Robust Wireless Access in Body Area Networks for m-Health Services

by

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Abstract

Mobile healthcare offers continuous monitoring of people’s health conditions while they are doing their daily activities. This service is realized using body area networks (BAN) that facilitate ubiquitous monitoring by eliminating wires between body nodes and the system that collect health signals for diagnostics by medical practitioners. To keep a constant flow of medical data over a BAN, body nodes have to have reliable and low-delay access to the medium when they have a sample to report. In an investigation of a proper medium access control (MAC) scheme for BANs, the IEEE 802.15.4 synchronous Beacon-Enabled mode, which is recommended for low-rate wireless personal area networks, is studied.

Because of a tight network synchronization requirement of the 802.15.4 MAC, which is hard to maintain in coexistence with heterogeneous networks, an interference-aware MAC for opportunistic access to the shared medium is proposed. The Centralized BAN Access Scheme (CBAS) resolves medium access contention within a BAN while protecting BAN transmissions from being interfered by coexistent networks. Feasibility of CBAS for handling pervasive monitoring and prompt medium access requirements is experimentally investigated over the unlicensed 2.4GHz band. For channel sensing in the experimental setup, the proposed dual-spectrum-sensing is applied to improve robustness of channel state detection without making any assumption about technologies of detected transmissions.

Regarding diverse service requirements of collocated BANs, a distributed channel selection strategy, for integration to CBAS, is proposed for quality of service (QoS) provisioning. The $k^{th}$-MAB strategy establishes a QoS-aware platform over which radio resources are
distributed amongst BANs proportional to their QoS levels determined by the health conditions of the respective subject.

Considering body nodes’ low power transmissions and continuously changing body posture, an adaptive cross layer design is proposed to capture BAN topology dynamism in packet routing over a BAN. In collaboration with the receiver-initiated CBAS, each body node extracts local information about its connectivity with other nodes within a BAN to contribute in improvement of the network’s packet delivery. By opportunistic capturing of high quality on-body links per packet transmission, this topology-adaptive scheduling scheme improves reliability while minimizing the need for multi-hop cooperative transmissions.
Preface

Hereby, I declare that Chapters 2-6 encompass work that has been published in papers that are co-authored by Dr. Victor Leung who supervised me through this research. Chapters 2, 4-6 include published work co-authored by Karim Rostamzadeh, William Wong, Chintan Kaur and Shantanu Bhate. Karim and William helped me in simulation verification. Chintan and Shantanu helped me with hardware implementation parts. The following publications are accomplished through this research.

Journal Papers, Published


Conference Papers, Published


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List of Abbreviations

ACK  Acknowledgement
BAN  Body Area Network
BCRS  Beacon Corruption Recovery Scheme
BI  Beacon Interval
CBAS  Centralized Body Area Network Access Scheme
CCA  Clear Channel Assessment
CCH  Control Channel
CSMA/CA  Carrier Sense Multiple Access with Collision Avoidance
CTMC  Continuous Time Markov Chain
CTS  Clear-to-Send
DC  Duty Cycle
ECG  Electrocardiography
EEG  Electroencephalography
EMG  Electromyography
FCC  Federal Communications Commission
FSM  Finite State Machines
GTS  Guaranteed Time Slot
ID  Identity
ISM  Industrial, Scientific and Medical
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>LQI</td>
<td>Link Quality Indication</td>
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<tr>
<td>M-health</td>
<td>Mobile Healthcare</td>
</tr>
<tr>
<td>MAB</td>
<td>Multi-Armed Bandit</td>
</tr>
<tr>
<td>MAC</td>
<td>Medium Access Control</td>
</tr>
<tr>
<td>MICS</td>
<td>Medical Implant Communication Service</td>
</tr>
<tr>
<td>NAV</td>
<td>Network Allocation Vector</td>
</tr>
<tr>
<td>NC</td>
<td>Network Coordinator</td>
</tr>
<tr>
<td>NACK</td>
<td>non-acknowledged</td>
</tr>
<tr>
<td>ODLF</td>
<td>On-Demand Listening and Forwarding</td>
</tr>
<tr>
<td>PD</td>
<td>Parkinson Disease</td>
</tr>
<tr>
<td>PDR</td>
<td>Packet Delivery Ratio</td>
</tr>
<tr>
<td>PU</td>
<td>Primary User</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>RAC</td>
<td>Radio Access Controller</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RSS</td>
<td>Received Signal Strength</td>
</tr>
<tr>
<td>RSSI</td>
<td>RSS Indicator</td>
</tr>
<tr>
<td>RTS</td>
<td>Request-to-Send</td>
</tr>
<tr>
<td>S/I</td>
<td>Signal-to-Interference</td>
</tr>
<tr>
<td>SD</td>
<td>Superframe Duration</td>
</tr>
<tr>
<td>SDR</td>
<td>Software Defined Radio</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
</tr>
<tr>
<td>SU</td>
<td>Secondary User</td>
</tr>
<tr>
<td>TDFS</td>
<td>Time Division Fair Sharing</td>
</tr>
<tr>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
</tr>
</tbody>
</table>
List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>TSMP</td>
<td>Time Synchronized Mesh Protocol</td>
</tr>
<tr>
<td>UCB</td>
<td>Upper Confidence Bound</td>
</tr>
<tr>
<td>USRP</td>
<td>Universal Software Radio Peripheral</td>
</tr>
<tr>
<td>UWB</td>
<td>Ultra Wide Band</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
</tr>
<tr>
<td>WMTS</td>
<td>Wireless Medical Telemetry Service</td>
</tr>
<tr>
<td>WPAN</td>
<td>Wireless Personal Area Network</td>
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Chapter 1

Introduction

1.1 M-health Service

Nowadays, increase of aging population, who usually suffer from chronic diseases, along with the demand for higher levels of life quality and well-being call for new systems for ambulatory collection of health information. In response to this new demand, mobile healthcare (m-health) service is proposed for continuous monitoring of physiological vital signs via unobtrusive mobile technologies.

