fig. 8, a graphical representation of the non-ABM model is shown.

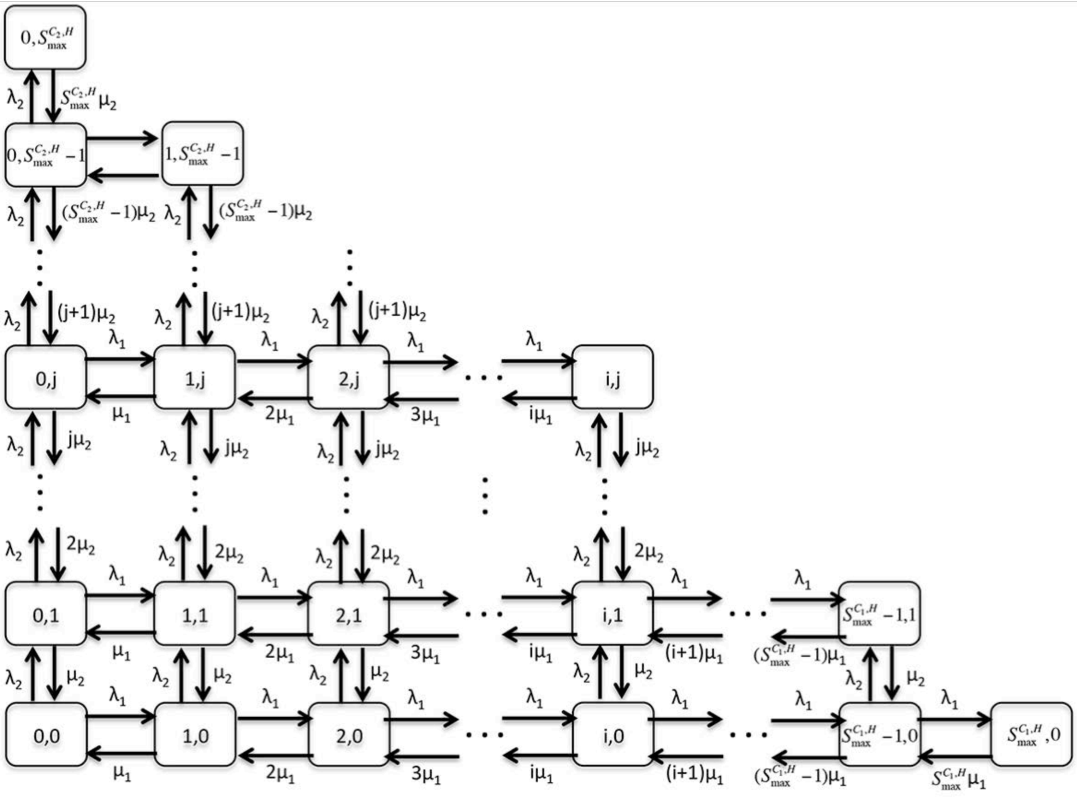


Fig. 8. State transition rate diagram for non-ABM model with two classes of modulations for high-resolution tele-consulting sessions.

4.4.3. ABM Blocking Probability

For the proposed ABM mechanism it is assumed that upon a user service request, high-resolution, medium-resolution or audio only tele-conference session can be granted according to the available resources. This means that under this approach the blocking probability of the system is not restricted to the state subset $\Omega_{\xi(i,j)}^{c_1,H} \cup \Omega_{\xi(i,j)}^{c_2,H}$. Consider that $Rb^{c_1,M}$ and $Rb^{c_1,A}$ are the number of RBs required to allocate a c_1 user that as a first option has requested high-resolution video, but can support medium resolution video as a second option and also audio only as a third option, respectively. Also, consider that $Rb^{c_2,M}$ and $Rb^{c_2,A}$ are the number of RBs required to allocate a c_2 user that can support medium resolution video and audio only, correspondingly. For the proposed model it is assumed that $Rb^{c_1,H} \neq Rb^{c_2,H} \neq Rb^{c_1,M} \neq Rb^{c_2,M} \neq Rb^{c_1,A} \neq Rb^{c_2,A}$

Because high-resolution video service is always preferred (while there is enough available resources), it can be said that the first decision level corresponds to the non-ABM state subset $\Omega_{\xi(i,j)}^{c_1,H} \cup \Omega_{\xi(i,j)}^{c_2,H}$. New decision levels emerge if a c_1, H user arrives requesting system resources and $\xi(i,j) \geq Rb^{c_1,M}, Rb^{c_1,A}$.

Likewise, if $\xi(i,j) \geq Rb^{c_2,M}, Rb^{c_2,A}$ and a c_2, H user arrives a new decision level is enabled. Thus, new transitions and states emerge from $\Omega_{\xi(i,j)}^{c_1,H}$ and $\Omega_{\xi(i,j)}^{c_2,H}$ for c_1 and c_2 users, when they can be allocated to medium video resolution or audio only services.

An admission request from a c_1 user will be allocated as medium video service, if $Rb^{c_1,M} \leq \xi(i,j) < Rb^{c_1,H}$. As a second option, a c_1 user will be allocated with audio only service, if $Rb^{c_1,A} \leq \xi(i,j) < Rb^{c_1,M}$, otherwise the admission request is rejected. The same procedure is used to evaluate an admission requests from c_2 users. Therefore, on each decision level there are up to four different chances of enabling new levels, as each user class has up to two additional options of being admitted from all $\xi(i,j) \in \Omega_{\xi(i,j)}$.

Let $Rb_t(d,f,g,h)$ be the total number of available RBs when there are *d* and *f* users of c_1; and *g* and *h* users of c_2 allocated in the system as medium resolution and audio only, respectively. Here, $Rb_t(d,f,g,h) = Rb_t$ in state space of non-ABM due to $d+f+g+h=0$. However, on ABM context $Rb_t(d,f,g,h) = Rb_t - (d * Rb^{c_1,M} + f * Rb^{c_1,A} + g * Rb^{c_2,M} + h * Rb^{c_2,A})$ if there is at least one class user allocated with medium resolution or audio only service. In this context, on each decision level the total number of RBs available for the system should be updated to guarantee the resource allocation for the new admitted user. Thus, based on the number of d, f, g, h active users allocated in the system, the state subset, $\Omega_{\xi}^{c_{1,2},(M,A)}$, defined by Eq. 4 represents the number of available resources for each decision level.

$$\Omega_{\xi}^{c_{1,2},(M,A)} := \{(d,f,g,h): [d * Rb^{c_1,M} + f * Rb^{c_1,A} + g * Rb^{c_2,M} + h * Rb^{c_2,A}] \leq Rb_t(d,f,g,h), \forall\, Rb_t(d,f,g,h) \geq 0, 0 \leq d \leq S^{c_1,M}(Rb_t(d,f,g,h), Rb^{c_1,M}), 0 \leq f \leq S^{c_1,A}(Rb_t(d,f,g,h), Rb^{c_1,A}), 0 \leq g \leq S^{c_2,M}(Rb_t(d,f,g,h), Rb^{c_2,M}), 0 \leq h \leq S^{c_2,A}(Rb_t(d,f,g,h), Rb^{c_2,A})\} \quad (4)$$

Furthermore, on each new decision level the high-resolution users will be allocated as a first option of utilization of $Rb_t(d,f,g,h)$, where $(d,f,g,h) \in \Omega_{\xi}^{c_{1,2},(M,A)}$. Thus, we can include the cases where there are *i* and *j* active users in the system for each new decision level by defining the state subset, $\Omega_{Rb_t(d,f,g,h)}^{c_{1,2},(M,A)}$, as shown in Eq. 5.

$$\Omega^{c_{1,2},(M,A)}_{Rb_t(d,f,g,h)} := \Big\{(i,j,d,f,g,h) :\ i * Rb^{c_1,H} + j * Rb^{c_2,H} + d * Rb^{c_1,M} + f * Rb^{c_1,A} + g * Rb^{c_2,M} + h * Rb^{c_2,A} \le Rb_t(d,f,g,h), \forall\ (d,f,g,h) \in \Omega^{c_{1,2},(M,A)}_{\xi}, 0 \le\ i \le S^{c_1,H}(Rb_t(d,f,g,h), Rb^{c_1,H}), 0 \le j \le S^{c_2,H}(Rb_t(d,f,g,h), Rb^{c_2,H})\Big\} \qquad (5)$$

The state subsets that contain those cases where there are not enough RBs to allocate an arriving c_1, H and c_2, H user, are defined by Eq. 6 and Eq. 7, respectively.

$$\Omega^{Rb_t(d,f,g,h),c_1(M,A)}_{\xi(i,j,d,f,g,h)} := \Big\{(i,j,d,f,g,h) : \big[Rb_t(d,f,g,h) - \big(i * Rb^{c_1,H} + j * Rb^{c_2,H} + d * Rb^{c_1,M} + f * Rb^{c_1,A} + g * Rb^{c_2,M} + h * Rb^{c_2,A}\big) = \xi(i,j,d,f,g,h)\big] < Rb^{c_1,A}\ \forall\ i,j,d,f,g,h \ge 0\ where\ (i,j,d,f,g,h) \in \Omega^{c_{1,2},(M,A)}_{Rb_t(d,f,g,h)},\Big\} \qquad (6)$$

$$\Omega^{Rb_t(d,f,g,h),c_2(M,A)}_{\xi(i,j,d,f,g,h)} := \Big\{(i,j,d,f,g,h) : \big[Rb_t(d,f,g,h) - \big(i * Rb^{c_1,H} + j * Rb^{c_2,H} + d * Rb^{c_1,M} + f * Rb^{c_1,A} + g * Rb^{c_2,M} + h * Rb^{c_2,A}\big) = \xi(i,j,d,f,g,h)\big] < Rb^{c_2,A}\ \forall\ i,j,d,f,g,h \ge 0\ where\ (i,j,d,f,g,h) \in \Omega^{c_{1,2},(M,A)}_{Rb_t(d,f,g,h)},\Big\} \qquad (7)$$

Therefore, the blocking probability of the system with an AC mechanism based on the proposed ABM is given by:

$$P\Big\{(i,j,d,f,g,h) \in \Omega^{Rb_t(d,f,g,h),c_1(M,A)}_{\xi(i,j,d,f,g,h)} \cup \Omega^{Rb_t(d,f,g,h),c_2(M,A)}_{\xi(i,j,d,f,g,h)}\Big\} = \sum_{(i,j,d,f,g,h) \in \Omega^{Rb_t(d,f,g,h),c_1(M,A)}_{\xi(i,j,d,f,g,h)}} (p_{i,j,d,f,g,h}) + \sum_{(i,j,d,f,g,h) \in \Omega^{Rb_t(d,f,g,h),c_2(M,A)}_{\xi(i,j,d,f,g,h)}} (p_{i,j,d,f,g,h}) \qquad (8)$$

A graphical example of the ABM analytic model is shown in Fig. 4. Here, it is assumed that $Rb^{c_2,H} > Rb^{c_2,M} > Rb^{c_2,A} > Rb^{c_1,H} > Rb^{c_1,M} > Rb^{c_1,A}$. Because c_2, H users require more RB resources than any other user, the highest underutilization of resources is when the system is on state $\big(0, S^{c_2,H}_{max}\big)$. Furthermore, it should be considered that the system always prefers to allocate an arriving user with the best available service level. Hence, an arriving $c_1/c_2, H$ user will be admitted as a $c_1/c_2, A$ user only if there are not enough RBs to be admitted as a $c_1/c_2, M$ user.

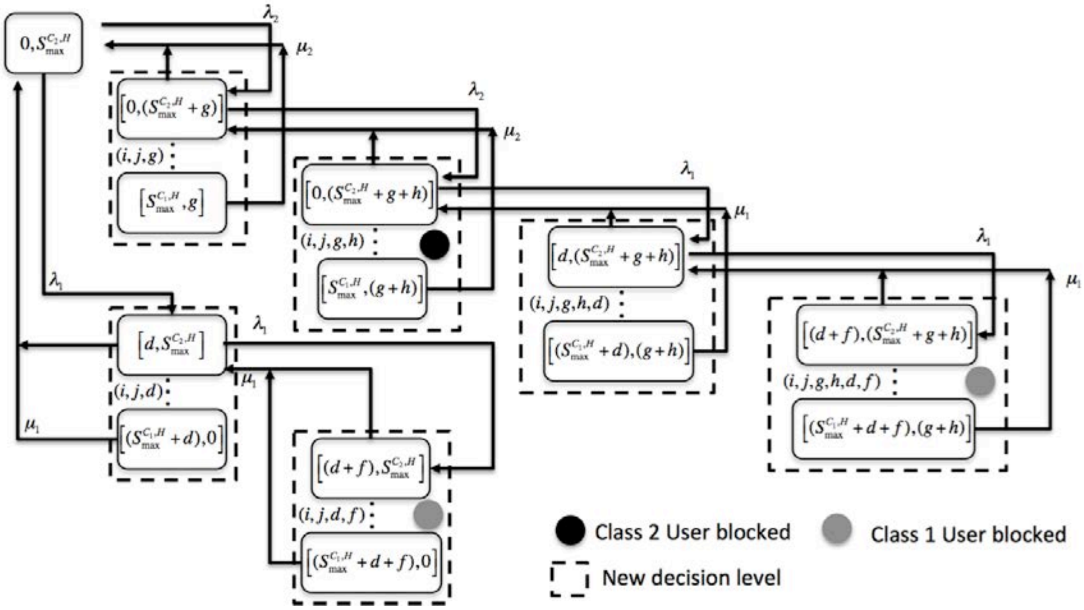


Fig. 9. Example of ABM model with two classes of modulations for tele-consulting sessions with three service levels.

As can be observed in Fig. 9, when the system is on state $\left(0, S_{max}^{c_2,H}\right)$ a c_2, H or c_1, H user can arrive requesting admission. On case a c_2, H user arrives, a new decision level that includes g users of medium resolution will emerge. Consequently, the highest underutilization of resources on the new decision level will be on state $\left[0, (S_{max}^{c_2,H} + g)\right]$. Similarly, when system is on state $\left[0, (S_{max}^{c_2,H} + g)\right]$, any arriving c_2, H user could be allocated as an audio only user (h), where the highest underutilization of resources is on state $\left[0, (S_{max}^{c_2,H} + g + h)\right]$. In case the system is on state $\left[0, (S_{max}^{c_2,H} + g + h)\right]$, any arriving c_2, H user will be blocked because there are not enough RB resources to grant admission.

Now, assume that the available RB resources on state $\left[0, (S_{max}^{c_2,H} + g + h)\right]$ are enough to allocate a c_1, H user with medium resolution. Thus, a new decision level will emerge when a c_1, H (d) arrives. This means that the highest underutilization of resources on this case will be on state $\left[d, (S_{max}^{c_2,H} + g + h)\right]$ and any arriving c_1, H user will be blocked if the system is on state $\left[(d + f), (S_{max}^{c_2,H} + g + h)\right]$ for the new decision level that includes allocation of c_1, A (f) users. Similar analysis can be performed when the system is on state $\left(0, S_{max}^{c_2,H}\right)$ and resource availability is not enough for any c_2 user, but there are sufficient RBs to allocate a c_1, H user with medium-resolution.

4.4.4. Analytical Model Application Example

As an application example, assume a scenario with a BS serving 3 clinics located within QPSK coverage range and one clinic located within 16-QAM coverage range (similar to the Monterrey, Nuevo Leon rural telemedicine project settings). It is further assumed that the clinics within QPSK coverage have a data rate of 4.54 Mbps, whereas the clinic within 16-QAM coverage has a data rate of 6.81 Mbps.

Following the system model described in Section 3 it is considered that: $\lambda = \{1,2, \dots ,30\}$, $\mu = 2$, $Rb_t = 1080$, $c_1 =$ QPSK and c_2 =16-QAM. Then the following values can be calculated for the model: $Rb^{c_1,H} = 186$, $Rb^{c_1,M} = 100$, $Rb^{c_1,A} = 71$, $Rb^{c_2,H} = 72$, $Rb^{c_2,M} = 44$, $Rb^{c_2,A} = 34$.

To calculate the non-ABM blocking probabilities note that $S_{max}^{c_1,H} = 5$ and $S_{max}^{c_2,H} = 15$. Furthermore, note that in the state subset $\left\{\Omega_{\xi(i,j)}^{c_1,H} \cup \Omega_{\xi(i,j)}^{c_2,H}\right\}$ of the non-ABM analytical model an admission request from a c_2 user is blocked when $(i,j) < Rb^{c_2,H}$. Similarly, an admission request from a c_1 user is blocked when $Rb^{c_2,H} \leq \xi(i,j) < Rb^{c_1,H}$.

For the ABM analytical model, a new decision level emerge from $\left\{\Omega_{\xi(i,j)}^{c_1,H} \cup \Omega_{\xi(i,j)}^{c_2,H}\right\}$ in case a $c_1$user request admission and $Rb^{c_1,M} \leq \xi(i,j,d,f,g,h) < Rb^{c_1,H}$ or $Rb^{c_1,A} \leq \xi(i,j,d,f,g,h) < Rb^{c_1,M}$. Similarly, a new decision level emerge in case a c_2 user request admission and $Rb^{c_2,M} \leq \xi(i,j,d,f,g,h) < Rb^{c_2,H}$ or $Rb^{c_2,A} \leq \xi(i,j,d,f,g,h) < Rb^{c_2,M}$. Therefore, the state subset $\left\{\Omega_{\xi(i,j,d,f,g,h)}^{Rb_t(d,f,g,h),c_1(M,A)} \cup \Omega_{\xi(i,j,d,f,g,h)}^{Rb_t(d,f,g,h),c_2(M,A)}\right\}$ comprises those cases where an admission request from c_2 is blocked because of $\xi(i,j,d,f,g,h) < Rb^{c_2,A}$ or a $c_1$user is blocked due to $Rb^{c_2,A} \leq \xi(i,j,d,f,g,h) < Rb^{c_1,A}$.

Once the state space for the non-ABM and the ABM analytical models were defined, the resulting continuous time Markov chain was solved numerically by means of a computer program. The results obtained for both models are shown in Fig. 10 for different average admission requests per hour, λ.

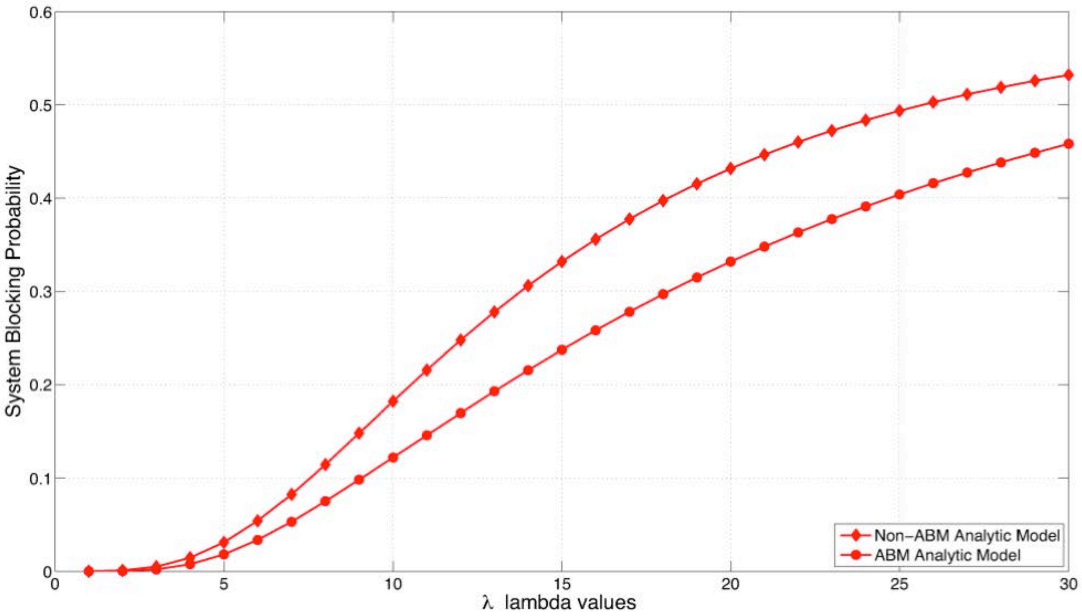


Fig. 10. Blocking probability comparative between non-ABM and ABM admission control analytical models.

In Fig. 10, it can be observed that the proposed ABM mechanism reduces the blocking probability of the IEEE 802.22/WRAN tele-consulting service compared to the non-ABM mechanism. Thus, by properly designing an AC mechanism able to provide alternative tele-consulting options with lower bandwidth requirements when the network resources become scarce, the number tele-consulting sessions cancelled can be significantly reduced.

4.5. Simulation Testbed and Numerical Results

In order to evaluate the proposed AC mechanism performance in a more realistic rural deployment scenario, a simulation testbed was implemented in MATLAB®. This testbed considers all the constraints and parameters introduced in Section 4.3 (e.g. peak data rates, PHY and MAC layers overhead, etc.). Furthermore, relevant conditions such as fading propagation channel, random NPUs appearance, and interaction between the different layers of the system were also included in the simulation model.

The propagation model implemented in this work considers the P.1546-4 path loss model (configured for rural environments) in accordance to the recommendation given by the International

Telecommunication Union (Recommendation ITU-R P.1546-4, 2009). Because no dynamic transmit power adaptation is considered, the transmit power will be fixed to 36 dBm for CPEs devices and 50 dBm for the BS. In addition to the P.1546-4 model, in order to characterize radio channel between BS and CPE, the Rayleigh fading model introduced in (Atat et al., 2014) is considered.

$$H_{(k,j,dB)} = -10log_{10}\Omega\left(d_{kj}\right) + 10log_{10}\mathrm{F}_{kj}(\sigma) \tag{9}$$

In Eq. (9), the first expression captures the propagation loss from the ITU model, depending on the distance between BS (user *k*) and CPE (user *j*). The second factor corresponds to Rayleigh fading, based on parameter σ = 2.17 that corresponds to the 600 MHz band statistics.

To validate the simulation model, the same considerations used in Subsection 4.4.4 were used in the simulation testbed to obtain blocking probabilities in absence of NPUs and under ideal propagation conditions, that is: $\lambda = \{1,2,\ldots,30\}$, $\mu = 2$, $Rb_t = 1080$, $c_1 =$ QPSK and $c_2 =$16-QAM. The simulation run for each λ value was divided in 100 batches, where each batch contains 10,000 network events per user (e.g. admission requests from a rural hospital). The blocking probability is then calculated as a reason between the total number of rejected connections and the total number of admission requests for each λ value. The Fig. 11 shows the comparison between the blocking probabilities obtained with the analytical model and the simulation testbed for non-ABM and ABM admission control. As it can be readily seen in this figure, the simulation testbed results closely follow the analytic results presented in Subsection 4.4.

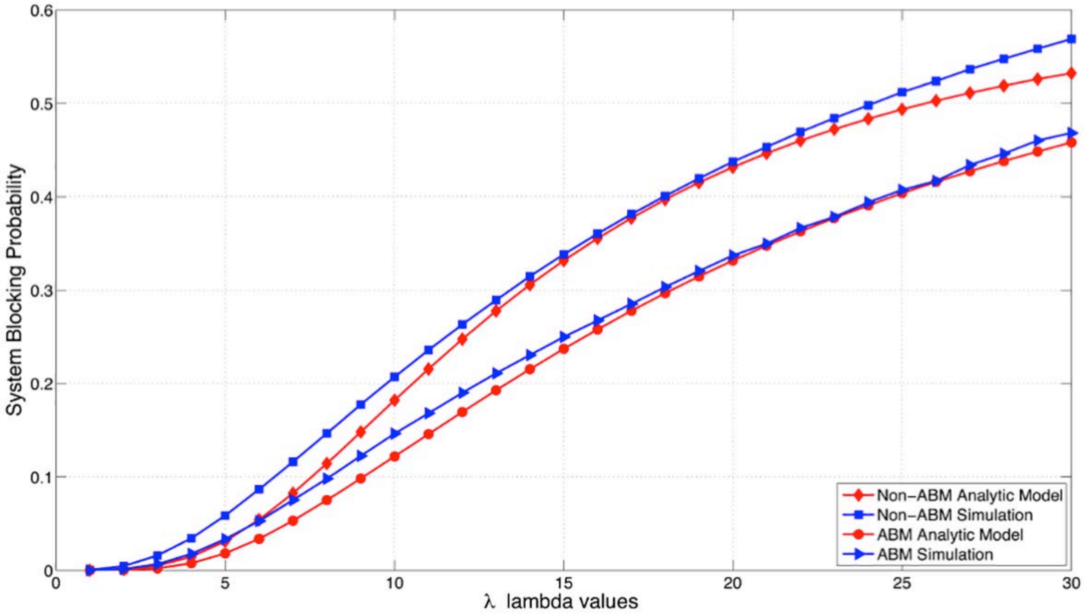


Fig. 11 Blocking probability comparative between non-ABM and ABM admission control based on analytic and simulation models.

By using the simulation testbed, the ratio of allocated resources for the three levels of tele-consulting services (high-quality video, medium-quality video and audio-only) can be obtained for each of the λ values previously considered. These ratios are shown in Fig. 12 as percentages where in addition to the ratios obtained when $\mu = 2$, the ratios obtained when $\mu = 4$ were included. Particularly, the first bar corresponds to $\mu = 4$ while the second bar corresponds to $\mu = 2$. It can be noticed that for the worst-case scenario considered (high traffic congestion with λ=30 and μ=2) 92% of the available resources were allocated to high-quality video, 5% of the resources were allocated to medium-quality video, and 3% of the resources were allocated to audio-only connections. Thus, from Fig. 12 it can be concluded that at least 97% of system resources were used to provide accepted users with high or medium quality video service.

In order to perform an in-depth performance evaluation of the proposed ABM for IEEE 802.22/WRAN rural tele-consulting deployments, results obtained when including realistic propagation conditions and random appearances of NPUs in the simulation testbed are provided next. Unless otherwise stated, to perform this evaluation it was assumed that $\lambda = \{1,2,\ldots,30\}$, $\mu = 2$, $Rb_t = 1080$, $c_1 =$ QPSK and c_2 =16-QAM as in previous examples.

It is fair to assume that on rural regions the average arrival rates and occupancy times of NPUs are lower than on urban regions. Therefore, in order to evaluate the effects of the average arrival rate of NPUs, λ_{NPU}, over the blocking probabilities, the simulation testbed considers average arrival rates of 3, 5 and 10 NPUs arrivals per hour for low, medium and high NPU congestion respectively. Similarly, average NPU occupancy times, $1/\mu_{NPU}$, corresponding to WMs transmissions sustained for 30, 60 and 90 minutes on the average are referred to be low, medium and high respectively.

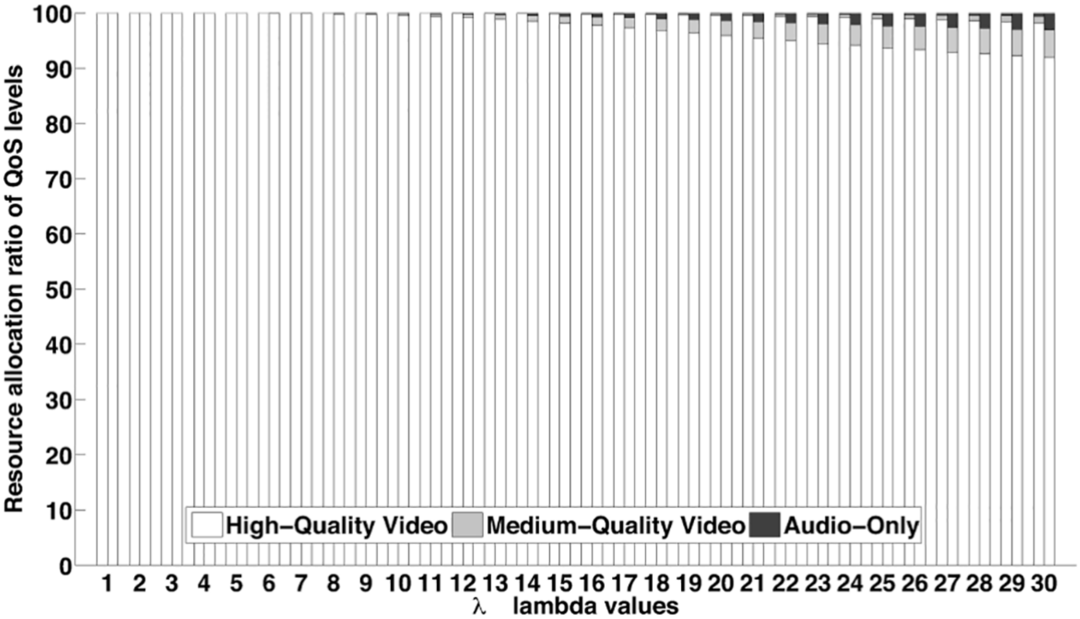


Fig. 12. Resource allocation percentage of high-quality video, medium-quality video and audio-only services.

Fig. 13 presents the blocking probabilities for the ABM and non-ABM AC mechanisms considering the NPUs average arrival rates previously defined with average NPU occupancy time of 30 minutes. It can be observed that the blocking probability is negatively affected by the random appearance of NPUs. Nevertheless, note how this effect is less for the proposed ABM mechanism. This means that the proposed ABM mechanism copes better with the presence of NPUs than the non-ABM mechanism. Note as well that for all cases the ABM mechanisms outperforms the non-ABM mechanism.

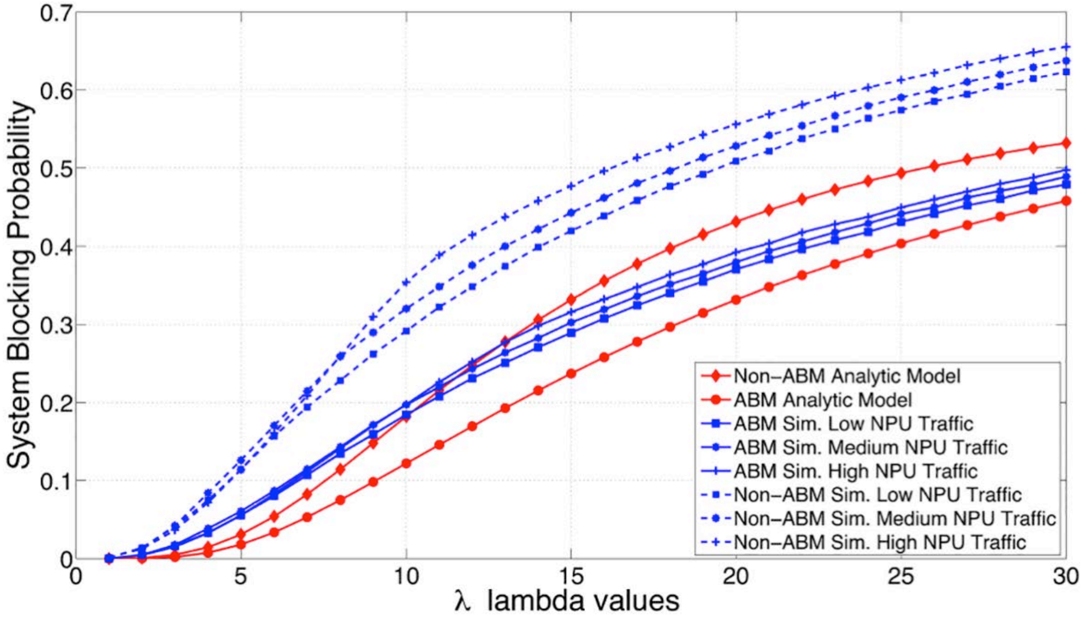


Fig. 13. Blocking probability obtained with the non-ABM mechanism and the proposed ABM mechanism in presence NPUs when the average occupancy time is fixed to low: $1/\mu_{NPU} = 30$ mins. Low, medium and high average arrive rates ($\lambda_{NPU} = 3$, 5, and 10 arrivals per hour respectively) were considered for this plot.

Fig. 14 presents the blocking probabilities for the ABM and non-ABM AC mechanisms considering the NPU average occupancy times previously defined with average arrival rate of 3 NPUs per hour. In this plot it can be observed that the blocking probability is larger when the average NPU occupancy time increases. Nevertheless, as in Fig. 13, this effect is less for the proposed ABM mechanism. This confirms that the proposed ABM mechanism copes better with the presence of NPUs. In other words, with proposed ABM mechanism an IEEE 802.22/WRAN-based rural tele-consulting service has more opportunities to achieve a successful admission.