M-health service contributes to the goal of disease prevention and early diagnosis by allowing doctors and caregivers to have continuous and real-time access to patients’ medical data. Formally in [1], m-health is defined as a service that employs “mobile computing, medical sensor, and communication technologies for healthcare”. Public m-health is realized by enabling this service for a wide group of people in society by outfitting people with body area networks (BAN) for the purpose of ambulatory health monitoring.

BAN, as the enabling component of m-health, facilitates this service by eliminating wires between a person and medical sensor devices to overcome restrictions of conventional monitoring solutions. BAN establishes an unobtrusive monitoring platform which allows a person to freely move from home to office, street, shopping mall, etc. while his/her health condition is being continuously monitored and conveyed to a medical center.

A BAN includes a small number of on-body sensor nodes for sensing of physiological data, such as electroencephalography (EEG), electrocardiography (ECG) and electromyo-
graphy (EMG) data, which are collected by a gateway and forwarded to a medical center over the existing telecommunication infrastructure for interpretation by a care-giver and detection of emergency conditions. Gateways may be implemented in commonly available mobile devices such as smart phones, and they are subject to a less stringent constraint on power consumption and processing resources than body nodes.

The objective of m-health service is continuous monitoring of a patient’s status throughout a day to improve life quality and reduce medical-care expenditures by preventing life threatening situations. For this reason, a BAN needs to handle three different categories of traffics including periodic, on-demand and emergency data.

*Periodic data* refers to monitored physiological signals, such as ECG and respiratory rate, which are sampled with a specific frequency and reported to a healthcare center through the gateway. Sampling rates vary from less than 1Hz to 1000Hz, depending on the type of a body signal.

*Emergency data* refers to the sampled data with values outside the acceptable range. An emergency situation needs to be reported to the healthcare center with a minimum delay before the patient’s condition gets worse. To distinguish a real abnormality from transient changes in the body condition, the body node goes to the intensive care mode by increasing its sampling rate from $f$ to $f'$ for a pre-configured duration to get more samples \[2\]. If the number of out-of-range data samples exceeds a threshold, a “real” abnormal condition is declared, which may trigger prompt intervention of medical staff to prevent emergence of life-threatening conditions.

*On-demand data* refers to sampled vital signs reported in response to the gateway’s requests. In treatments (e.g., drug delivery) or surgical operations, it is common that a specific body node is called upon (at some specific instant) by the gateway to sample and report its measurement. In fact, a body node should always be ready (on call) to
work on demand and report its recent measurements to the gateway. Differences in traffic requirements for an exemplary set of biomedical applications are presented in Table 1.1 in which “Emergency” models occurrence of out-of-range sampled data that each body node may experience and “Doctor PDA” resembles on-demand traffics.

Table 1.1: Traffic requirements of biomedical applications

<table>
<thead>
<tr>
<th>Medical Sensor</th>
<th>Emergency</th>
<th>Doctor PDA</th>
<th>ECG</th>
<th>Blood Pressure</th>
<th>Respiratory Rate</th>
<th>Endoscope Imaging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic distribution</td>
<td>Poisson</td>
<td>Poisson</td>
<td>Constant</td>
<td>Constant</td>
<td>Constant</td>
<td>Constant</td>
</tr>
<tr>
<td>Sampling Period</td>
<td>10s</td>
<td>0.1s</td>
<td>0.2s</td>
<td>0.195s</td>
<td>0.097s</td>
<td>0.065s</td>
</tr>
<tr>
<td>Data Rate</td>
<td>10Bps</td>
<td>1000Bps</td>
<td>500Bps</td>
<td>512Bps</td>
<td>1024Bps</td>
<td>1538.46Bps</td>
</tr>
<tr>
<td>Latency</td>
<td>~ 0</td>
<td>1s</td>
<td>0.3s</td>
<td>0.75s</td>
<td>0.6s</td>
<td>0.5s</td>
</tr>
</tbody>
</table>

An example of m-health application is continuous observation of motor signals for Parkinson Disease (PD) patients to speed up the fall detection process and consequently protect these patients from being injured. PD is a neurodegenerative disorder of the central nervous system that affects motor skills and speech. The syndrome typically appears around the age of 60 and its characteristic features include bradykinesia (i.e., slowness of movement), tremor, rigidity (i.e., resistance to externally imposed movements), flexed posture, postural instability, freezing of gait and loss of normal prosody of the speech [4, Chapter 14].

For PD patient monitoring, a BAN includes miniature motion sensors, like accelerometers and gyroscopes, which are worn on different limbs and constantly transmit motor symptom information to the gateway. Data acquired from sensors are pre-processed and integrated through fusion algorithms via the gateway to detect falls in real time. Activity recognition and classification allow health professionals to remotely monitor the overall status of a patient, adjust medication schedules and personalize treatment by keeping track of timing and doses of the medication and meals that the patient is taking [5, Chapter 10].
1.2 Research Problems

Medical data typically consist of periodically-sampled body signals that have relatively low data rates. As a result, unlike other conventional wireless networks that are designed for capacity maximization, a BAN is not required to support a high throughput. Instead, contribution of m-health service in disease prevention, early diagnosis and reduction of medical-care expenses is possible only if medical data are reported promptly and reliably at all times regardless of diverse environments such as streets, homes, offices, shopping malls, etc., in which subjects may be located. However, BAN proprietary characteristics including low-complexity and extremely low-power budget of body nodes make ubiquitous real-time monitoring over a BAN challenging especially from the following aspects:

On one hand, from everywhere and at anytime reporting of medical data demands a frequency band with no spatial or temporal access constraints. The unlicensed bands meet these requirements since they not only provide large bandwidths, but also are almost available everywhere with little access constraints. Despite these benefits, a BAN accessing an unlicensed frequency band must share the medium with a dynamic set of collocated networks which usually operate with much higher data rates or/and transmit power than a BAN. Consequently, a BAN is handicapped by these networks and may not be able to promptly access the medium when there is a new sample of physiological data to report. When BAN communications suffer from large medium access delays, m-health service loses its contribution in early detection of abnormalities and in prevention of severe life threatening situations. In this regard, the first challenge in realization of m-health service is managing the coexistence problem to support low-latency access of a BAN to a shared frequency band. By handling this challenge, sampled body signals are transmitted over a BAN in real-time without compromise of data fidelity.