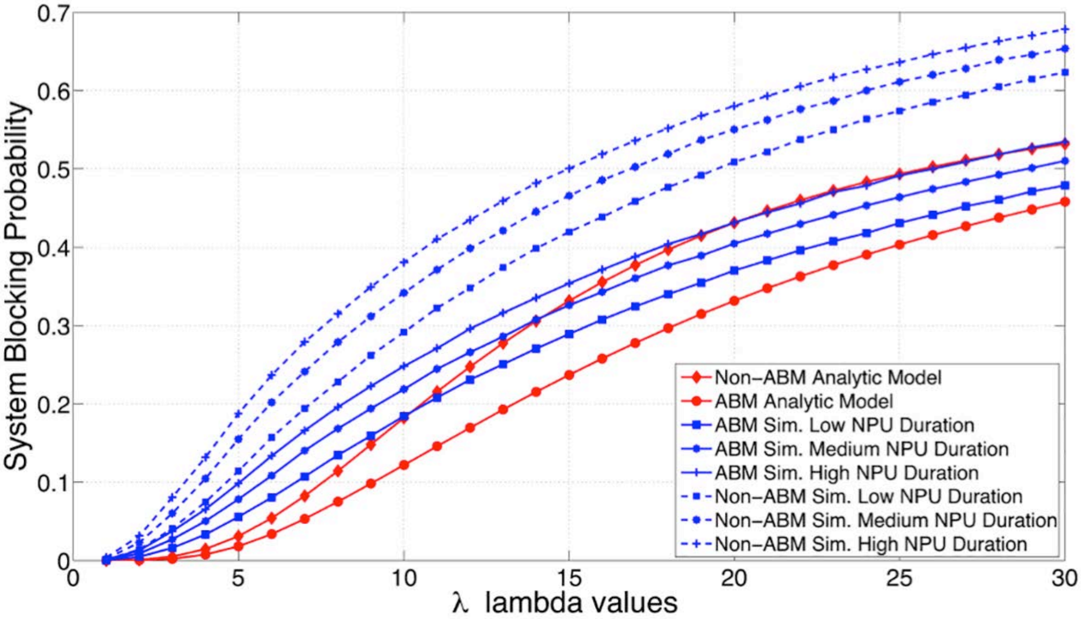


Fig. 14. Blocking probability obtained with the non-ABM mechanism and the proposed ABM mechanism in presence NPUs when the average arrival rate is fixed to low: $\lambda_{NPU} = 3$ arrivals per hour. Low, medium and high average NPU occupancy durations ($1/\mu_{NPU} = 0.5$, 1, and 1.5 hours respectively) were considered for this plot.

4.5.1. Results Discussion

From the results shown in Fig. 13 and Fig. 14, it is clear that because of the data bandwidth availability reduction resulting from random NPUs appearances, the blocking probability of tele-consulting sessions shows an increment regardless of the AC mechanism used in the IEEE 802.22/WRAN deployment for rural tele-consulting services. Nevertheless, it is important to note that for all the cases analyzed, the proposed ABM mechanism for IEEE 802.22/WRAN-based rural tele-consulting deployments keeps the blocking probability below 0.1 for average arrival rates, λ, below 5 tele-consulting sessions requests per hour (see Fig. 11, Fig. 12 and Fig. 13). Considering that, as discussed in Section 2, current rural tele-consulting deployments have an average arrival rate of 1 or 2 session requests per hour, deployment of IEEE 802.22/WRAN-based rural tele-consulting services is feasible when using the proposed ABM mechanism.

Additionally, it is important to note that when using the proposed ABM mechanism, more than 92% of available system resources are used to provide accepted users with high-resolution video service (see Fig. 12). In addition, in a rural deployment context, the acceptance of a telemedicine connection with less quality instead, its rejection may lead to a better perception of the system performance and adequacy, as an appointment cancellation may result on serious inconveniences for patients and the inefficient use of medical resources. Nonetheless, an in-depth analysis comprising measurement of mean opinion score (MOS) factor should be performed in order to be conclusive about the impact of the AC mechanism on the quality of experience (QoE). Such analysis is out of the scope of this work.

4.6. Chapter Summary

The growing use of wireless networks for health applications has made it necessary to look into new paradigms for the delivery of rural telemedicine services. With this in mind, in this work a cross-layer admission control scheme based on adaptive bandwidth management was introduced for rural tele-consulting services delivery over IEEE 802.22/WRAN networks. The proposed AC mechanism enables the admission of tele-consulting connections that under a typical AC scheme would have been blocked.

The presented results show that when compared with a typical AC mechanism, the proposed ABM mechanism achieves a significant improvement on the blocking probability of tele-consulting session requests, even under high-traffic congestion scenarios. This is possible by coupling the QoS service level at the APP layer with the network resources availability at the PHY layer, and then providing new admission control criteria for telemedicine applications that can support different levels of QoS.

The analog TV switch off presents an important opportunity for the delivery a variety of data services over TVWS for rural communities. Among them, provisioning of telemedicine services for these communities it is really important for social and economic reasons. In this sense, the results presented in

Subsection 4.5 show the potential for the delivery of rural tele-consulting services over IEEE 802.22/WRAN networks when the proposed ABM mechanism is used. However, this is only the first phase of an integral solution for deployment of telemedicine networks based on the IEEE 802.22/WRAN, since it has to be considered the design of complementary scheduling algorithms to establish resource allocation priorities between different telemedicine services, such as tele-diagnosis, tele-consulting, and tele-monitoring. Therefore, in the following chapter a cross-layer scheduler for telemedicine services based on the IEEE 802.22/WRAN standard is presented.

Chapter 5. Scheduling Algorithm for Telemedicine Service Delivery based on the IEEE 802.22/WRAN Standard

5.1. Introduction

In last decade, technological solutions that enable the remote monitoring of patients as part of a diagnostic procedure, supervision of a chronic condition, or post-operative recovery have been proposed (Hadjidj et al., 2013; Hamdi et al., 2014; Kulkarni & Ozturk, 2011; McGregor et al., 2007). This has led to the development of telemedicine as a new paradigm for the provisioning of health services. However, the lack of technological infrastructure and connection availability towards the deployment of a telemedicine network may limit the medical services that can be offered. In other words, a telemedicine model designed to offer diagnosis services using high definition video (with a minimal bandwidth requirement of 400 Kbps connection) may require QoS provisioning that a modem connection over a POTS network (with a bandwidth of 56 Kbps) cannot offer. It is important to note that on a rural telemedicine deployment scenario the number of telemedicine services that can be served is limited by bandwidth and QoS requirements. Hence, the system resources for the telemedicine services must be reserved by means of resource scheduling algorithms. Therefore, this chapter considers the provisioning of basic medical services from urban to rural regions by enabling tele-diagnosis, tele-consulting and tele-monitoring services.

In IEEE 802.16/WiMAX, the use of scheduling algorithms towards QoS provisioning has been widely studied in (Kas et al., 2010; Niyato et al., 2007b; So-In et al., 2009b). However, by considering that IEEE 802.22/WRAN operates in unlicensed TVWS channels, and its maximum transmission range doubles the one offered by IEEE 802.16e/WiMAX, then the deployment of IEEE 802.22/WRAN rural telemedicine networks can offer lower operating and implementation costs compared to WiMAX or another rural connectivity solutions (e.g. BSC). For this reason, IEEE 802.22/WRAN has the potential of enabling the delivery of different multimedia-based telemedicine services (e.g. tele-consulting) over long distances, and hence seems to be a viable option for the deployment of rural telemedicine networks. In this context, the IEEE 802.22/WRAN standard includes QoS provisioning for several type of traffic profiles that represents an alternative solution to the transmission of telemedicine applications. Because the disruption in the transmission of a telemedicine service, such as tele-diagnosis over an emergency scenario, may represent a risk for the patient health; the enabling of telemedicine service delivery is limited by its condition as a secondary user of the spectrum. In other words, before using a particular TVWS channel, the BS and the CPE must verify that it is not being occupied by transmissions from primary users. Thus, the IEEE 802.22 standard includes cognitive radio capabilities in order to protect the primary users of the TVWS spectrum. Hence, one of the main issues to overcome for the implementation of effective telemedicine services over IEEE 802.22, is the spectrum allocation restriction caused by the protection of primary users. Thus, before deploying telemedicine services over IEEE 802.22, the design of mechanisms aimed at guaranteeing the availability of enough bandwidth resources for telemedicine applications, even in the presence of primary users, is needed. Note that even though the standard considers four different levels of QoS, the design of such mechanisms is not trivial, as none of the QoS levels guarantees availability of resources when a primary user is found.

Telemedicine comprises emergency and non-emergency scenarios. This means that a priority scheme should be considered within the scheduling algorithm design. In order to established a hierarchy that rules the allocation of system resources, among telemedicine services, is necessary to collect information related to telemedicine traffic profiles, QoS requirements, data bandwidth availability, presence of primary users and radio channel details, among others. Thus, a cross-layer architecture is proposed to enable this feature in a resource allocation mechanism for telemedicine services, which couples the APP and MAC layers. Since all included telemedicine services requires at least a minimum of QoS provisioning. Therefore the ERrt, nERrt and nERnrt telemedicine services must be transmitted under the UGS, rtPS and nrtPS of the IEEE 802.22/WRAN QoS type of services, respectively. It should be noted that, although the IEEE 802.22 standard defines the type of QoS services, it does not provides any pre-defined mechanism to assign system resources, by leaving the resource allocation scheduling as an open issue.

Consequently, without a resource allocation scheduling for telemedicine services, there will not be system resources that can be reserved to guarantee their data bandwidth requirements, which it is not desirable in health applications where information about patient health status is included. In fact, the restricted access to spectrum as secondary users within an overlay scheme may cause an increase in the blocking and interruption probabilities, because of the requirement of stopping transmissions in the frequency bands where the primary users are found (Fitch et al., 2011; Gao et al., 2012; Shellhammer et al., 2009). For telemedicine service delivery this fact represents a major issue, and become relevant by considering that tele-diagnosis sessions from ambulances (under emergency scenarios) could be blocked or interrupted, even when those sessions are active.

Therefore, the design of a dynamic spectrum allocation is required to avoid throughput drops, or disruptions in the transmission of telemedicine traffic, even in presence of primary users. This way, the resource allocation mechanism can enable a dynamic resource reservation by means of implementing a scheduling algorithm based on data bandwidth requirements of telemedicine services. Additionally, in order to overcome throughput disruptions that result from the presence of primary users (according to the overlay spectrum access scheme that has been defined in the IEEE 802.22 standard), the scheduler should be designed with a channel-aware feature. To the best of our knowledge, a scheduling algorithm that provides the required resources for enabling telemedicine services over IEEE 802.22, that considers data bandwidth restrictions resulting from the presence of primary users, has not been previously proposed. Therefore, in this chapter a Telemedicine Cross-Layer Scheduling (TelemedCLSch) algorithm that enables the deployment of rural telemedicine services over the IEEE 802.22 standard is proposed.

The proposed TelemedCLSch algorithm aims to perform scheduling of network resources for tele-monitoring, tele-consulting and tele-diagnosis services in a hierarchical way. Here, TelemedCLSch scheduler has to deal with bandwidth constraints resulting from PU presence. Particularly, the bandwidth availability on IEEE 802.22/WRAN networks could be seriously affected by the random appearance of NPUs (i.e. wireless microphones), since it has been established an overlay spectrum access scheme. However, authors in (Park et al., 2012) have shown that IEEE 802.22/WRAN networks can operate in coexistence with NPUs, by means of implementing a subchannel notching technique to avoid interference, and a subchannel bonding technique to improve efficiency on spectrum utilization. This way, the subscribed users to IEEE 802.22/WRAN do not have to stop transmitting and abandon the operating channel to protect NPU transmissions. Instead, the IEEE802.22/WRAN network can protect NPU transmissions by isolating particular portions of channel bandwidth, while remaining spectrum is re-allocated to enable SU transmissions. Thus, the TelemedCLSch scheduler has to consider variations on bandwidth availability given by presence of PU transmissions.

In this context, bandwidth availability variations can be determined by means of abstracting information related to presence of PUs from MAC layer, which is periodically updated through results from spectrum sensing functions on PHY layer. Differently, information related to telemedicine priorities, QoS requirements and traffic characteristics can be obtained from the application (APP) layer. Hence, by coupling APP and MAC layers through a cross-layer architecture the two main elements (telemedicine priorities and bandwidth availability) that affects scheduling of resource allocation for telemedicine service delivery, can be characterized for rural deployments based on the IEEE 802.22/WRAN standard. Therefore, the proposed TelemedCLSch scheduling algorithm includes the cross-layer architecture depicted in Chapter 4, as a fundamental tool for resource allocation purposes.

5.2. The Cross-layer Telemedicine Priority Scheduling for the IEEE 802.22/WRAN standard

In the IEEE 802.22 standard, the BS manages the system resources, and assigns them to the CPEs. Since the BS is in charge of the management of upstream and downstream links, it will be considered that the scheduling algorithm will be performed at the BS. The data bandwidth load per link is considered asymmetric, because for telemedicine services a high-load of data bandwidth may be required, either in the downlink or in the uplink. For instance, if a local physician is accessing a medical record from a patient, the maximum data bandwidth will be loaded on the downlink. Differently, if an ambulance is transmitting medical information from a patient, the maximum data bandwidth will be loaded on the uplink. This case study will be focused on the downlink traffic, since it has been defined that in the most restricted telemedicine scenario (emergency), the data are collected from the ambulance to the urban hospital. Based on the single cell condition, no co-channel interference, or interference from the CPEs to the PUs throughput, will be considered. Moreover, because the simulation is focused on the data bandwidth transmission, the performance metrics will be calculated on the MAC layer, for all CPEs traffic.

Similar to the conditions described in Chapter 4, the subchannel notching and bonding techniques shown in (Park et al., 2012) will be assumed to enable coexistence between secondary and primary users. In same direction, the proposed TelemedCLSch scheduler considers that the data traffic connections generated by the PUs and CPEs present a negative exponential distribution, for the interarrival and departure times (Van Mieghem, 2009). Here, the average interarrival times are expressed as, $1/\lambda_{PU}$, $1/\lambda_{TD}$, $1/\lambda_{TC}$, $1/\lambda_{TM}$ for PUs, tele-diagnosis, tele-consulting and tele-monitoring users, respectively; correspondingly, the average departure times are denoted as, $1/\mu_{PU}$, $1/\mu_{TD}$, $1/\mu_{TC}$, $1/\mu_{TM}$. Additionally, a fixed number of subchannels will be assigned for PUs, and tele-diagnosis users to guarantee QoS, under a UGS profile. Since the cross-layer scheduler is focused on interlayer coupling between the MAC and APP layers, the study of spectrum management and PUs sensing function, is beyond the scope of this paper.

5.2.1. Density of Wireless Microphones in Rural Regions

At the writing time of this work, a traffic pattern of PUs reported in the literature could not be found. However, the reports issued by the European Commission Directorate General for Communications

Networks, Content and Technology, as well as the FCC in United States, establish that a highest density of WMs is observed in major sports and cultural major events (i.e. super bowl games, concerts, etc.) (The Coalition of Wireless Microphone Users 2009; European Commission and Directorate-General for the Information Society and Media 2013; Microsoft Corporation 2013). In this context, up to 50 WMs can be operating steadily for up to 3 hours. Another case where a high density of WMs can be found is on theater play events, where microphones use for hours can be found, and their operating location can be estimated. For instance, in Broadway Avenue at New York City, the density of WMs operating can be up to 20 WMs operating continuously on a regularly scheduled play duration. Different to previously mentioned cases, a low to medium density use of WMs (of up to 10) can be mostly found in sporadic cultural public events, in school buildings and religious churches. Additionally in this case, the WMs operating time is approximately of up to 1 hour for cultural public events and religious churches, while in school buildings an average use duration of 15 minutes can be estimated, by considering its main use to deliver announcements, or instructions to students. None of these WMs density cases involves rural regions. However, by considering that even in rural regions we may find school buildings within BS coverage area, this work will assume WMs use time of up to 20 minutes. Since regularly school operating hours are ranging from 8 AM to 9 PM, it will be assumed that WMs transmit every 3 hours. Hence, different to simulation model shown in Chapter 4, in this evaluation scenario a density of WMs (of up to 10) will be considered. This assumption is based on a low to medium use density that corresponds to sporadic cultural public events, in school buildings and religious churches. Therefore, the utilization rate and transmission duration times of primary users will be characterized by the parameters $\lambda_{PU} = 1/3$ and $\mu_{PU} = 3$, respectively.