Moreover, deciding about which part of the shared spectrum to use determines the
level of quality of service (QoS) achieved by the corresponding BAN. There is always a competition for access to the channel with the highest mean availability. This competition gives rise to the trade-off between achieving a higher QoS by access to the most available part of the spectrum and experiencing more collision, from collocated BANs, after launching a transmission on that channel. In this regard, a proper distributed channel selection strategy is required that not only takes differences in service requirements of other BANs into consideration but also reduces the chance of collision occurred by selecting the same channel.

On the other hand, reliable delivery of medical data from body nodes to the gateway is challenging because subject’s posture frequently changes. Movements of limbs and very low-power transmissions of body nodes result in a completely dynamic BAN topology that is determined by relative positions and orientations of body nodes toward the gateway and instantaneous quality of wireless links. In this regard, the second challenge in realization of an m-health service is handling the reliability issue which requires a topology-adaptive network layer design to improve packet delivery ratio (PDR) over BAN unreliable links.

In the following section we provide the brief summary of our contributions and then conclude the chapter with the thesis organization.

1.3 Contributions

To study and address real-time requirement for reporting medical data over a shared frequency band, we investigate applicability of the IEEE 802.15.4 [6] standard in support of low-delay medium access for a BAN. IEEE 802.15.4 is recommended by the IEEE 802.15.6 working group as the communication standard for BANs [7]. The synchronous Beacon-Enabled mode of the IEEE 802.15.4 standard is suitable for short-range wireless personal area networks (WPANs) that need long-term operability under a low power budget without
battery replacement. However, our experimental and analytical investigations show that there is a loss of network synchronization problem which leads to exclusion of a 802.15.4-based network from communication which makes real-time connectivity under question. Our study justifies that satisfaction of timeliness and energy conservative features strictly hinges on a tight network synchronization achieved via proper functionality of the beaconing strategy. We show that loss of network synchronization is a serious issue in a coexistence medium which makes the perfect beaconing, extensively assumed in the literature, and consequently reaching the required level of QoS for WPANs under question.

In this regard, we study a standard-conforming enhancement which better fulfills the expected synchronization and mitigates the resulted 802.15.4-performance degradation over a shared medium. Applying this enhancement partially satisfies biomedical application requirements while retaining compatibility with the existing 802.15.4 standard.

To expand the set of biomedical applications for which the QoS requirements are satisfied, we propose a new medium access control (MAC) scheme based on the BAN’s unique features. The objective is applying an opportunistic medium access idea in the BAN context, to make continuous and real-time report of medical data feasible, with establishment of a highly available platform for BAN prompt medium access. The significance of this study is enabling a peaceful coexistence of BANs with high power/data-rate networks by 1) reducing intermittent service interruptions imposed by coexisting networks, 2) improving visibility of a low-power BAN in a shared environment. Our cognitive MAC approach dynamically adjusts BAN channel access patterns according to an instantaneous interference environment by opportunistic extraction of white-spaces from a pool of orthogonal channels. We provide performance analysis of a BAN with dynamic spectrum access capability to illustrate how much the queuing-delay and throughput of a BAN outperforms those of a BAN that utilizes a single channel statically, as channel access opportunities suffer less
Chapter 1. Introduction

fragmentations and interruptions.

Regarding practical feasibility of an opportunistic medium access idea in establishing a highly available medium, for seamless connectivity over a BAN, we launch experimental tests over 2.4GHz ISM band. We set up a software defined radio (SDR) platform to take power spectral density snapshots from the ISM band at different times and locations. Then we examine how frequently medium access opportunities with the sufficient length for BAN communication occur per snapshot. The observed occurrence frequency determines whether equipping BANs with dynamic spectrum access capability guarantees low-latency and continuous report of medical data. For identifying idle/busy parts of the spectrum in our experimental tests, we propose a robust channel sensing strategy. The strength of this strategy is offering more accurate channel predictions without making any assumption about the coexisting networks and their design parameters such as the coding/modulation schemes or power spectral density of detected radio transmissions. Results of this study justify whether implementation of public m-health over unlicensed frequency bands is just a hypothetical idea or a practically feasible one.

Although opportunistic medium access may significantly mitigate BAN service interruptions, it is blind to service requirements of coexisting BANs unless under a QoS-aware platform. In this regard, we propose a learning strategy for distributed channel selection to help QoS provisioning amongst collocated BANs. The significance of a QoS-aware resource distribution proposal is preventing life-critical issues especially when the overall capacity is not sufficient to support transmission bandwidth of all collocated BANs. For instance, adopting this strategy in an emergency room, where patients with various levels of consciousness wear telemetry medical devices, guarantees that vital signs of a patient who fainted are served with a higher priority than those of a patient with a broken leg. By deployment of our proposed channel selection strategy in the BAN gateway, BANs
cooperatively get their sharing from radio resources proportional to QoS requirements and health condition of the person carrying a BAN.

To study the reliability issue imposed by frequent changes in the body posture and very low power transmissions over a BAN, we propose an adaptive network layer design which is tolerant of highly dynamic changes in the BAN topology. By applying this topology-related network layer design, each body node applies the local information, provided by the underlying MAC layer, about its on-body link quality to estimate how successfully it communicates with the gateway over the current BAN topology. Therefore, for every single packet transmission, the most reliable link is identified in a distributed manner to improve the chance of one-hop packet delivery. The significances of on-the-fly scheduling and capturing of high quality on-body links per packet transmission are: 1) increasing the number of successful one-hop packet transmissions, 2) enabling cooperative multi-hop transmissions with little overhead for maintaining network connectivity, end-to-end routing paths and body posture tracking, 3) meeting BAN packet delivery requirements using a smaller number of transmission opportunities. We validate our study with extensive experimental results to give insights on how taking advantage of dynamic scheduling and multi-hop relaying as warranted by the link conditions improve packet delivery ratio and reduce BAN packet delivery time.