5.3. Simulation Model for Evaluation of the proposed TelemedCLSch scheduler

Previously, it has been stated that the BS will be located in the urban hospital. This means that the utilization rate of telemedicine services (i.e. tele-diagnosis, tele-consulting or tele-monitoring) will be based on the number of calls arriving at the urban hospital requesting a specific telemedicine session. In order to estimate utilization rates and transmission duration of tele-diagnosis and tele-consulting services; the evaluation of the proposed TelemedCLSch scheduler will be based on the case studies shown in (Scheulen et al., 2001; Li et al., 2008; Stripe and Susman, 1991; Newgard et al., 2010; Zanaboni et al., 2009; Pacheco-López et al., 2011; Zachariah et al., 2012; Vargas et al., 2014). About the provision of emergency medical services, authors in (Li et al., 2008; Scheulen et al., 2001; Stripe and Susman, 1991) performed an analysis that shows ambulance arrival rates in emergency departments or hospitals in rural areas of central Maryland, Taiwan Island in China, and Richardson County in Nebraska, respectively. Reported population density in rural areas of central Maryland is ranging from 26.52 people/Km2 (in Anne Arundel County), to 56.92 people/Km2 in Carroll County. In contrast, rural Richardson County has an approximate population density of 6 people/Km2, while Taiwan Island presents a rural population density of 73 people/Km2. By considering an average rural population density of 39.33 people/Km2 (in Central Maryland), it can be said that Richardson County has a low rural population density, in comparison with rural population density shown in Taiwan Island. In order to study ambulance arrival rates for rural regions, the authors in (Scheulen et al., 2001) classified the emergency patients based on three levels of attention: critical condition (requires emergency immediate medical attention), less serious condition (requires emergency medical attention but not immediately) and non-emergency condition (requires medical attention but not emergency). In this context, an ambulance arrival rate of 0.56 patients/hour has been reported by considering all priority levels, and an arrival rate of 0.28 patients/hour by considering only those that require emergency medical attention. In the Taiwan Island case study (Li et al., 2008), the EMS utilization is based on rural road traffic accident (RTA) characteristics. Here, a 5.63% of deaths that were attended by post-trauma units are identified in rural regions, and 32% of those patients died before being admitted in the hospital. By considering that every RTA event (served by hospitals or post-trauma units) requires ambulance transportation services, it can be calculated an ambulance arrival rate of 0.033 patients/hour that requires emergency immediate medical attention. Differently, in (Stripe and Susman, 1991) the ambulance transportation in rural Richardson County involves elderly people that requires pre-hospital EMS. Here, 70% of EMS patients aged more than 64 years old. Consequently, more than 58% of EMS calls attended by an ambulance involved patients with fractures, or cardiorespiratory and neurologic problems. In this context, an average of one call requesting EMS every 19.2 hours is observed in rural Richardson County, which results in an ambulance arrival rate of 0.052 patients/hour. Authors in (Newgard et al., 2010), studied ambulance EMS time intervals after the onset of out-hospital traumatic injury in the United States and Canada. The EMS "Golden Hour" analysis includes the following time intervals: activation, response, on-scene and transport. In the United States and Canada an average total EMS interval of 35.7 minutes and 38.1 minutes was found, respectively. The highest EMS interval times were observed on-scene, ranging from 13.0 to 25.5 minutes in United States, and from 14.9 to 27 minutes in Canada.

Since the proposed TelemedCLSch scheduler considers tele-diagnosis service with the highest priority level, its evaluation will include three rural scenarios. The first two scenarios include unrestricted, and restricted patient level attention, which aim to serve rural regions (with a high population density). In a different way, the third scenario corresponds to rural regions with a low population density without any priority patient level restriction. Thus, based on case study shown in (Scheulen et al., 2001), a rate of 0.56 patients/hour is observed in rural regions without any patient level attention restriction. Similarly, a rate of 0.28 patients/hour was registered in the same rural regions, by considering only those patients classified in attention level I, and II. By taking into account the rural Richardson County case study, a rate of 0.052 patients/hour will be considered in the third scenario. Therefore, the corresponding rates for tele-diagnosis traffic included in the simulation are: $1/\lambda_{TD-HRU} = 1.78\ h$, $1/\lambda_{TD-HRR} = 3.57\ h$ and $1/\lambda_{TD-LRU} = 19.23\ h$ for the high rural unrestricted scenario (HRU), the high rural restricted scenario (HRR) and the low rural unrestricted scenario (LRU), respectively. As this work assumes the transmission of tele-diagnosis service in emergency site only, a tele-diagnosis session duration of 15 minutes will be considered. Hence, the service time parameter will be set as $\mu_{TD} = 4$, for all tele-diagnosis scenarios.

It is important to note that evaluation conditions of tele-consulting services will be based on what was shown in Chapter 4. However, In order to evaluate the performance of scheduling algorithms and its response to given telemedicine priorities, the tele-consulting utilization rate considered within this simulation will be set to one session/hour. This way, the metrics of blocking and interruption probabilities will show the performance of proposed scheduling algorithm, and its response to the data bandwidth allocation of tele-diagnosis traffic, under a scenario where the access to system resources is highly restricted. Therefore, the utilization and transmission duration times for tele-consulting traffic included are: $1/\lambda_{TC} = 1\ h$ and $1/\mu_{TC} = 0.5\ h$, correspondently.

Regarding scheduling algorithms previously implemented on cognitive radio networks, a comparative with the WRR algorithm will be presented in this Chapter. However, it is important to note that previous implementations of WRR algorithm in cognitive radio networks presented in (Jianfeng Chen et al., 2005; Markarian et al., 2012, 2010), does not include the channel awareness feature. Since this study considers an underlay spectrum access scheme that requires the awareness of the number of primary users present in the operation channel, the direct implementation of the WRR algorithm is considered unsuitable. Therefore, the channel-aware feature has been enabled in the WRR by extending its implementation to cross-layer architecture, in order to perform a comparative evaluation with the proposed TelemedCLSch algorithm. In this context, both algorithms will be ruled by the same architecture, and will schedule the system resources under the same circumstances. The WRR scheduler allocates the system resources in a priority scheme based on a predefined weighted value (per type of user) that represents a percentage of the available bandwidth. This means that the highest weighted value must be assigned to the user with the highest priority. Moreover, the WRR algorithm allocates the system resources in a circular way by following the weighted value priority, which means that the resource blocks will be assigned in the same manner. Therefore, in order to establish a priority scheme under this scheduling algorithm, a weighted relation between tele-diagnosis and tele-consulting services of 2:1 will be considered.

In this context, this performance evaluation follows a Monte Carlo methodology (Jeruchim et al., 2002) to find the statistical properties of the blocking and interruption probabilities resulting from implementation of scheduling algorithm. This way, the cross-layer implementation evaluates the objective function by searching exhaustively a tuple that maximizes the use of system resources. Then, it distributes the resulting alternative admission option to the APP layer based on resource availability. Otherwise, the admission request is rejected by the system. Once the APP layer accepts the alternative option, the cross-layer implementation informs the MAC layer to allocate corresponding resources. Within all simulation, the statistics of admission requests, admission rejections, admission service level, resource allocation ratio and resources availability are collected. Based on this methodology, we can generate sufficient data from statistics to approximate the blocking probability with high precision, in order to perform an evaluation of the proposed TelemedCLSch scheduling (see Fig. 15).

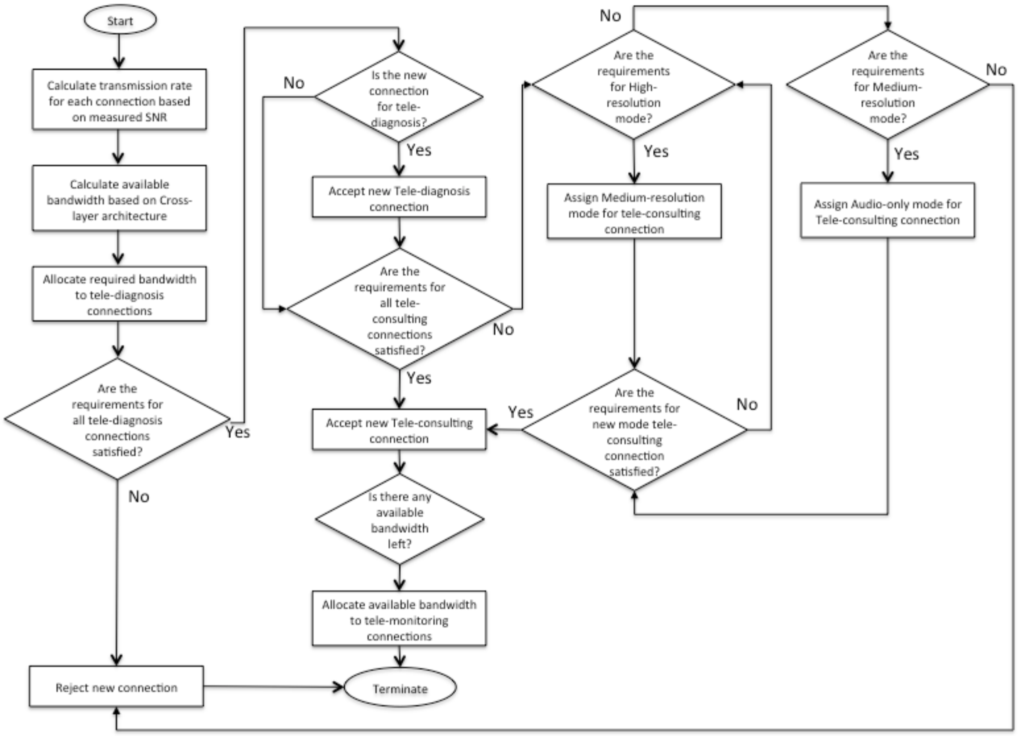
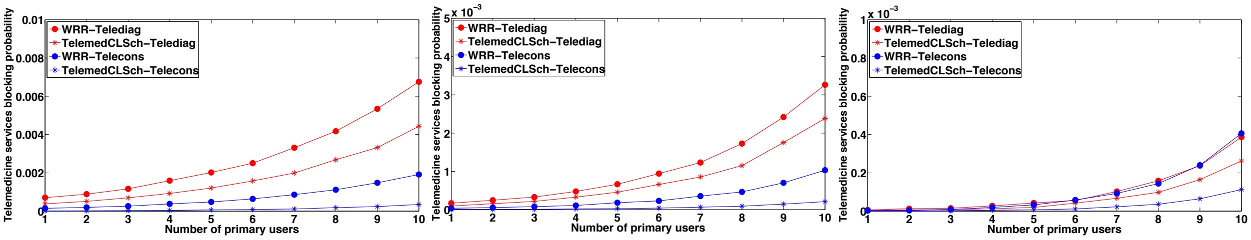


Fig. 15. Block diagram for the operation of proposed TelemedCLSch based on Montecarlo Simulation.

5.4. Numerical Results

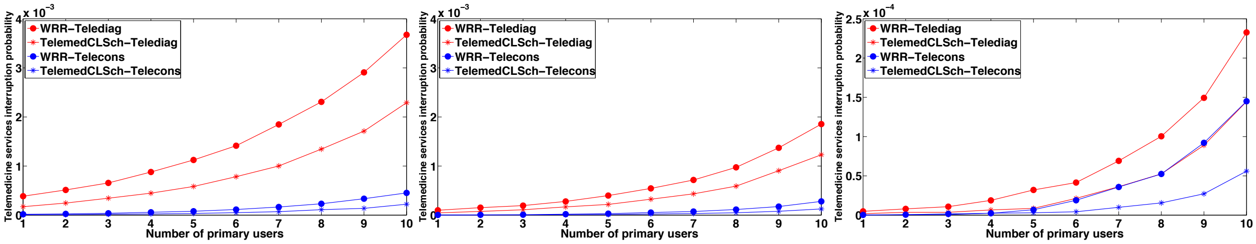
The performance evaluation of the TelemedCLSch algorithm is based on the blocking and interruption probabilities, measured at the MAC layer. Here, each simulation runs 100 batches, where each run contains 100,000 network events. A MATLAB environment is used to write the custom simulation. Here, the simulation is focused on the resource block scheduling for telemedicine services in the presence of PUs. Thus, the numerical research will be limited to observe the impact of varying the number of PUs on both performance metrics. The performance evaluation between the WRR and TelemedCLSch schedulers will include a tele-diagnosis priority admission control. Additionally, the proposed priority admission control scheme based on ABM mechanism (see Chapter 4) will be considered for tele-consulting services. This way, the effects of admission control and scheduler schemes, over blocking and interruption probabilities from telemedicine services can be observed. Furthermore, by considering the HRU, HRR and LRU rural scenarios, a performance evaluation of both schedulers can be measured, from a population density and offered EMS services (based on patient attention levels) perspectives.

Previously mentioned TelemedCLSch scheduling capabilities includes a priority system resource management that is only restricted by the presence of primary users. From a different direction, WRR scheduling capabilities for priority allocation purposes are based on a weighted factor. Since it has been designed to serve all traffic connections in a fair way. Thus, WRR scheduling is not only restricted by the presence of primary users, but is also affected by its fairness scheme. These differences become noticeable in rural scenarios where tele-diagnosis service’s utilization rates are high, in response to a high population density. In this context, the results from blocking and interruption probabilities for telemedicine services over all three rural scenarios are shown in Fig. 16 and Fig. 17, respectively.



(a) (b) (c)

Fig. 16. Telemedicine services blocking probability in rural scenarios: a) HRU, b) HRR and c) LRU



(a) (b) (c)

Fig. 17. Telemedicine services interruption probability in rural scenarios: a) HRU, b) HRR and c) LRU

In Fig. 16, it can be observed that both scheduling algorithms have a blocking probability under 0.01, which is the recommended probability for the evaluation of wireless systems (Schwartz, 2005). The proposed admission control for TelemedCLSch scheduling shows a better performance than WRR, which is up to 54% for tele-diagnosis services within a high population density region scenario (HRU and HRR), by considering emergency medical services for all levels of patient attention. The WRR algorithm shows its best performance within a low population density rural scenario (LRU), due to the utilization rate of tele-diagnosis services is the lowest.

According to, (Anttonen and Mammela, 2014a, 2014b) the recommended interruption probability for wireless video streaming must be under .001, by considering a video length of up to 15 minutes. In this context, the tele-diagnosis service interruption probability from both scheduling algorithms are capable to support the presence of up to 4, 7 and 10 active primary users in HRU, HRR and LRU rural scenarios, respectively. Differently, tele-consulting service interruption probability is under 0.001 for all rural scenarios despite of the presence of a maximum of 10 active primary users (see Fig. 17).

5.4.1. Results Discussion

From the results shown in Fig. 16 and Fig. 17, it is clear that because of the data bandwidth availability reduction resulting from random NPUs appearances, the blocking probability of tele-diagnosis sessions is higher than tele-consulting sessions regardless of the scheduling algorithm used in the IEEE 802.22/WRAN deployment for rural regions. Nevertheless, it is important to note that for all the cases of HRU and HRR, the proposed TelemedCLSch algorithm for IEEE 802.22/WRAN-based rural tele-consulting and tele-diagnosis deployments shows a better blocking and interruption probabilities than WRR scheduling.

As expected, on LRU scenario the blocking probability of tele-diagnosis and tele-consulting sessions are highly similar between them, since it is based on a fair scheduling which is the best observed performance of WRR scheduling (see Fig. 16-C), when there are enough data bandwidth resources for network users as in low traffic congestion scenarios. Differently, the blocking probability of tele-diagnosis service is higher than tele-consulting service on proposed TelemedCLSch algorithm for LRU scenario, which results from its preemptive condition to maintain tele-diagnosis services with highest priority on data bandwidth resource allocation. However, the proposed TelemedCLSch algorithm shows a better performance on blocking probability of telemedicine services than WRR scheduling algorithm over all rural deployment scenarios of HRU, HRR, and LRU.

On the other hand, on LRU scenario the interruption probability of tele-diagnosis service resulting from implementation of WRR scheduling is higher than tele-consulting services since tele-diagnosis service requires more data bandwidth resources than tele-consulting (see Fig. 17-C). Regarding the performance of the proposed TelemedCLSch algorithm, it can be observed that on LRU scenario the interruption probability of tele-diagnosis service is highly similar to the best performance of interruption probability for tele-consulting services based on WRR scheduling. This means that the proposed TelemedCLSch algorithm can achieve similar performance for the highest priority telemedicine service (i.e. tele-diagnosis services) than the best-case scenario of interruption probability for tele-consulting services based on WRR-based scheduling for LRU deployments. Furthermore, the proposed TelemedCLSch algorithm is able to maintain a low interruption probability of tele-consulting services in comparison with tele-diagnosis services. This implies that based on blocking and interruption probabilities of telemedicine services, the proposed TelemedCLSch algorithm outperformed the WRR scheduling algorithm for all rural deployment scenarios.

5.5. Chapter Summary

In this chapter we present a resource allocation scheduler that aims to enable telemedicine applications using the IEEE 802.22/WRAN standard in presence of narrowband primary users. We propose a new cross-layer priority resource block scheduler algorithm for telemedicine traffic profiles, in order to evaluate the effects of data bandwidth availability restrictions given by the presence of primary users.

Since the wireless regional area network environment is oriented to rural regions, a comparative evaluation that considers population density and telemedicine services characteristics has been included. In order to evaluate the effects of data bandwidth availability restrictions given by the presence of primary users, a performance evaluation based on telemedicine services blocking and interruption probabilities between the Telemedicine Cross-Layer Scheduler algorithm, and a Weighted Round Robin algorithm has been performed.