1.4 Thesis Organization

Thesis contributions and results are organized as follows:

1. In Chapter 2 we study the synchronous Beacon-Enabled mode of the IEEE 802.15.4 standard to investigate whether this standard is suitable for supporting mission critical applications with stringent medium access delay requirements. We experimentally and analytically study how interference from collocated networks affects the
expected synchronization and consequently medium access delays. We propose a standard-conforming enhancement, called the Beacon Corruption Recovery Scheme (BCRS), for better fulfillment of real-time bidirectional flow of monitoring information. BCRS allows a 802.15.4-based network to have a less fragmented access to the shared medium and mitigate the beacon corruption issue by migration of the network to a cleaner channel.

2. In Chapter 3 we propose an opportunistic medium access management, called Centralized Body Area Network Access Scheme (CBAS), to provide a highly available medium for BAN transmissions. This MAC scheme reduces queuing delays (interval between sampling and reporting of a body signal) by coping with dynamic service interruptions experienced by a BAN operating in a coexistence environment. CBAS also aims to support low duty cycles for power savings in body nodes by placing most of the complexity at the gateway, which has much higher power and resource budgets.

3. In Chapter 4 we experimentally investigate feasibility of CBAS in establishing a highly available platform for a BAN in the ISM band. In this regard we propose a sensing strategy, called the dual-spectrum-sensing, to detect idle/busy parts of the spectrum. We set up an SDR platform to take power variations of the ISM band at different locations/times to examine whether ample white-spaces exist for a frequency-agile BAN to have prompt access to the ISM band. Our test platform applies the dual-spectrum-sensing strategy on snapshots taken from the ISM band to extract target white-spaces, i.e., idle parts of the spectrum with sufficient length. Based on the examined occurrence frequency of target white-spaces we conclude how successfully equipping a BAN with dynamic spectrum access capability guarantees seamless connectivity and real-time communication over a BAN operating in a shared
environment (like ISM band).

4. In Chapter 5, we provide a highly reliable platform for BANs by incorporating the MAC information into the network layer to capture the high quality wireless links for transmissions. We propose an on-the-fly topology-related scheduling scheme, built on top of the CBAS framework, to improve PDR while minimizing the need for multi-hop cooperative transmissions. The proposed dynamic scheduling scheme applies the local information, implicitly provided by the CBAS MAC layer, about the quality of on-body links to identify the most reliable links in a distributed manner. We validate the efficiency of this proposal in improving PDR and examine the tradeoff between PDR and packet delivery time via extensive experimental results.

5. In Chapter 6, we support a QoS-aware platform for a multi priority telemedicine service (Inter-BAN priority) over heterogeneous wireless systems by proposing a learning strategy, called $k^{th}$-MAB, for distributed channel selection in frequency-agile BANs. Adoption of this strategy by the gateway resolves contention amongst collocated BANs with diverse QoS requirements such that each BAN gets services proportional to the health condition of the person carrying that BAN. $k^{th}$-MAB helps the gateway to take traffic requirements of collocated BANs into consideration when it opportunistically captures a channel.

6. In Chapter 7, we provide thesis conclusions and discuss potential future extensions. Each of the main chapters in this thesis is included in separate journal articles or conference papers.
Chapter 2

Feasibility of the IEEE 802.15.4 Beacon-Enabled Mode for m-Health Service

2.1 Introduction

Zigbee, a standardized protocol based on the IEEE 802.15.4 physical and MAC layer specifications, is a suitable communication standard for short-range low-power WPANs that operate in the license-free ISM frequency band. Zigbee-based networks are mainly adopted for monitoring and control applications such as sensor networks, home automation systems and BAN for remote healthcare monitoring. Low transmission power and energy conserving features of the IEEE 802.15.4 standard enable these networks to work for extended periods of time without battery replacement.

Zigbee is specifically recommended by the IEEE 802.15.6 BAN working group [7] as a suitable communication standard for BANs. As pointed in Chapter [1] a Zigbee-based BAN may be used in support of m-health service only if it provides a reliable platform for continuous real-time exchange of data over BAN different entities (body nodes and the

This chapter is based on the following papers:
Chapter 2. Feasibility of the IEEE 802.15.4 Beacon-Enabled Mode for m-Health Service Gateway.

The IEEE 802.15.4 MAC supports two different modes of Non-Beacon and Beacon-Enabled [6]. The Non-Beacon mode employs the un-slotted Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) while the latter uses slotted CSMA/CA. In the Beacon-Enabled mode, there is a Network Coordinator (NC) that manages and synchronizes a group of end-devices by applying the beaconing strategy. Beacon packets identify available communication intervals for end-devices and keep them in synchronization with the NC. Synchronization reduces the probability of collision amongst end-devices contending for channel access, allows bandwidth reservation and supports sleeping of end-devices for power saving. These characteristics make the Beacon-Enabled mode more suitable than the Non-Beacon mode for Zigbee-based networks that require real-time and long-term operability under a low energy budget.

However, due to the myopic transmissions of beacons by the NC and a lack of cooperation between coexistence systems in the ISM band, beacons may be corrupted by interference and not be reliably received by end-devices. According to the IEEE 802.15.4 Beacon-Enabled mode, reception of a beacon is a permission for transmissions and so if an end-device does not receive a beacon, it loses its eligibility for access to the medium until it successfully receives a beacon and get re-synchronized to the NC. Therefore, loss of a beacon is beyond a simple packet corruption since this loss causes the wireless medium to be unavailable to the affected end-devices which may significantly increase network delay. This problem motivates a comprehensive study about the effect of the coexistence problem in ISM band on the beaconing functionality and consequently performance of IEEE 802.15.4-based networks.