Results have shown that the blocking probability of telemedicine services reaches a recommended target value of 0.01 despite of the presence of up to 10 active primary users. Additionally, the interruption probability of tele-diagnosis services is capable to support the presence of up to 4 active primary users, even in a rural scenario that considers a high population density. Furthermore, the performance of TelemedCLSch scheduling exceeded the results given by the implementation of WRR algorithm.

Chapter 6. Conclusions and Future Work

The research and results presented here primarily focused on the design of a dynamic spectrum allocation mechanism to enable wireless telemedicine service delivery on network deployments based on the IEEE 802.22/WRAN standard. The deployment of wireless regional area network has been identified as a prominent option for rural implementations, since its operation is based on the use of TVWS channels, and its propagation characteristics results in larger coverage ratios than any other BWA technology (e.g. Cellular, WiMAX, WiFi, etc). The IEEE 802.22/WRAN standard comprises cognitive radio capabilities based on an overlay spectrum access scheme. This implies that any IEEE 802.22 associated device can use a TVWS channel as a secondary user while there is not any primary user present (i.e. Analog/Digital TV signal or FCC Part 74 auxiliary device). Hence, this may result in increasing interruptions of transmissions, unexpected throughput drops or an increment on denial of service based on call admission requests. By considering that telemedicine data comprises biomedical signals and information related to the patient's health status on user case scenarios that include emergency medical services, it is highly important to guarantee QoS provisioning during a tele-diagnosis, tele-consulting or tele-monitoring session. In this context, the deployment of telemedicine service delivery based on cognitive radio networks such as the IEEE 802.22/WRAN standard represents a major challenge. Therefore, the present research work considers the effects of enabling telemedicine applications on IEEE 802.22 networks by means of implementing scheduling algorithms, such that data bandwidth resources could be dynamically allocated based on QoS requirements. Additionally, an Adaptive Bandwidth Management mechanism is presented to cover the special case of call admission control for tele-consulting services.

6.1. Conclusions

In summary, this research work presents one of the firsts proposals of a new dynamic scheduling algorithm for network resource allocation purposes based on the IEEE 802.22/WRAN standard for telemedicine applications on rural wireless network deployments. From the cross-layer design of a priority scheduling algorithm to enable telemedicine service delivery, it can be concluded that implementation of the proposed TelemedCLSch algorithm for telemedicine applications represents the best solution to provide a low blocking probability over all rural deployment scenarios in presence of narrowband primary users, in comparison with the WRR scheduling. Thus, the new design proposed in this thesis about a priority scheduling algorithm for telemedicine applications based on the IEEE 802.22/WRAN standard has improve the data bandwdith resource allocation for telemedicine service delivery by leading to a reduction on the cancellation of rural telemedicine sessions, which contribute to avoid subutilization of medical resources from a telemedicine service delivery perspective and to reduce reschedule of telemedicine session appointment from a patient perspective. Regarding interruption probability of telemedicine service delivery over rural scenarios of HRU,HRR and LRU, it can be concluded that the proposed TelemedCLSch algorithm outperformed the WRR scheduling algorithm (see Fig. 17). In this sense, the proposed TelemedCLSch algorithm is able to reduce the number of interruptions of telemedicine sessions that results on presence of narrowband primary users. Therefore, it can be concluded that the impact of always giving the highest priority to tele-diagnosis service in the proposed TelemedCLSch algorithm is better than keeping a fair scheme in the WRR scheduling for rural networks based on the IEEE 802.22/WRAN standard, that include the presence of narrowband primary users on the operating channel.

It is important to note that on matter of blocking probability of tele-consulting session an admission control mechanism based on an adaptive bandwidth management of network resources has been proposed in Chapter 4, to reduce the effects of data bandwidth constraints resulting from the presence of narrowband primary users on rural networks based on the IEEE 802.22/WRAN standard. In order to evaluate the proposed adaptive bandwidth management admission control mechanism, an analytical model based on a multi-dimensional Markov chain has been developed to characterize the blocking probability of tele-consulting services with different service levels of videoconference. In this context, it has been proved that tele-consulting service blocking probability of the proposed adaptive bandwidth management scheme outperformed a typical admission control approach for rural networks based on the IEEE 802.22/WRAN standard that consider the presence of narrowband primary users. Therefore, it can be concluded that the proposed adaptive bandwidth management scheme can reduce the number of cancellations for tele-consulting sessions by means of including alternative admission criteria based on different videoconference service levels (i.e. high video resolution, medium video resolution and audio only), even in the presence of narrowband primary users.

Based on comparative results shown in Chapter 4 and Chapter 5 it has been stated that particular characteristics regarding the deployment scenario of telemedicine networks: telemedicine traffic profiles, medical interaction scheme with telemedicine patients and priorities of telemedicine services, among others; are one of the most important factors that affect the design of admission control and scheduling mechanisms to enable telemedicine service delivery on rural networks based on the IEEE

802.22/WRAN standard. However, before this research work that establishes a rural telemedicine framework in Chapter 3, no rural telemedicine model had been previously reported on literature. Even more, this is the first work reported in literature that from design phase to performance evaluation phase of admission control and scheduling of networks resources consider a realistic rural deployment scenario for telemedicine service delivery based on the IEEE 802.22/WRAN standard.

In this context, this thesis proposes an integral analysis of telemedicine service delivery for rural telemedicine networks based on the IEEE 802.22/WRAN standard. This way, the negative effects on blocking and interruption probabilities of telemedicine services resulting from the data bandwidth constraints given by the presence of narrowband primary users can be reduced on IEEE 802.22 networks that comprise a cognitive radio spectrum access scheme. Furthermore, the novelty of this research work includes a cross-layer architecture that has been implemented to couple the MAC and APP layers for telemedicine service delivery. This way, a channel aware feature has been included in the design of solutions for admission control and scheduling of network resources. Thus, the proposed cross-layer architecture a dynamic resource allocation of data bandwidth can be scheduled according to the presence of narrowband primary users under a coexistence approach with secondary users of the IEEE 802.22 network. The shown results about blocking and interruption probabilities of telemedicine services respond to the design of a scheduling algorithm and an admission control mechanism based on the IEEE 802.22/WRAN standard that require particular information about the telemedicine applications, channel conditions and data bandwidth availability, among others. Therefore, it can be concluded that consideration of the cross-layer architecture is a necessary condition on the design of dynamic spectrum allocation algorithms for telemedicine service delivery in rural networks that include the IEEE 802.22/WRAN standard.

On the interest of offer a detail analysis on the conclusions regarding to proposed solutions developed in this research work, the sections 6.1.1 and 6.1.2 highlight the findings on the adaptive bandwidth management admission control mechanism and the priority scheduling algorithm, respectively.

6.1.1. Conclusion on the design of admission control mechanisms for telemedicine service delivery

Regarding proposed design of the admission control mechanism, we can conclude the following:

- The poor or null connectivity infrastructure on rural regions results on limited telemedicine services provisioning in comparison with the wide range of available medical services offered in urban regions. Therefore, the evaluation of an admission control mechanism for rural telemedicine service delivery should consider the rural framework characteristics.
- The design of an admission control mechanism for telemedicine applications based on videoconference systems (i.e. tele-consulting services) can offer alternative admission options before rejecting an admission request, by means of taking advantage of its capacity to offer different service levels. By considering the comparative results shown in Chapter 4, between a traditional admission control scheme and the proposed ABM mechanism, it can be concluded that the proposed AC mechanism enables the admission of tele-consulting connections that under a typical AC scheme would have been blocked, while achieving a significant improvement on the blocking probability of tele-consulting session requests, even under high-traffic congestion scenarios.
- The implementation of a cross-layer architecture on the design of an AC mechanism results in enabling new admission control criteria for telemedicine applications that can support different levels of QoS. Moreover, with the proposed ABM mechanism more than 92% of available system resources are allocated to high-quality video services, even on scenarios with high traffic congestion. Thus, it can be stated that the main advantages of the proposed ABM mechanism for IEEE 802.22/WRAN-based rural tele-consulting deployments are reducing the blocking probability and maximizing available resource utilization.
- The consideration of primary users (i.e. NPUs) on the design of an admission control mechanism for telemedicine networks based on the IEEE 802.22/WRAN standard must be included on the evaluation of AC mechanisms. In this context, it can be concluded that the blocking probability of tele-consulting sessions will be negatively affected regardless of the AC mechanism. Nevertheless, the proposed ABM mechanism can keep the blocking probability below 0.1 when average arrival rates are under 5 tele-consulting session requests per hour. Considering that, as discussed in Chapter 3, current rural tele-consulting deployments have an average arrival rate of 1 or 2 session requests per hour. Therefore, it has been demonstrated that the deployment of IEEE 802.22/WRAN-based rural tele-consulting services is feasible when using the proposed ABM mechanism.

6.1.2. Conclusion on the design of scheduling algorithms for telemedicine applications.

Regarding the design of the proposed scheduling algorithm, we can conclude the following:

- The design of a scheduling algorithm for telemedicine service delivery on rural wireless networks based on the IEEE 802.22/WRAN should consider the use of case scenario for telemedicine services to establish a priority scheme that can guarantee QoS provisioning whenever is needed.
- The used case scenarios among telemedicine services includes emergency medical services, where an ambulance requires immediate communication with health specialists in order to provide treatment suggestions and pre-hospital arrangements, among other services. Thus, tele-diagnosis services have the highest priority on telemedicine service delivery. Therefore, a preemptive schedule scheme should be considered for this type of telemedicine services.
- The spectrum access scheme on cognitive radio networks establishes the interaction rules between primary and secondary users of spectrum frequency. Since the IEEE 802.22/WRAN standard comprises an overlay access scheme, the unexpected appearance of NPUs has become an important issue. In a telemedicine context, the guarantee of QoS provisioning for telemedicine service delivery is jeopardized under this circumstances. Therefore, from results about the proposed scheduling algorithm presented in Chapter 5, it can be concluded that a guarantee of network resources can be provided for high priority telemedicine services (i.e ele-diagnosis), while keeping certain level of quality of service on tele-consulting and tele-monitoring services by means of including a scheduling algorithm within a priority scheme.
- The design of scheduling algorithms that includes a priority scheme is an important requirement on cognitive radio technologies. Typically, the priority scheme is based on the type of QoS services that the wireless network can offer. In Chapter 5, comparative results between the proposed preemptive-priority scheduling algorithm and the WRR scheduling algorithm have shown that blocking probability and interruption probability of proposed scheduling outperformed the results shown by the implementation of a typical WRR scheduler. Therefore, it can be concluded that the design of scheduling algorithms for telemedicine applications should not be limited to allocate network resources based on the type of QoS, but also has to consider a priority scheme based on a rural telemedicine framework that defines which telemedicine service has the highest priority on resource allocation.

6.2. Contributions

The conducted research has produce several contributions to the state of the art, which were reflected in a publication and in obtaining a set of results with a relevant potential to be published in the short term. The main contributions of this thesis work are mentioned below:

- Based on obtained results it has been proved that the consideration of a rural telemedicine framework on the design of a scheduling algorithm for wireless networks based on the IEEE 802.22/WRAN standard allows defining a priority schedule of network resources, towards enabling telemedicine service delivery on rural regions.
- A new scheduling algorithm for telemedicine networks based on cognitive radio technology that considers a priority scheme based on telemedicine services has been designed and evaluated. This mechanism allowed a significant reduction of blocking and interruption probabilities for high priority telemedicine services in comparison with a typical WRR scheduling algorithm.
- Based on the proposed cross-layer architecture and the rural telemedicine framework, a new admission control mechanism named ABM has been designed. The blocking probability of tele-consulting services has been highly reduced in comparison with a typical AC mechanism. This contributes to reduce cancellation of telemedicine sessions on use case scenarios where scarcity of bandwidth is present.
- An analytical model based on a multi-dimensional Markov chain has been developed to evaluate the proposed ABM mechanism that comprises new alternative admission criteria. This analytical model characterizes the system blocking probability of a typical AC mechanism and the proposed ABM mechanism. This way, by means of using the blocking probability as a performance metric, the design of an ABM mechanism can be evaluated and compared with a non-ABM AC mechanism approach.

6.3. Future Work

The obtained results, altogether with the conclusions presented in this chapter allowed us to identify several research subjects that can be based on this thesis work.

- In this research, the telemedicine sessions of tele-consulting and tele-monitoring are performed between a rural hospital and a local clinic by considering fixed locations. An improvement on the rural telemedicine framework will be on including a semi-fixed approach for telemedicine service delivery. This way, the use case scenario where medical services are provided on a different rural community every day, during a period of time through a scheduled route can be included.

- The proposed scheduling algorithm could be adapted to cover urban or suburban telemedicine use case scenarios. However, an extensive research on traffic profile conditions and density of primary users on this type of regions should be considered.
- The proposed ABM admission control mechanism comprises a dynamic overhead calculation based on data bandwidth requirements of a videoconference system that uses a H.264/AVC video codec to define different levels of service. The adaptation of ABM mechanism to a different video codec will affect its performance due it results on new data bandwidth requirements and, hence, an increment or decrement in the number of users that can be allocated with available network resources. Therefore, more research work aimed to characterize the proposed ABM mechanism over several types of videoconference systems should consider different video codec options.

List of references

802.22-2011. 2011. Retrieved from http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5951707

Ahmad, A., Ahmad, S., Rehmani, M. H., & Hassan, N. U. 2015. A Survey on Radio Resource Allocation in Cognitive Radio Sensor Networks. IEEE Communications Surveys & Tutorials. , 17(2), 888–917. doi:10.1109/COMST.2015.2401597

Ahmed, M. H. 2005. Call admission control in wireless networks: a comprehensive survey. IEEE Communications Surveys & Tutorials. , 7(1), 49–68. doi:10.1109/COMST.2005.1423334

Akyildiz, I. F., Lee, W.-Y., Vuran, M. C., & Mohanty, S. 2006. NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey. Computer Networks. , 50(13), 2127–2159. doi:10.1016/j.comnet.2006.05.001

Al-Howaide, A. Z., Doulat, A. S., & Khamayseh, Y. M. 2011. Performance evaluation of different scheduling algorithms in WiMAX. International Journal of Computer Science, Engineering and Applications. , 1(5), 81–94. doi:10.5121/ijcsea.2011.1508

Ali, A., Faisal, A., & Sorwar, G. 2010. Telemedicine framework for Bangladesh. Presented at the TENCON 2010 - 2010 IEEE Region 10 Conference, IEEE, pp. 335–338. doi:10.1109/TENCON.2010.5686024

Alinejad, A., Istepanian, R. S. H., & Philip, N. 2012. Dynamic subframe allocation for mobile broadband m-health using IEEE 802.16j mobile multihop relay networks. Presented at the Engineering in Medicine and Biology Society (EMBC), 2012 Annual International Conference of the IEEE, IEEE, pp. 284–287. doi:10.1109/EMBC.2012.6345925

Alinejad, A., Philip, N., & Istepanian, R. S. H. 2011. Mapping of multiple parameter m-health scenarios to mobile WiMAX QoS variables. Presented at the Engineering in Medicine and Biology Society,EMBC, 2011 Annual International Conference of the IEEE, IEEE, pp. 1532–1535. doi:10.1109/IEMBS.2011.6090447

AlQahtani, S. A., & Mahmoud, A. S. 2006. Uplink Call Admission Schemes for 3G and Beyond Mobiles Wireless Networks Supporting Heterogeneous Traffic. IEEE, Vol. 2, pp. 2657–2662. doi:10.1109/ICTTA.2006.1684829

AlQahtani, S., & Ashraf, S. M. 2006. A QoS-Aware call admission control algorithm for 3G cellular wireless networks. IEEE, pp. 1–6. doi:10.1109/IEEEGCC.2006.5686183

Anttonen, A., & Mammela, A. 2014a. Interruption Probability of Wireless Video Streaming With Limited Video Lengths. IEEE Transactions on Multimedia. , 16(4), 1176–1180. doi:10.1109/TMM.2014.2306656

Anttonen, A., & Mammela, A. 2014b. Reducing Video Interruption Probability with Cooperative Heterogeneous Networks. IEEE, pp. 1–5. doi:10.1109/VTCSpring.2014.7023071

Ariananda, D. D., Lakshmanan, M. K., & Nikookar, H. 2009. A survey on spectrum sensing techniques for cognitive radio. IEEE, pp. 74–79. doi:10.1109/COGART.2009.5167237

Asadi, A., & Mancuso, V. 2013. A Survey on Opportunistic Scheduling in Wireless Communications. IEEE Communications Surveys & Tutorials. , 15(4), 1671–1688. doi:10.1109/SURV.2013.011413.00082

Atat, R., Yaacoub, E., Alouini, M.-S., Filali, F., & Abu-Dayya, A. 2014. Delay-sensitive content distribution via peer-to-peer collaboration in public safety vehicular ad-hoc networks. Ad Hoc Networks. , 16, 182–196. doi:10.1016/j.adhoc.2013.12.007

Athavale, A., & Zodpey, S. 2010. Public health informatics in India: The potential and the challenges. Indian Journal of Public Health. , 54(3), 131. doi:10.4103/0019-557X.75735

Bae, Y. H., Park, J. S., & Choi, B. D. 2010. Admission Control Scheme for Voice Calls Guaranteeing Both Packet-Level QoS and Call-Level QoS in IEEE 802.16e. IEEE, pp. 1–5. doi:10.1109/VETECF.2010.5594227

Bai, V., & K, S. 2008. Design and Simulation of Portable Telemedicine System for High Risk Cardiac Patients. World Academy of Science, Engineering and Technology. , 2(International Science Index 24), 797–802.