In this chapter we mainly investigate whether loss of beacons in the beacon-enabled mode of operation significantly handicap the BAN in support of m-health applications with strict
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delay requirements and how Zigbee-based networks may still benefit from beaconing even in a coexistence environment.

The rest of this chapter is organized as follows: Related literature is surveyed in Section 2.2 and Section 2.3 reviews the IEEE 802.15.4 Beacon-Enabled mode. Section 2.4 examines analytically the extent to which an end-device loses medium access opportunities for communications as a result of a beacon loss. Section 2.5 proposes an enhancement, called the BCRS, to the existing IEEE 802.15.4 standard to improve successful beaconing operation in a coexistence medium. Simulation scenarios in Section 2.6 evaluate beaconing and BCRS performance in the ISM band and finally Section 2.7 summarizes this chapter.

2.2 Literature Review

An extensive search in the literature indicates that there is no work that evaluates the effect of 1) coexistence on beaconing functionality and 2) beaconing on system performance and medium access delay. However, there are categories of proposals that improve performance of IEEE 802.15.4-based networks in shared frequency bands. The objective of this section is to examine whether these proposals may also improve the reliability of beaconing.

Busy Tone Strategy [8, 9]: Tuning strategies improve visibility of an 802.15.4-based network in coexistence with WLAN where NC sends tuning-signals to make a virtual busy-channel condition for coexisting wireless local area network (WLAN) systems. In [8], medium capturing is done by fake Clear-To-send (CTS) signals. Since fake CTSs are transmitted periodically and regardless of the 802.15.4 traffic demand, 802.11 performance degrades and channel resources are wasted if 802.15.4 application does not have any packet for transmission. In [9], the busy-tone-scheduler obtains 802.15.4 traffic demands at each superframe to avoid the drawbacks of [8]. These methods require the 802.15.4 devices to generate CTS packets according to the WLAN standard, which may substantially increase
the complexity and cost of devices. They also require a tight cooperation of the 802.15.4 network with an additional module called signaler. The signaler is equipped with an AC power and helps the 802.15.4 network to have a better visibility in a coexistence environment by sending busy-tones ahead of 802.15.4 packets to reserve the medium for the upcoming transmissions.

To apply the busy tone strategy for improving beaconing reliability, NC is required to send a CTS packet before transmission of each beacon to trigger the signaler to send a busy tone. To force WLAN to back-off, the busy-tones should be sent according to the specifications of the IEEE 802.11 standard. The signaler does clear channel assessment (CCA) to opportunistically capture the medium by sending a busy tone. However, this procedure is useful only if 1) providing the AC powered signaler compatible with both IEEE 802.15.4 and IEEE 802.11 standards is acceptable, and 2) reliable transmission of traffic demands to the signaler is guaranteed which is obviously not trivial in a coexistence environment.

Super-frame hopping [10]: Contrary to an IEEE 802.15.4 network that operates on only one channel, this scheme utilizes multiple channels by sending superframes on a set of clean channels where the hopping sequence is negotiated at the network association phase. If an end-device misses a beacon on its current channel, it hops to the next channel of the sequence to capture the beacon on a different channel. Although resistant to interference, this scheme is not proper for time-sensitive applications because an actual new superframe is transmitted every $|\text{hopping sequence}| \times \text{BI}$ seconds instead of $\text{BI}$ seconds where $\text{BI}$ is the superframe length. This is a very conservative recovery scheme since corresponding to each BI, an extra delay of $(|\text{hopping sequence}| - 1) \times \text{BI}$ seconds is imposed to protect the 802.15.4 network from possible occurrence of interference. Therefore, this approach contributes in reliable delivery of beacons from NC toward end-devices only if the tar-
get application could tolerate this extra delay which is usually not the case for m-health applications.

*Re-association to the NC* \[11\] \[12\]: This recovery scheme is part of the IEEE 802.15.4 standard. The MAC layer of a receiving end-device indicates a loss of synchronization and starts re-association to the NC if the train of lost beacons exceeds the \(aMaxLostBeacons\) threshold. However, this approach does not effectively recover an interfered 802.15.4 network because of the following. 1) Re-association takes \(~\) one second, which is a fairly large delay considering that (re)association is a black-out period in which services to the application is completely halted. Moreover, when the NC is surrounded by interference, it is likely that *most* of end-devices reach the \(aMaxLostBeacons\) bound and try re-association at approximately the same time which makes re-association phase even longer in comparison to when a few end-devices are affected by interference and do re-association. Thus it is not a prompt recovery scheme. 2) If an interfering traffic on the working channel leads to a train of lost beacons which is much larger or smaller than \(aMaxLostBeacons\), this recovery scheme is not beneficial. The former case causes unnecessary switching overheads since shortly after joining the NC, the end-device may reach the limit of beacon loss and decides to initiate re-association. In the latter case, the recovery scheme may not be triggered at all like when no strategy for beacon loss mitigation is applied. The proposed BCRS similarly applies the cardinality of the loss train as an indication of interference but resolves the aforementioned issues; as explained in Section 2.5.

*Changing the working frequency* \[13\] \[16\]: Under this category, an interfered end-device informs other network entities about the presence of the interference and the need to hop to another channel or the NC sends a channel switching command to announce the next clean channel. However, while the working channel is under strong interference, neither the reception of the notification nor the command to hop to a clear channel can
be guaranteed which bring the risk of network partitioning and large interference recovery
time. A partitioned 802.15.4 network consists of clusters of end-devices communicating on
different channels.