Barjis, J., Kolfschoten, G., & Maritz, J. 2013. A sustainable and affordable support system for rural healthcare delivery. Decision Support Systems. , 56, 223–233. doi:10.1016/j.dss.2013.06.005

Beidokhti, R. K., Yaghmaee Moghaddam, M. H., & Chitizadeh, J. 2011. Adaptive QoS scheduling in wireless cellular networks. Wireless Networks. , 17(3), 701–716. doi:10.1007/s11276-010-0308-5

Belghith, A., & Nuaymi, L. 2008. Comparison of WiMAX scheduling algorithms and proposals for the rtPS QoS class. IEEE, pp. 1–6. doi:10.1109/EW.2008.4623857

Belghith, A., & Nuaymi, L. 2009. Scheduling Techniques for WiMax. In M. Ma (Ed.), Current Technology Developments of WiMax Systems. Dordrecht: Springer Netherlands, pp. 61–84. doi:10.1007/978-1-4020-9300-5_4

Bidgoli, H. (Ed.). 2008. Distributed networks, network planning, control, management, and new trends and applications. Hoboken, NJ: Wiley.

Bravo, S., Valero, M. A., Blandino, J. R., & Ruiz, M. 2013. A telematics solution for the remote follow-up of malnourished children in underserved areas. In Point-of-Care Healthcare Technologies (PHT), 2013 IEEE. IEEE, pp. 65–68. doi:10.1109/PHT.2013.6461285

Chakraborty, M., & Bhattacharyya, D. 2010. Overview of End-to-End WiMAX Network Architecture. In S.-Y. Tang, P. Müller, & H. R. Sharif (Eds.), WiMAX Security and Quality of Service. Chichester, UK: John Wiley & Sons, Ltd, pp. 1–22. Retrieved from http://doi.wiley.com/10.1002/9780470665749.ch1

Chan, F. Y., Whitehall, J., Hayes, L., Taylor, A., Soong, B., Lessing, K., … Whiting, R. 1999. Minimum requirements for remote realtime fetal tele-ultrasound consultation. Journal of Telemedicine and Telecare. , 5(3), 171–176.

Channouf, N., L'Ecuyer, P., Ingolfsson, A., & Avramidis, A. N. 2007. The application of forecasting techniques to modeling emergency medical system calls in Calgary, Alberta. Health Care Management Science. , 10(1), 25–45. doi:10.1007/s10729-006-9006-3

Chau, T.-C., Wong, K. Y. M., & BO Li. 2006. Optimal call admission control with QoS guarantee in a voice/data integrated cellular network. IEEE Transactions on Wireless Communications. , 5(5), 1133–1141. doi:10.1109/TWC.2006.1633366

Chavez-Santiago, R., & Balasingham, I. 2011. Cognitive radio for medical wireless body area networks. IEEE, pp. 148–152. doi:10.1109/CAMAD.2011.5941105

Chen, H.-S., & Gao, W. 2011. Spectrum Sensing for TV White Space in North America. IEEE Journal on Selected Areas in Communications. , 29(2), 316–326. doi:10.1109/JSAC.2011.110205

Chen, Y., Feng, Z., & Chen, X. 2011. Cross-layer Resource Allocation with heterogeneous QoS requirements in cognitive radio networks. IEEE, pp. 96–101. doi:10.1109/WCNC.2011.5779113

Chorbev, I., & Mihajlov, M. 2009. Building a wireless telemedicine network within a WiMax based networking infrastructure. Presented at the Multimedia Signal Processing, 2009. MMSP '09. IEEE International Workshop on, Rio de Janeiro: IEEE, pp. 1–6. doi:10.1109/MMSP.2009.5293305

Chorbev, I., Mihajlov, M., & Jolevski, I. 2008. WiMAX supported telemedicine as part of an integrated system for e-medicine. Presented at the Information Technology Interfaces, 2008. ITI 2008. 30th International Conference on, IEEE, pp. 589–594. doi:10.1109/ITI.2008.4588476

CONEVAL. 2012. Anexo estadistico pobreza 2012. Mexico: Consejo Nacional de Evaluacion de la Politica de Desarrollo.

Danobeitia, B., & Femenias, G. 2011. Cross-layer scheduling and resource allocation in OFDMA wireless networks. IEEE, pp. 1–6. doi:10.1109/WD.2011.6098206

Dapeng Wu, & Negi, R. 2003. Downlink scheduling in a cellular network for quality of service assurance. IEEE, p. 1391–1395 Vol.3. doi:10.1109/VETECF.2003.1285253

De Domenico, A., Calvanese Strinati, E., & Di Benedetto, M.-G. 2012. A Survey on MAC Strategies for Cognitive Radio Networks. IEEE Communications Surveys & Tutorials. , 14(1), 21–44. doi:10.1109/SURV.2011.111510.00108

Deb, S., Srinivasan, V., & Maheshwari, R. 2009. Dynamic spectrum access in DTV whitespaces: design rules, architecture and algorithms. Presented at the Complex Medical Engineering (CME), 2010 IEEE/ICME International Conference on, ACM Press, p. 1. doi:10.1145/1614320.1614322

Debono, C. J., Micallef, B. W., Philip, N. Y., Alinejad, A., Istepanian, R. S. H., & Amso, N. N. 2012. Cross-Layer Design for Optimized Region of Interest of Ultrasound Video Data Over Mobile WiMAX. IEEE Transactions on Information Technology in Biomedicine. , 16(6), 1007–1014. doi:10.1109/TITB.2012.2201164

Dhrona, P., Abu Ali, N., & Hassanein, H. 2008. A performance study of scheduling algorithms in Point-to-Multipoint WiMAX networks. IEEE, pp. 843–850. doi:10.1109/LCN.2008.4664291

DigiTAG. 2008. Analogue switch-off - learning from experience in Europe. Geneva, Switzerland: The Digital Terrestrial Television Action Group.

Doost-Mohammady, R., Naderi, M. Y., & Chowdhury, K. R. 2014. Spectrum Allocation and QoS Provisioning Framework for Cognitive Radio With Heterogeneous Service Classes. IEEE Transactions on Wireless Communications. , 13(7), 3938–3950. doi:10.1109/TWC.2014.2319307

Dussault, G., & Franceschini, M. C. 2006. Not enough there, too many here: understanding geographical imbalances in the distribution of the health workforce. Human Resources for Health. , 4(1). doi:10.1186/1478-4491-4-12

Eggert, L., & Fairhurst, G. 2008. Unicast UDP Usage Guidelines for Application Designers (No. RFC5405). RFC Editor. Retrieved from https://www.rfc-editor.org/info/rfc5405

European Commission, & Directorate-General for the Information Society and Media. 2013. Assessment of socio-economic aspects of spectrum harmonisation regarding wireless microphones and cordless video-cameras (PMSE equipment): final report. Luxembourg: Publications Office. Retrieved from http://dx.publications.europa.eu/10.2759/18518

FCC. 2003. Notice of Proposed Rule Making and Order (ET Docket No. 03–322). Federal Communications Commission.

FCC. 2008a. Evaluation of performance of prototype TV-band white space devices Phase II (OET Docket No. 8-NaN-1005). Federal Communications Commission.

FCC. 2008b. In the matter of unlicensed operation in the TV Broadcast Bands: second report and memorandum opinion and order. (Technical Report No. 08–260). Federal Communications Commission.

FCC. 2011. In the matter of unlicensed operation in the TV Broadcast Bands. Discontinuance Activities 11–131. (ET Docked No. 04–186). Federal Communications Commission.

Feng, S., Liang, Z., & Zhao, D. 2010a. Providing telemedicine services in an infrastructure-based cognitive radio network. IEEE Wireless Communications. , 17(1), 96–103. doi:10.1109/MWC.2010.5416356

Feng, S., Liang, Z., & Zhao, D. 2010b. Providing telemedicine services in an infrastructure-based cognitive radio network. IEEE Wireless Communications. , 17(1), 96–103. doi:10.1109/MWC.2010.5416356

Fitch, M., Nekovee, M., Kawade, S., Briggs, K., & MacKenzie, R. 2011. Wireless service provision in TV white space with cognitive radio technology: A telecom operator's perspective and experience. IEEE Communications Magazine. , 49(3), 64–73. doi:10.1109/MCOM.2011.5723802

Fong, B., & Pecht, M. G. 2010. Prognostics in wireless telecare networks: A perspective on serving the rural Chinese population. Presented at the Prognostics and Health Management Conference, 2010. PHM '10, IEEE, pp. 1–6. doi:10.1109/PHM.2010.5413506

Foster, K. 2010. Telehealth in Sub-Saharan Africa: Lessons for Humanitarian Engineering. IEEE Technology and Society Magazine. , 29(1), 42–49. doi:10.1109/MTS.2010.935977

Foukalas, F., Gazis, V., & Alonistioti, N. 2008. Cross-layer design proposals for wireless mobile networks: A survey and taxonomy. IEEE Communications Surveys & Tutorials. , 10(1), 70–85. doi:10.1109/COMST.2008.4483671

Fu, B., Xiao, Y., Deng, H. J., & Zeng, H. 2014. A Survey of Cross-Layer Designs in Wireless Networks. IEEE Communications Surveys & Tutorials. , 16(1), 110–126. doi:10.1109/SURV.2013.081313.00231

Gallego, J. R., Hernandez-Solana, A., Canales, M., Lafuente, J., Valdovinos, A., & Fernandez-Navajas, J. 2005. Performance Analysis of Multiplexed Medical Data Transmission for Mobile Emergency

Care Over the UMTS Channel. IEEE Transactions on Information Technology in Biomedicine. , 9(1), 13–22. doi:10.1109/TITB.2004.838362

Gao, B., Park, J.-M., Yang, Y., & Roy, S. 2012. A taxonomy of coexistence mechanisms for heterogeneous cognitive radio networks operating in TV white spaces. IEEE Wireless Communications. , 19(4), 41–48. doi:10.1109/MWC.2012.6272422

Grigsby, J., Barton, P.L., & Kaehny, M.M. 1994. Analysis of Expansion of Access to Care Through Telemedicine, Report 4, Study Summary and Recommendations for Further Research. Denver, CO: Center for Health Policy Research, p. 43.

Gronsund, P., Pawelczak, P., Park, J., & Cabric, D. 2014. System level performance of IEEE 802.22-2011 with sensing-based detection of wireless microphones. IEEE Communications Magazine. , 52(1), 200–209. doi:10.1109/MCOM.2014.6710084

Guesmi, H., & Maaloul, S. 2013. A Cross-Layer Qos Based Scheduling Algorithm WRR Design in Wimax Base Stations. American Journal of Electrical and Electronic Engineering. , 1(1), 1–9. doi:10.12691/ajeee-1-1-1

Guha Roy, A., Mandal, R., Misra, I. S., & Saha, K. 2008. Pre-emption based call admission control with QoS and dynamic bandwidth reservation for cellular networks. IEEE, pp. 745–752. doi:10.1109/COMSWA.2008.4554510

Guy Pujolle, S. K., & Nadjib Achir, K. B. 2012. A Cross-Layer Radio Resource Management in WiMAX Systems. In R. Hincapie (Ed.), Quality of Service and Resource Allocation in WiMAX. InTech. doi:10.5772/28946

Hadjidj, A., Souil, M., Bouabdallah, A., Challal, Y., & Owen, H. 2013. Wireless sensor networks for rehabilitation applications: Challenges and opportunities. Journal of Network and Computer Applications. , 36(1), 1–15. doi:10.1016/j.jnca.2012.10.002

Hamdi, O., Chalouf, M. A., Ouattara, D., & Krief, F. 2014. eHealth: Survey on research projects, comparative study of telemonitoring architectures and main issues. Journal of Network and Computer Applications. , 46, 100–112. doi:10.1016/j.jnca.2014.07.026

Han, F., Liu, Y., & Zhu, G. 2006. A Cross-layer Resource Allocation Scheme with Guaranteed QoS in Multiuser OFDM Systems. IEEE, pp. 1–4. doi:10.1109/ICCT.2006.341863

Hind, A. M. S., Ghada, A. M. A., Mohammed, A. A., & Hamid, A. 2016. MAC Layer strategies in Cognitive Radio Networks DSA protocols for cognitive networks. IOSR Journal of Electrical and Electronics. , 11(6), 1–12.

Husni, E., & Waworundeng, J. 2011. Telemedicine system based on Delay Tolerant Network. Presented at the Electrical Engineering and Informatics (ICEEI), 2011 International Conference on, IEEE, pp. 1–5. doi:10.1109/ICEEI.2011.6021824

Hyang-Won Lee, & Song Chong. 2006. Combined QoS Scheduling and Call Admission Control Algorithm in Cellular Networks. IEEE, pp. 1–10. doi:10.1109/WIOPT.2006.1666524

Ibikunle, F. A. 2009. Comparative Analysis of Alternative Last Mile Broadband Access Technologies (Wi-Fi and WiMAX). The Pacific Journal of Science and Technology. , 10(1), 280–285.

IEEE Computer Society, LAN/MAN Standards Committee, IEEE Microwave Theory and Techniques Society, Institute of Electrical and Electronics Engineers, & IEEE-SA Standards Board. 2009. IEEE standard for local and metropolitan area networks. Part 16, Part 16,. New York: Institute of Electrical and Electronics Engineers. Retrieved from http://ieeexplore.ieee.org/servlet/opac?punumber=5062428

IEEE-SA Standards Board. 2011. IEEE standard for information technology--telecommunications and information exchange between systems-wireless regional area networks (WRAN)-specific requirements. Part 22. New York: Institute of Electrical and Electronics Engineers. Retrieved from http://ieeexplore.ieee.org/servlet/opac?punumber=5951705

INEGI. 2011. Anuario estadistico de los Estados Unidos Mexicanos. Mexico: Instituto Nacional de Estadistica y Geografia.

Institute of Medicine (U.S.). 2012. The role of telehealth in an evolving health care environment: workshop summary. Washington, D.C: National Academies Press.

Ito, K., Tsuruta, K., Sugano, S., & Iwata, H. 2011. Evaluation of a wearable tele-echography robot system: FASTele in a vehicle using a mobile network. Presented at the Engineering in Medicine and Biology Society,EMBC, 2011 Annual International Conference of the IEEE, IEEE, pp. 2093–2096. doi:10.1109/IEMBS.2011.6090389

Jeruchim, M. C., Balaban, P., & Shanmugan, K. S. 2002. Simulation of communication systems modeling, methodology, and techniques. New York: Kluwer Academic. Retrieved from http://site.ebrary.com/id/10053278

Jia Tang, & Xi Zhang. 2007. Cross-layer resource allocation over wireless relay networks for quality of service provisioning. IEEE Journal on Selected Areas in Communications. , 25(4), 645–656. doi:10.1109/JSAC.2007.070502

Jianfeng Chen, Wenhua Jiao, & Hongxi Wang. 2005. A service flow management strategy for IEEE 802.16 broadband wireless access systems in TDD mode. IEEE, Vol. 5, pp. 3422–3426. doi:10.1109/ICC.2005.1495056

Jirgens, L., Dekorsy, A., & Fliege, J. 2005. A Homotopy Method for Call Admission Control Employing Different User and Service Classes. IEEE, Vol. 3, pp. 1880–1884. doi:10.1109/PIMRC.2005.1651767

Jun Zhao, Haitao Zheng, & Guang-Hua Yang. 2005. Distributed coordination in dynamic spectrum allocation networks. IEEE, pp. 259–268. doi:10.1109/DYSPAN.2005.1542642

Kachieng'a, M. O. 2011. Challenges in managing diffusion of telemedicine technology in South Africa. Presented at the Technology Management Conference (ITMC), 2011 IEEE International, IEEE, pp. 121–125. doi:10.1109/ITMC.2011.5995936

Kae Won Choi, Wha Sook Jeon, & Dong Geun Jeong. 2009. Resource Allocation in OFDMA Wireless Communications Systems Supporting Multimedia Services. IEEE/ACM Transactions on Networking. , 17(3), 926–935. doi:10.1109/TNET.2008.2001470

Kailas, A., & Ingram, M. A. 2009. Wireless Aspects of Telehealth. Wireless Personal Communications. , 51(4), 673–686. doi:10.1007/s11277-009-9763-7

Kalikivayi, S., Misra, I. S., & Saha, K. 2008. Bandwidth and Delay Guaranteed Call Admission Control Scheme for QOS Provisioning in IEEE 802.16e Mobile WiMAX. IEEE, pp. 1–6. doi:10.1109/GLOCOM.2008.ECP.246

Kapoor L, Mishra SK, & Singh K. 2005. Telemedicine: experience at SGPGIMS, Lucknow. J Postgrad Med. , 51(4).

Kas, M., Yargicoglu, B., Korpeoglu, I., & Karasan, E. 2010. A Survey on Scheduling in IEEE 802.16 Mesh Mode. IEEE Communications Surveys & Tutorials. , 12(2), 205–221. doi:10.1109/SURV.2010.021110.00053

Khalil, K., Karaca, M., Ercetin, O., & Ekici, E. 2011. Optimal scheduling in cooperate-to-join Cognitive Radio Networks. IEEE, pp. 3002–3010. doi:10.1109/INFCOM.2011.5935142

Khan, S., Peng, Y., Steinbach, E., Sgroi, M., & Kellerer, W. 2006. Application-driven cross-layer optimization for video streaming over wireless networks. IEEE Communications Magazine. , 44(1), 122–130. doi:10.1109/MCOM.2006.1580942

Kim, D.-K., Yoo, S. K., Park, I.-C., Choa, M., Bae, K. Y., Kim, Y.-D., & Heo, J.-H. 2009. A mobile telemedicine system for remote consultation in cases of acute stroke. Journal of Telemedicine and Telecare. , 15(2), 102–107. doi:10.1258/jtt.2008.080713

Kim, H., & de Veciana, G. 2007. Losing Opportunism: Evaluating Service Integration in an Opportunistic Wireless System. IEEE, pp. 982–990. doi:10.1109/INFCOM.2007.119

Knopp, R., & Humblet, P. A. 1995. Information capacity and power control in single-cell multiuser communications. IEEE, Vol. 1, pp. 331–335. doi:10.1109/ICC.1995.525188

Komnakos, D., Vouyioukas, D., Maglogiannis, I., & Constantinou, P. 2008. Performance Evaluation of an Enhanced Uplink 3.5G System for Mobile Healthcare Applications. International Journal of Telemedicine and Applications. , 2008, 1–11. doi:10.1155/2008/417870

Kulkarni, P., & Ozturk, Y. 2011. mPHASiS: Mobile patient healthcare and sensor information system. Journal of Network and Computer Applications. , 34(1), 402–417. doi:10.1016/j.jnca.2010.03.030

Kumar, R., Adhikary, K., & Vaid, R. 2011. WiMAX Propagations. International Journal of Computer Science Engineering and Technology. , 1(8), 480–483.

Kuran, M. S., & Tugcu, T. 2007. A survey on emerging broadband wireless access technologies. Computer Networks. , 51(11), 3013–3046. doi:10.1016/j.comnet.2006.12.009

Lakkakorpi, J., Sayenko, A., & Moilanen, J. 2008. Comparison of Different Scheduling Algorithms for WiMAX Base Station: Deficit Round-Robin vs. Proportional Fair vs. Weighted Deficit Round-Robin. IEEE, pp. 1991–1996. doi:10.1109/WCNC.2008.354

Lam, K. L., Tung, H. Y., Tsang, K. F., & Ko, K. T. 2009. WiMAX telemedicine system for emergence medical service. Presented at the Information, Communications and Signal Processing, 2009. ICICS 2009. 7th International Conference on, IEEE, pp. 1–5. doi:10.1109/ICICS.2009.5397729

Lee, L.-T., Wu, C.-F., Tseng, C.-Y., & Liu, K.-Y. 2006. A Dynamic Reservation and Call Admission Control Policy with HMM for Multimedia Cellular Networks. IEEE, pp. 82–87. doi:10.1109/ISCIT.2006.339892

Leem, C., Lee, J., Kim, S., Kim, C., & Kang, S. 2008. The Spectral Efficiency analysis of the Spectrum Overlay technology of the TV band. IEEE, pp. 1–5. doi:10.1109/CROWNCOM.2008.4562522

Li, B., Qin, Y., Low, C., & Gwee, C. 2007. A Survey on Mobile WiMAX [Wireless Broadband Access]. IEEE Communications Magazine. , 45(12), 70–75. doi:10.1109/MCOM.2007.4395368

Li, M., Doong, J., Chang, K., Lu, T., & Jeng, M. 2008. Differences in urban and rural accident characteristics and medical service utilization for traffic fatalities in less-motorized societies. Journal of Safety Research. , 39(6), 623–630. doi:10.1016/j.jsr.2008.10.008

Li, W., & Pan, Y. (Eds.). 2006. Resource allocation in next generation wireless networks. New York, NY: Nova Science Publ.

Lievens, F., & Jordanova, M. 2007. Telemedicine and Medical Informatics: The Global Approach. In Proceedings of World Academy of Science, Engineering and Technology. World Academy of Science, Engineering and Technology, Vol. 25, pp. 258–262.

Lu, W.-P., Leung, H., & Estrada, E. 2010. Transforming telemedicine for rural and urban communities Telemedicine 2.0 - any doctor, any place, any time. Presented at the e-Health Networking Applications and Services (Healthcom), 2010 12th IEEE International Conference on, IEEE, pp. 379–385. doi:10.1109/HEALTH.2010.5556538

Luo, C., Yu, F. R., Ji, H., & Leung, V. C. M. 2011. Optimal channel access for TCP performance improvement in cognitive radio networks. Wireless Networks. , 17(2), 479–492. doi:10.1007/s11276-010-0292-9

Luo Kun, & Wen Hao. 2010. Remote medicine in Xinjiang province of China. Presented at the Computer Application and System Modeling (ICCASM), 2010 International Conference on, IEEE, pp. V15-623-V15-626. doi:10.1109/ICCASM.2010.5622470

Luo, S., Li, Z., Hu, J., Liu, T., & Cai, B. 2009. A Policy-Based CAC Scheme for Fixed WiMAX System. IEEE, pp. 376–379. doi:10.1109/ICCSN.2009.72

Magana-Rodriguez, R., Villarreal-Reyes, S., Galaviz-Mosqueda, A., Rivera-Rodriguez, R., & Conte-Galvan, R. 2015. Telemedicine Services over Rural Broadband Wireless Access Technologies: IEEE 802.22/WRAN and IEEE 802.16 WiMAX. In S. Adibi (Ed.), Mobile Health. Cham: Springer International Publishing, Vol. 5, pp. 743–769. Retrieved from http://link.springer.com/10.1007/978-3-319-12817-7_32

Malindi, P. 2011. QoS in Telemedicine. In G. Graschew & Rakowsky (Eds.), Telemedicine techniques and applications. Rijeka: InTech, pp. 119–120.

Mamoon, I. A., Muzahidul-Islam, A. K. M., Baharun, S., Komaki, S., & Ahmed, A. 2015. Architecture and communication protocols for cognitive radio network enabled hospital. IEEE, pp. 170–174. doi:10.1109/ISMICT.2015.7107522

Mandioma, M. T., Rao, G. S. ., Terzoli, A., & Muyingi, H. 2007. Deployment of WiMAX for Telecommunication and Internet Access in Dwesa-Cwebe Rural Areas. IEEE, pp. 2141–2143. doi:10.1109/ICACT.2007.358796

Mariscal-Aviles, J., Wohlers de Almeida, M., & Barrantes, R. 2014. Aplicaciones TIC America Latina. Mejores Practicas de liderazgo, innovacion en y gestion publica: los casos de Brasil, Mexico y Peru. International Telecommunication Union (ITU).

Markarian, G., Dmitry, T., & Anna, Z. 2010. Novel technique for efficient video distribution over WiMAX networks. IEEE, pp. 399–404. doi:10.1109/PIMRCW.2010.5670403

Markarian, G., Mihaylova, L., Tsitserov, D. V., & Zvikhachevskaya, A. 2012. Video Distribution Techniques Over WiMAX Networks for m-Health Applications. IEEE Transactions on Information Technology in Biomedicine. , 16(1), 24–30. doi:10.1109/TITB.2011.2174157

Martinez, A., Villarroel, V., Seoane, J., & Del Pozo, F. 2004a. Rural telemedicine for primary healthcare in developing countries. IEEE Technology and Society Magazine. , 23(2), 13–22. doi:10.1109/MTAS.2004.1304394

Martinez, A., Villarroel, V., Seoane, J., & Del Pozo, F. 2004b. Rural telemedicine for primary healthcare in developing countries. IEEE Technology and Society Magazine. , 23(2), 13–22. doi:10.1109/MTAS.2004.1304394

Matalgah, M. M., Paudel, B., & Hammouri, O. M. 2013. Cross-layer resource allocation approach in OFDMA systems with multi-class QoS services and users queue status. IEEE, pp. 1385–1390. doi:10.1109/GLOCOM.2013.6831267

Matteson, D. S., McLean, M. W., Woodard, D. B., & Henderson, S. G. 2011. Forecasting emergency medical service call arrival rates. The Annals of Applied Statistics. , 5(2B), 1379–1406. doi:10.1214/10-AOAS442

Mattson, J. 2011. Transportation, Distance, and Health Care Utilization for Older Adults in Rural and Small Urban Areas. Transportation Research Record: Journal of the Transportation Research Board. , 2265, 192–199. doi:10.3141/2265-22

McGregor, C., Kneale, B., & Tracy, M. 2007. On-demand Virtual Neonatal Intensive Care units supporting rural, remote and urban healthcare with Bush Babies Broadband. Journal of Network and Computer Applications. , 30(4), 1309–1323. doi:10.1016/j.jnca.2006.09.008

Meethal, S. P., & J., J. 2011. A Low Cost Connectivity Solution for Rural Mobile Telemedicine. Presented at the Global Humanitarian Technology Conference (GHTC), 2011 IEEE, IEEE, pp. 506–511. doi:10.1109/GHTC.2011.55

Mendez-Rangel, J., & Lozano-Garzon, A. S. I. G. on A. 2012. A network design methodology proposal for E-health in rural areas of developing countries. In Proceedings of the 6th Euro American Conference on Telematics and Information Systems. [S.l.]: ACM, pp. 1–7. Retrieved from http://encompass.library.cornell.edu/cgi-bin/checkIP.cgi?access=gateway_standard%26url=http://dl.acm.org/citation.cfm?id=2261605

Menon, R., Buehrer, R. M., & Reed, J. H. 2005. Outage probability based comparison of underlay and overlay spectrum sharing techniques. IEEE, pp. 101–109. doi:10.1109/DYSPAN.2005.1542623

Microsoft Corporation. 2013. Comments of Microsoft Corporation. Washington, D.C: Federal Communications Commission.

Mignanti, S., Castellano, M., Augusti, V., Martufi, G., Neves, P. M., Mambretti, C., & Andreotti, F. 2008. WEIRD - Real Use Cases and Applications for the WiMAX Technology. Presented at the Consumer Communications and Networking Conference, 2008. CCNC 2008. 5th IEEE, IEEE, pp. 948–952. doi:10.1109/ccnc08.2007.219

Moffatt, J. J., & Eley, D. S. 2011. Barriers to the up-take of telemedicine in Australia--a view from providers. Rural and Remote Health. , 11(2), 1581.

Molisch, A. F., Greenstein, L. J., & Shafi, M. 2009. Propagation Issues for Cognitive Radio. Proceedings of the IEEE. , 97(5), 787–804. doi:10.1109/JPROC.2009.2015704

Mulvaney, D., Woodward, B., Datta, S., Harvey, P., Vyas, A., Thakker, B., & Farooq, O. 2010. Mobile communications for monitoring heart disease and diabetes. Presented at the Engineering in Medicine and Biology Society (EMBC), 2010 Annual International Conference of the IEEE, IEEE, pp. 2208–2210. doi:10.1109/IEMBS.2010.5627117

Naeem, M., Pareek, U., Lee, D. C., Khwaja, A. S., & Anpalagan, A. 2015. Wireless Resource Allocation in Next Generation Healthcare Facilities. IEEE Sensors Journal. , 15(3), 1463–1474. doi:10.1109/JSEN.2014.2363571

Neves, P., Simoes, P., Gomes, A., Mario, L., Sargento, S., Fontes, F., … Bohnert, T. 2007. WiMAX for Emergency Services: An Empirical Evaluation. Presented at the Next Generation Mobile Applications, Services and Technologies, 2007. NGMAST ’07. The 2007 International Conference on, IEEE, pp. 340–345. doi:10.1109/NGMAST.2007.4343443

Newgard, C. D., Schmicker, R. H., Hedges, J. R., Trickett, J. P., Davis, D. P., Bulger, E. M., … Nichol, G. 2010. Emergency Medical Services Intervals and Survival in Trauma: Assessment of the “Golden Hour” in a North American Prospective Cohort. Annals of Emergency Medicine. , 55(3), 235–246.e4. doi:10.1016/j.annemergmed.2009.07.024

Niyato, D., Hossain, E., & Diamond, J. 2007a. IEEE 802.16/WiMAX-based broadband wireless access and its application for telemedicine/e-health services. IEEE Wireless Communications. , 14(1), 72–83. doi:10.1109/MWC.2007.314553

Niyato, D., Hossain, E., & Diamond, J. 2007b. IEEE 802.16/WiMAX-based broadband wireless access and its application for telemedicine/e-health services. IEEE Wireless Communications. , 14(1), 72–83. doi:10.1109/MWC.2007.314553

Pacheco-López, A., Silva-Flores, M., Aparicio-Gómez, G., López-Uroza, P., López-Arreola, C., Ramírez-Espinoza, J. E., & López-Basilio, M. A. 2011. 4 Telemedicine Experiences in Mexico. México: National Center for Health Technology Excellence (CENETEC-Salud), Colección Telesalud.

Panayides, A., Antoniou, Z. C., Mylonas, Y., Pattichis, M. S., Pitsillides, A., & Pattichis, C. S. 2013. High-Resolution, Low-Delay, and Error-Resilient Medical Ultrasound Video Communication Using H.264/AVC Over Mobile WiMAX Networks. IEEE Journal of Biomedical and Health Informatics. , 17(3), 619–628. doi:10.1109/TITB.2012.2232675

Panayides, A., Antoniou, Z., Pattichis, M. S., & Pattichis, C. S. 2012. The use of H.264/AVC and the emerging high efficiency video coding (HEVC) standard for developing wireless ultrasound video telemedicine systems. Presented at the Signals, Systems and Computers (ASILOMAR), 2012 Conference Record of the Forty Sixth Asilomar Conference on, IEEE, pp. 337–341. doi:10.1109/ACSSC.2012.6489019

Park, J., Pawelczak, P., Gronsund, P., & Cabric, D. 2012. Analysis Framework for Opportunistic Spectrum OFDMA and Its Application to the IEEE 802.22 Standard. IEEE Transactions on Vehicular Technology. , 61(5), 2271–2293. doi:10.1109/TVT.2012.2188550

Pawar, P., Jones, V., van Beijnum, B.-J. F., & Hermens, H. 2012. A framework for the comparison of mobile patient monitoring systems. Journal of Biomedical Informatics. , 45(3), 544–556. doi:10.1016/j.jbi.2012.02.007

Phunchongharn, P., Hossain, E., Niyato, D., & Camorlinga, S. 2010. A cognitive radio system for e-health applications in a hospital environment. IEEE Wireless Communications. , 17(1), 20–28. doi:10.1109/MWC.2010.5416346

Polze, A., Tröger, P., Hentschel, U., & Heinze, T. 2010. A Scalable, Self-Adaptive Architecture for Remote Patient Monitoring. Presented at the Object/Component/Service-Oriented Real-Time Distributed Computing Workshops (ISORCW), 2010 13th IEEE International Symposium on, IEEE, pp. 204–210. doi:10.1109/ISORCW.2010.31

Prasad, R. 2010. OFDMA WiMAX Physical Layer. In WiMAX networks: techno-economic vision and challenges. Dordrecht ; London: Springer, pp. 63–135.

Qing Zhao, & Sadler, B. M. 2007. A Survey of Dynamic Spectrum Access. IEEE Signal Processing Magazine. , 24(3), 79–89. doi:10.1109/MSP.2007.361604

Ramos-Contreras, P. 2016, February. Estado Actual de la Telemedicina en America Latina. http://www.amdtelemedicine.com/telemedicine-resources/documents/WebinarSlidesALL_FINAL022216.pdf, accessed,. Retrieved from http://www.amdtelemedicine.com/telemedicine-resources/EstadoTelemedicinaAmericaLatina.htm

Rao, S. P., Jayant, N. S., Stachura, M. E., Astapova, E., & Pearson-Shaver, A. 2009. Delivering Diagnostic Quality Video over Mobile Wireless Networks for Telemedicine. International Journal of Telemedicine and Applications. , 2009, 1–9. doi:10.1155/2009/406753

Recommendation ITU-R P.1546-4. 2009. Method for Point-to-Area Predictions for Terrestrial Services in the Frequency Range 30 MHz to 300 MHz. Geneva, Switzerland: International Telecommunication Union, 2012th ed.