*Improving 802.15.4 packet delivery probability*\[17, 18\]: To increase packet delivery over
an 802.15.4 network, authors in \[17\] suggest to model white-spaces between WiFi trans-
missions and adapt ZigBee frame sizes to the lifetime of these white-spaces to bound the
collision probability resulting from unequal carrier sensing abilities of WLANs and Zigbee.
Note that 1) to keep the network in synchronization, beacon packets are transmitted peri-
odically and so their opportunistic transmission is not applicable and 2) these approaches
are effective when an end-device is about to start a transmission after it has successfully
received the recent beacon, completed the back-off period and found the medium idle for
two consecutive CCAs periods. In other words, these approaches try to improve the packet
reception probability while they implicitly assume perfect beaconing.

This chapter shows that beacon corruption is a serious issue in a coexistence medium
and perfect beaconing is not a valid assumption. Therefore, proposals in this category
have limited contribution on proper functionality of beaconing strategy and consequently
reduction of transmission opportunities resulting from the beacon loss issue.

### 2.3 IEEE 802.15.4 Beaconing Procedure

#### 2.3.1 IEEE 802.15.4 MAC Specifications

For an 802.15.4-based network operating in the synchronous Beacon-Enabled mode, time
is divided into Beacon Intervals (BI) and the NC transmits a beacon at the start of each BI
to inform network parameters to all end-devices (see Fig. 2.1). The length of a BI is equal
to $a_{\text{Base Superframe Duration}} \times 2^{BO} = 960 \times 2^{BO}$ symbols. The Superframe Duration (SD)
is the first part of the BI in which communications happen. A SD is optionally followed by an inactive period where end-devices go to sleep for power saving. BO is a configuration parameter that determines the lengths of BIs. SD includes the Contention Access Period in which end-devices contend to access the shared channel using CSMA/CA, and potentially a Contention Free Period in which end-devices communicate in their allocated slot(s).

In the license-free ISM band, an 802.15.4-based BAN may coexist with a family of IEEE 802-based systems (802.11b/g/n, 802.15.1/3/4). Differences among transmission power, data rate and signal-to-interference (S/I) threshold of coexistence networks lead to asymmetric mutual interference and unequal carrier sensing abilities. For instance, in coexistence with a WLAN, 802.15.4 transmissions are vulnerable to corruption while WLAN traffic is generally not affected [19]. Besides, low-power and low data rate features make an 802.15.4 network unable to force a high power interferer to respect its traffic requirements and thus restrict 802.15.4 transmissions to unused spaces left between transmissions of high-power collocated networks.

Among all possible coexisting systems, IEEE 802.11 WLANs represent the most problematic source of interference since their transmission power is significantly higher than that of 802.15.4 transmissions. Investigation of a large scale WiFi traffic in public hotspots shows that the probability of having at least one and 10 WiFi clients are above 99.99% and 93%, respectively. It means that, during normal operations, BANs have to overcome interference from WiFi networks [20]. For this reason, this chapter specifically
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targets evaluation of the beaconing strategy in a presence of WLAN interference.

2.3.2 Beacon Corruption Issue

Description

Beacon, the most critical control packet in the IEEE 802.15.4 Beacon-Enabled mode, is transmitted periodically by the NC and regardless of the availability of the medium. An interference-agnostic transmission of beacons makes their corruption quite likely specifically under the persistent WLAN traffic. Since beacons identify the communication intervals, an end-device with a missed beacon finds the medium unavailable for CSMA/CA until it is synchronized to the NC by receiving another beacon. Therefore, an end-device perceives the time domain as cycles where each cycle is composed of an eligible period in which it can access the wireless medium followed by an ineligible period.

An eligible period consists of a sequence of BIs, each starting with a successfully received beacon. Similarly, an ineligible period includes a sequence of BIs, each starting with a lost beacon. As illustrated in Fig. 2.2, an 802.15.4 network with a larger BO exponent experiences larger ineligible periods.

Figure 2.2: Beaconing strategy and medium access fragmentation
Experimental Evaluation

To study how severe the beacon corruption issue is, a WLAN/802.15.4 coexistence scenario is set up. Although lots of work in the literature experimentally studied 802.15.4 performances in coexistent with WLANs, we believe that this is the first experimental study about the effect of the coexistence on beaconing performance. Experimental setup includes an 802.15.4 network, including two Crossbow TelosB motes, and a WLAN ad-hoc network, consisting of two laptops. The WLAN is tuned to channel 11 and works as a collocated interferer. The 802.15.4 network is tuned to channel 23 which overlaps with WLAN channel 11. The TelosB motes are equipped with Chipcon CC2420 IEEE 802.15.4-compliant radio transceivers and configured to operate in the Beacon-Enabled mode. One mote works as a NC and the other one as an end-device. The 802.15.4 network is placed in close proximity of the WLAN such that its transmissions cause the WLAN to back-off.

To compare results related to various 802.15.4 configuration parameters, a regenerative interfering traffic pattern is preferred over a random one. For this reason, instead of doing experiments in public places like streets or offices where WLAN traffic is dynamic and hard to be regenerated, transferring of a 262 MB file from one laptop to the other is used. File-transfer starts at a random time between [0,45) seconds of the start of the experiment. To determine the extent of time that the WLAN traffic captures the medium, CommView sniffer, a network monitor and analyzer, is used to gather information from the 802.11 adapter of a laptop. For the mentioned setup, traffic sniffing shows that the WLAN channel usage, i.e., fraction of time that the WLAN packets are in transmissions, is around 45%. Reception of beacons by an end-device during the file transfer is logged via the USB interface of the end-device.
By defining the percentage of beacon loss as:

\[ P_{\text{loss}}(t) = \frac{\text{cumulative number of lost beacons at } t}{\text{cumulative number of generated beacons at } t} \]  \hspace{1cm} (2.1)

statistical results in Fig. 2.3 reveal that an end-device loses an average of 40% of beacons at each BO setting. It means that the beacon loss is a function of the WLAN airtime usage and not the BO setting. Considering that beacon reception is a perquisite for medium access, results indicate that an end-device is prevented from data communications during 40% of times. These exclusion periods cause a large accumulation of backlogged packets in an end-device’s queue and may lead to excessive delays in the transmission of these packets.

2.4 Theoretical Analysis of Beacon Loss Problem

Empirical measurements show that WLAN behavior is modeled by a Continuous Time Markov Chain (CTMC) with two states of idle and busy, which transition times are exponentially distributed with parameters \( \lambda \) and \( \mu \), respectively [21]. Also as discussed in [22], the coexistence of WLAN/802.15.4 does not change the overall behavior (data rate) of WLAN but only increases the WLAN packet error rate. These two observations indicate
that in coexistence with an 802.15.4-based network, the approximated CTMC for WLAN is still applicable and 802.15.4 finds the shared channel as busy or idle at any time instant with probabilities:

\[ P_{\text{busy}} = \frac{\lambda}{\lambda + \mu}, \quad P_{\text{idle}} = \frac{\mu}{\lambda + \mu} \]  

(2.2)

Since NC usually has less power constraints than end-devices, as an intuitive beacon-protection scheme, NC may decide to send beacons with higher power to make them more visible to surrounding WLANs. This approach forces WLAN to back-off when beacon transmission is in progress. However, beacons are transmitted without any prior carrier sensing and so they still may collide with a previously launched WLAN packet. In an ideal case that WLAN perfectly detects 802.15.4 packets, a beacon is successfully transmitted if its first few bytes do not overlap with an ongoing WLAN transmission since WLAN never starts a transmission in the middle of the beacon transmission. As a result, the beacon is lost if the coexistent WLAN is in the busy state when the beacon transmission begins. Therefore, the beacon loss probability is estimated by \( P_{\text{loss}} \approx P_{\text{busy}} \) which is consistent with our experimental observations with \( P_{\text{loss}} = 40\% \) and \( P_{\text{busy}} = 45\% \).

Since unequal carrier sensing is a serious issue when transmission powers of collocated networks are highly different [19], a WLAN may not detect the ongoing beacon transmission and launches a packet in the middle of the beacon. As a result and based on the above discussion, the beacon loss probability is lower bounded by \( P_{\text{loss}} \approx P_{\text{busy}} \).

Given that an end-device just missed (received) a beacon; it experiences a lost
cessful) train of beacons with the following lengths:

\[
E[\text{loss-train}] = 1 + \sum_{k=0}^{\infty} k \, P_{11}^k(BI) \, P_{10}(BI),
\]

\[
E[\text{succ-train}] = 1 + \sum_{k=0}^{\infty} k \, P_{00}^k(BI) \, P_{01}(BI)
\]

where \( P_{ij}(t) \), the probability of visiting state \( j \) after \( t \) unit-times by starting from state \( i \), for the mentioned CTMC is:

\[
P_{ij}(t) = \frac{1}{\lambda + \mu} \times \left[ \begin{array}{cc} \mu + \lambda e^{-(\lambda+\mu)t} & \lambda - \lambda e^{-(\lambda+\mu)t} \\
\mu - \mu e^{-(\lambda+\mu)t} & \lambda + \mu e^{-(\lambda+\mu)t} \end{array} \right]
\]

and consequently the average length of (in)eligible periods in Fig. 2.2 is:

\[
\bar{X}_{\text{ineligible}} = BI \cdot E[\text{loss-train}],
\]

\[
\bar{X}_{\text{eligible}} = BI \cdot E[\text{succ-train}]
\]

It means that an end-device participates in contention with the WLAN to access the medium for \( \bar{X}_{\text{eligible}} \) sec and then it loses its permission for data communication for \( \bar{X}_{\text{ineligible}} \) sec. In other words, frequently and every \( \bar{X}_{\text{eligible}} + \bar{X}_{\text{eligible}} \) sec, the 802.15.4 network is excluded from communication for \( \bar{X}_{\text{ineligible}} \) sec.

By considering the \( BO \) range specified in the standard, \( 0 \leq BO \leq 14 \), these periodic service disruptions expose 802.15.4 packets with large delays specially when \( BO \) is large. The effect of the configuration parameter \( BO \) on the length of (in)eligible periods is presented in Fig. 2.4 when the average stay of the coexistent WLAN in the busy state is \( \mu^{-1} = 0.1 \) sec. On this shared channel, if the WLAN transmissions occupy half of the medium’s time, i.e., \( \mu^{-1} = \lambda^{-1} \), a Zigbee-based BAN with \( BO = 0 \) experiences service interruptions of \( \bar{X}_{\text{ineligible}} = 0.116 \) sec while this value increases to \( \bar{X}_{\text{ineligible}} = 1.966 \) sec.
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when \( BO = 6 \).

Despite bounded delay transmissions demanded by most m-health applications, the service rate of an end-device drops to zero within an ineligible period. As a result, an end-device should wait for the next eligible period to at least find a chance for performing CSMA/CA to report the sampled data. Under a large \( X_{\text{ineligible}} \), reports may be delayed too much to be useful to prevent health threatening situations.

![Figure 2.4: \( X_{\text{eligible}} \) and \( X_{\text{ineligible}} \) under different settings of BO parameter](image)

2.5 Beacon Corruption Recovery Scheme

2.5.1 System Parameters and Assumptions

This section presents BCRS, as an enhancement to the IEEE 802.15.4 standard, to mitigate service fragmentation and large delays caused by the beacon corruption issue. Before going through the algorithm, some clarifications are stated.