Sachpazidis, I., Ohl, R., Polanczyk, C., Torres, M., Messina, L., Sales, A., & Sakas, G. 2005. Applying Telemedicine to Remote and Rural Underserved Regions in Brazil using eMedical Consulting Tool. In Conference proceedings: ... Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Annual Conference. Vol. 2, pp. 2191–2195. doi:10.1109/IEMBS.2005.1616897

Sansoy, M., & Buttar, A. S. 2015. Spectrum sensing algorithms in Cognitive Radio: A survey. IEEE, pp. 1–5. doi:10.1109/ICECCT.2015.7226181

Saponara, S., Donati, M., Bacchillone, T., Sanchez-Tato, I., Carmona, C., Fanucci, L., & Barba, P. 2012. Remote monitoring of vital signs in patients with Chronic Heart Failure: Sensor devices and data analysis perspective. Presented at the Sensors Applications Symposium (SAS), 2012 IEEE, IEEE, pp. 1–6. doi:10.1109/SAS.2012.6166310

Scheulen, J. J., Li, G., & Kelen, G. D. 2001. Impact of ambulance diversion policies in urban, suburban, and rural areas of Central Maryland. Academic Emergency Medicine: Official Journal of the Society for Academic Emergency Medicine. , 8(1), 36–40.

Schwartz, M. 2005. Mobile wireless communications. Cambridge ; New York: Cambridge University Press.

Shakeel, H., Best, M., Miller, B., & Weber, S. 2001. Comparing Urban and Rural Telecenters Costs. The Electronic Journal of Information Systems in Developing Countries. , 4, 1–13.

Shariat, M., Quddus, A., Ghorashi, S., & Tafazolli, R. 2009. Scheduling as an important cross-layer operation for emerging broadband wireless systems. IEEE Communications Surveys & Tutorials. , 11(2), 74–86. doi:10.1109/SURV.2009.090206

Sharma, M. K., & Kunwar Singh Vaisla. 2012. E-health for rural areas of Uttarakhand under e-Governance service delivery model. Presented at the Recent Advances in Information Technology (RAIT), 2012 1st International Conference on, IEEE, pp. 622–625. doi:10.1109/RAIT.2012.6194601

Shellhammer, S. J., Sadek, A. K., & Wenyi Zhang. 2009. Technical challenges for cognitive radio in the TV white space spectrum. IEEE, pp. 323–333. doi:10.1109/ITA.2009.5044964

Siddiqua, P., & Awal, M. A. 2012. A portable Telemedicine system in the context of rural Bangladesh. Presented at the Informatics, Electronics & Vision (ICIEV), 2012 International Conference on, IEEE, pp. 608–611. doi:10.1109/ICIEV.2012.6317463

Singh, R., Mathiassen, L., Stachura, M. E., & Astapova, E. V. 2010. Sustainable Rural Telehealth Innovation: A Public Health Case Study: Sustainable Rural Telehealth Innovation. Health Services Research. , 45(4), 985–1004. doi:10.1111/j.1475-6773.2010.01116.x

Skorin-Kapov, L., & Matijasevic, M. 2010. Analysis of QoS Requirements for e-Health Services and Mapping to Evolved Packet System QoS Classes. International Journal of Telemedicine and Applications. , 2010, 1–18. doi:10.1155/2010/628086

Smith, A. C., Bensink, M., Armfield, N., Stillman, J., & Caffery, L. 2005. Telemedicine and rural health care applications. Journal of Postgraduate Medicine. , 51(4), 286–293.

So-In, C., Jain, R., & Tamimi, A.-K. 2009a. Scheduling in IEEE 802.16e mobile WiMAX networks: key issues and a survey. IEEE Journal on Selected Areas in Communications. , 27(2), 156–171. doi:10.1109/JSAC.2009.090207

So-In, C., Jain, R., & Tamimi, A.-K. 2009b. Scheduling in IEEE 802.16e mobile WiMAX networks: key issues and a survey. IEEE Journal on Selected Areas in Communications. , 27(2), 156–171. doi:10.1109/JSAC.2009.090207

So-In, C., Jain, R., & Tamimi, A.-K. 2010. Capacity Evaluation for IEEE 802.16e Mobile WiMAX. Journal of Computer Systems, Networks, and Communications. , 2010, 1–12. doi:10.1155/2010/279807

Sorwar, G., & Ali, A. 2010. Advanced Telemedicine System Using 3G Cellular Networks and Agent Technology. In H. Takeda (Ed.), E-Health. Berlin, Heidelberg: Springer Berlin Heidelberg, Vol. 335, pp. 187–197. Retrieved from http://www.springerlink.com/index/10.1007/978-3-642-15515-4_20

Stockhammer, T., Hannuksela, M. M., & Wiegand, T. 2003. H.264/AVC in wireless environments. IEEE Transactions on Circuits and Systems for Video Technology. , 13(7), 657–673. doi:10.1109/TCSVT.2003.815167

Stripe, S. C., & Susman, J. 1991. A rural-urban comparison of prehospital emergency medical services in Nebraska. The Journal of the American Board of Family Practice / American Board of Family Practice. , 4(5), 313–318.

Su, H., & Zhang, X. 2008. Cross-Layer Based Opportunistic MAC Protocols for QoS Provisionings Over Cognitive Radio Wireless Networks. IEEE Journal on Selected Areas in Communications. , 26(1), 118–129. doi:10.1109/JSAC.2008.080111

Su, Y., & Soar, J. 2010. Integration of VSAT with WiMAX technology for E-health in Chinese rural areas. Presented at the Computer Communication Control and Automation (3CA), 2010 International Symposium on, IEEE, pp. 454–457. doi:10.1109/3CA.2010.5533764

Sudhahar, S., Vatsalan, D., Wijethilake, D., Wickramasinghe, Y., Arunathilake, S., Chapman, K., & Seneviratna, G. 2010. Enhancing Rural Healthcare in Emerging Countries through an eHealth Solution. Presented at the eHealth, Telemedicine, and Social Medicine, 2010. ETELEMED '10. Second International Conference on, IEEE, pp. 23–28. doi:10.1109/eTELEMED.2010.11

Sunho Lim, Guohong Cao, & Das, C. R. 2002. An admission control scheme for QoS-sensitive cellular networks. IEEE, Vol. 1, pp. 296–300. doi:10.1109/WCNC.2002.993511

Suseela, B., & Sivakumar, D. 2015. Non-cooperative spectrum sensing techniques in cognitive radio-a survey. IEEE, pp. 127–133. doi:10.1109/TIAR.2015.7358544

Syed, A. R., & Yau, K.-L. A. 2013. On Cognitive Radio-based Wireless Body Area Networks for medical applications. IEEE, pp. 51–57. doi:10.1109/CICARE.2013.6583068

Takagi, H., & Walke, B. H. (Eds.). 2008. Spectrum requirement planning in wireless communications: model and methodology for IMT-Advanced. Chichester: Wiley.

Tarhini, C., & Chahed, T. 2007. On capacity of OFDMA-based IEEE802.16 WiMAX including Adaptive Modulation and Coding (AMC) and inter-cell interference. Presented at the Local & Metropolitan Area Networks, 2007. LANMAN 2007. 15th IEEE Workshop on, IEEE, pp. 139–144. doi:10.1109/LANMAN.2007.4295989

The Coalition of Wireless Microphone Users. 2009. Reply of the coalition of wireless microphone users to oppositions to petitions for reconsideration. Washington, D.C: Federal Communications Commission.

Tsapatsoulis, N., Loizou, C., & Pattichis, C. 2007. Region of interest video coding for low bit-rate transmission of carotid ultrasound videos over 3G wireless networks. Conference Proceedings: ... Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Annual Conference. , 2007, 3717–3720. doi:10.1109/IEMBS.2007.4353139

Tumuluru, V. K., Wang, P., & Niyato, D. 2011. A Novel Spectrum-Scheduling Scheme for Multichannel Cognitive Radio Network and Performance Analysis. IEEE Transactions on Vehicular Technology. , 60(4), 1849–1858. doi:10.1109/TVT.2011.2114682

Umamaheswari, A., Subashini, V., & Subhapriya, P. 2012. Survey on performance, reliability and future proposal of Cognitive Radio under wireless computing. IEEE, pp. 1–6. doi:10.1109/ICCCNT.2012.6395960

Vamsi Krishna, T., & Das, A. 2009. A survey on MAC protocols in OSA networks. Computer Networks. , 53(9), 1377–1394. doi:10.1016/j.comnet.2009.01.003

Van Mieghem, P. 2009. Performance analysis of communications networks and systems. Cambridge: Cambridge University Press.

Vargas, A., Ugalde, M., Vargas, R., Narvaez, R., & Geissbuhler, A. 2014. Telemedicine in Bolivia: RAFT-Altiplano project, experiences, future prospects, and recommendations. Revista Panamericana De Salud Pública = Pan American Journal of Public Health. , 35(5–6), 359–364.

Vergados, D. D. 2007. Simulation and Modeling Bandwidth Control in Wireless Healthcare Information Systems. SIMULATION. , 83(4), 347–364. doi:10.1177/0037549707083114

Vergados, D. J., Vergados, D. D., & Maglogiannis, I. 2006. NGL03-6: Applying Wireless DiffServ for QoS Provisioning in Mobile Emergency Telemedicine. Presented at the Global Telecommunications Conference, 2006. GLOBECOM ’06. IEEE, IEEE, pp. 1–5. doi:10.1109/GLOCOM.2006.260

Vouyioukas, D., Maglogiannis, I., & Komnakos, D. 2007. Emergency m-Health Services through High-Speed 3G Systems: Simulation and Performance Evaluation. SIMULATION. , 83(4), 329–345. doi:10.1177/0037549707083113

Wang, X., & Giannakis, G. B. 2011. Resource Allocation for Wireless Multiuser OFDM Networks. IEEE Transactions on Information Theory. , 57(7), 4359–4372. doi:10.1109/TIT.2011.2145770

Wang, Y., Wang, Y., & Wang, L. 2007. Providing QoS Guarantee for Real-Time Service in Wireless OFDM Networks with Effective Capacity Method. IEEE, pp. 1988–1991. doi:10.1109/WICOM.2007.497

Wang, Y.-K., Even, R., Kristensen, T., & Jesup, R. 2011. RTP Payload Format for H.264 Video (No. RFC6184). RFC Editor. Retrieved from https://www.rfc-editor.org/info/rfc6184

Whitacre, B. E., Hartman, P. S., & Boggs, S. W. 2007. The Economic Impact of Telemedicine Capability in a Rural Hospital. United States of America: National Center for Rural Health Works. Retrieved from www.ruralhealthworks.org

Wickramasinghe, Y., Wijethilake, D., Vatsalan, D., Sudhahar, S., Runathilake, S., Seneviratne, G., … Mahanamahewa, P. 2010. BudhuDas: An eHealth Business Model for Emerging Countries. In P. Cunningham & M. Cunningham (Eds.). Presented at the IST-Africa, 2010, Africa. Retrieved from http://ieeexplore.ieee.org/servlet/opac?punumber=5749993

Wiegand, T., Sullivan, G. J., Bjontegaard, G., & Luthra, A. 2003. Overview of the H.264/AVC video coding standard. IEEE Transactions on Circuits and Systems for Video Technology. , 13(7), 560–576. doi:10.1109/TCSVT.2003.815165

WiMAX Network Capacity and Radio Resource Management. 2009. In Radio resource management in WiMAX: from theoretical capacity to system simulations. London, UK : Hoboken, NJ: ISTE ; Wiley, pp. 53–107.

World Health Organization. 2010a. Atlas eHealth country profiles based on the findings of the second Global survey on eHealth. Geneva, Switzerland: World Health Organization. Retrieved from http://www.who.int/goe/publications/goe_atlas_2010.pdf

World Health Organization. 2010b. Telemedicine: opportunities and developments in member states: report on the second Global survey on eHealth. Geneva, Switzerland: World Health Organization.

Wu, D. 2005. QoS provisioning in wireless networks. Wireless Communications and Mobile Computing. , 5(8), 957–969. doi:10.1002/wcm.359

Yang Peng, Shoaib Khan, Steinbach, E., Sgroi, M., & Kellerer, W. 2005. Adaptive resource allocation and frame scheduling for wireless multi-user video streaming. IEEE, p. III-708. doi:10.1109/ICIP.2005.1530490

Yasnoff, W. A., O'Carroll, P. W., Koo, D., Linkins, R. W., & Kilbourne, E. M. 2000. Public Health Informatics: Improving and Transforming Public Health in the Information Age. J of Public Health Practice and Management. , 6(6), 67–75.

Ying Su, & Caballero, I. 2010. Deployment of broadband wireless access for E-health in Chinese rural areas. IEEE, pp. 34–37. doi:10.1109/ICCSNA.2010.5588948

Ying-Chang Liang, Yonghong Zeng, Peh, E. C. Y., & Anh Tuan Hoang. 2008. Sensing-Throughput Tradeoff for Cognitive Radio Networks. IEEE Transactions on Wireless Communications. , 7(4), 1326–1337. doi:10.1109/TWC.2008.060869

Yucek, T., & Arslan, H. 2009. A survey of spectrum sensing algorithms for cognitive radio applications. IEEE Communications Surveys & Tutorials. , 11(1), 116–130. doi:10.1109/SURV.2009.090109

Yun-Sheng Yen, Wen-Chen Chiang, Sheng-Fang Hsiao, & Yi-Pei Shu. 2011. Using WiMAX network in a telemonitoring system. Presented at the Computer Research and Development (ICCRD), 2011 3rd International Conference on, IEEE, pp. 313–318. doi:10.1109/ICCRD.2011.5764027

Zachariah, R., Bienvenue, B., Ayada, L., Manzi, M., Maalim, A., Engy, E., … Harries, A. D. 2012. Practicing medicine without borders: tele-consultations and tele-mentoring for improving paediatric care in a conflict setting in Somalia?: **Practicing medicine without borders**. Tropical Medicine & International Health. , 17(9), 1156–1162. doi:10.1111/j.1365-3156.2012.03047.x

Zambrano, A., Garcia Betances, R. I., Huerta, M. K., & De Andrade, M. 2012. Municipal Communications Infrastructure for Rural Telemedicine in a Latin-American Country. IEEE Latin America Transactions. , 10(2), 1489–1495. doi:10.1109/TLA.2012.6187591

Zanaboni, P., Scalvini, S., Bernocchi, P., Borghi, G., Tridico, C., & Masella, C. 2009. Teleconsultation service to improve healthcare in rural areas: acceptance, organizational impact and appropriateness. BMC Health Services Research. , 9(1), 238. doi:10.1186/1472-6963-9-238

Zhang, R., Liang, Y., & Cui, S. 2010. Dynamic Resource Allocation in Cognitive Radio Networks. IEEE Signal Processing Magazine. , 27(3), 102–114. doi:10.1109/MSP.2010.936022

Zhang, Y., Ansari, N., & Tsunoda, H. 2010a. Wireless telemedicine services over integrated IEEE 802.11/WLAN and IEEE 802.16/WiMAX networks. IEEE Wireless Communications. , 17(1), 30–36. doi:10.1109/MWC.2010.5416347

Zhang, Y., Ansari, N., & Tsunoda, H. 2010b. Wireless telemedicine services over integrated IEEE 802.11/WLAN and IEEE 802.16/WiMAX networks. IEEE Wireless Communications. , 17(1), 30–36. doi:10.1109/MWC.2010.5416347

Zhao, Q., & Swami, A. 2007. A Survey of Dynamic Spectrum Access: Signal Processing and Networking Perspectives. IEEE, p. IV-1349-IV-1352. doi:10.1109/ICASSP.2007.367328

Zhu, H., & Dong, J. 2011. Wearable ECG terminal and its telemedicine-health services. Presented at the System Integration (SII), 2011 IEEE/SICE International Symposium on, IEEE, pp. 133–137. doi:10.1109/SII.2011.6147433

Zvikhachevskaya, A., Markarian, G., & Mihailova, L. 2009. Quality of Service Consideration for the Wireless Telemedicine and E-Health Services. Presented at the Wireless Communications and Networking Conference, 2009. WCNC 2009. IEEE, IEEE, pp. 1–6. doi:10.1109/WCNC.2009.4917925