*Control Channel (CCH)*: BCRS hinges on a dedicated *CCH* used for control information exchanges. This channel should be as free from interference as possible. To decide on the
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Consider that the 2.4 GHz ISM band is divided into 16 channels for IEEE 802.15.4 while it provides 13 overlapping channels (plus a 14th channel used in Japan) for the IEEE 802.11 standard. Each 802.11 channel overlaps with four 802.15.4 channels. While the mentioned channel allocation is globally accepted for IEEE 802.15.4 standard, it is subject to regional spectrum regulations for WLANs. For instance, channels 13 and 14 of IEEE 802.11 in the 2.4 GHz band are not used by most WLAN devices in North America due to transmit power restrictions. Therefore, channels 25 or 26 of IEEE 802.15.4 would be free of WLAN interference. Further, channel 26 is not legal in a number of countries and it is not supported by certain standards. As a result, channel 25 is a suitable candidate for CCH. Although locating a CCH in the part of ISM band that does not overlap with WLAN activities removes the most important source of interference, it still does not guarantee a perfectly reliable exchange of control information since coexisting 802.15-based networks, like collocated Zigbee and Bluetooth networks, may operate on this channel. However, these networks generally have much lower transmit power and data rate than WLANs, so interference from these systems is less of a concern.

$k$: This parameter reflects the interference tolerance of an end-device. When an end-device encounters a train of $k$ consecutive lost beacons, it concludes the presence of harmful interference in its proximity and triggers the recovery process. Pertinent to the specifications of the target application, each end-device sets its desired value for $k$ instead of using the constant value of $aMaxLostBeacons$ suggested by the IEEE802.15.4 standard.

Alarm-slot: A 320$\mu$ sec slot that starts immediately after the beacon.

Switching-slot: A 320$\mu$ sec slot located right before the next scheduled beacon.

Considering the NC as a less energy-constrained entity in an 802.15.4 network, it is assumed that the NC constantly monitors the conditions of the IEEE 802.15.4 channels to track the level of interference on its working channel and make a list of clean channels.

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2.5.2 Description of BCRS

In the network initialization phase, the NC selects a *CCH* for its high reliability data exchanges, encapsulates this additional information into the beacon and periodically sends a beacon at the start of each BI. Thus, each new end-device that is associated and synchronized with the NC would be aware of the *CCH* assigned to the network.

Based on the modified BI structure illustrated in Fig. 2.5, the enhanced IEEE 802.15.4 standard reacts to interference as follow:

**On the end-device side:**

- The end-device that has already encountered a run of *k* lost beacons tunes its radio to the *CCH* at the boundary of the *Alarm-slot* which is the first slot of a SD. The end-device sends a short alarm message at a random time within the *Alarm-slot* to inform the NC about the interference. Since the *CCH* is approximately interference-free, the end-device is confident that the NC receives the alarm with a high probability. Since the alarm message is very short, a robust channel coding can be used to increase the chance of a successful reception of the message by the NC under a low S/I, without unduly increasing the overhead.

- End-devices that have successfully received the recent beacon start data communications based on the IEEE 802.15.4 standard from the second slot of the SD (the one that comes after the *Alarm-slot*).
• All end-devices listen to the CCH during the last slot of the BI, i.e., the one that is called the Switching-slot and comes right before the next scheduled beacon.

On the NC side:
• When the NC receives an alarm message, it knows that parts of the network are experiencing interference. In response, the NC chooses a new working channel from the list of available channels and announces its selection through the CCH during the Switching-slot. Since CCH is approximately interference free, almost all end-devices receive this announcement and tune their radios to the announced channel since they expect to receive the next beacon on it. As a result, end-devices smoothly migrate to the new channel without losing their synchronization with the NC.
• When the NC senses a low S/I on the current working channel, it considers this as an indication of the presence of interference around itself and so predicts that the next beacon will be corrupted with a high probability. In response and regardless of reception of an alarm message from an interfered end-device, the NC proactively invokes the recovery scheme by announcing a new working channel within the Switching-slot. As a result, regardless of whether end-devices or NC are affected by interference, the coexistence scheme is invoked to mitigate interference effects.
• As a conservative strategy to protect the network from being partitioned due to the lack of an ideal CCH, the NC always announces the working channel for the next BI in the Switching-slot to guarantee that all end-device switch to the new channel at approximately the same time. Under a non-ideal CCH, it is likely that an end-device is not informed about the new working channel and continues its communication on a channel different from the one that the rest of the network has switched to.
2.5.3 Practical Considerations

- In the IEEE 802.15.4 Beacon-Enabled mode, the end-devices calculate sleep time (when SD finishes), wake-up time (at the end of the inactive period), slot boundaries and the expected time for receiving beacons by considering reception time of the first beacon received after successful association to the network, as their reference point. Therefore, locating Alarm-slot and Switching-slot is trivial.

- To have minimal adjustments to the recovery scheme incorporated in the IEEE 802.15.4 standard, BCRS considers the cardinality of the run of lost beacons as an indication of severe interference. Note that when an end-device experiences a loss run of length $E[\text{loss-train}]$, it does not have permission to access the medium and send any packet; so the number of transmitted packets and consequently the number of non-acknowledged (NACK) packets remain unchanged even though part of the network needs recovery from interference. It means that the NACK criteria, as suggested by [16], does not precisely reflect presence of interference.

- By enhancement of the IEEE 802.15.4 standard with BCRS, an end-device tunes its radio to the $CCH$ at most two times per BI. This switching overhead is not a concern since it is less frequent than what is implemented in similar low power networks. For instance, the Time Synchronized Mesh Protocol (TSMP) overlays frequency hopping on top of 802.15.4 to increase the available bandwidth [24]. Despite using hopping patterns, the complexity of TSMP is reasonable for consideration as a standard for sensor networks with low power and low bandwidth constraints.

2.5.4 Analysis of BCRS

The main questions about BCRS are 1) how frequently an interfered 802.15.4 network switches to a new channel and 2) to what extent medium access opportunities are missed
before the network detects the interference and decides to perform channel switching.

To answer the first question, let random variable $x$ be defined as the number of beacons transmitted until the first occurrence of a loss run of length $k$. Therefore, the network continues its operation on the current working channel for $BI \cdot E[x]$ seconds before it decides to switch to another channel. Considering the WLAN CTMC with transition matrix (2.4) and initial probabilities $p_0 = P_{idle}$ and $p_1 = P_{busy}$, random variable $x$ would have Markov-geometric distribution of order $k$\cite{25}.

By applying the similar proof methodology used in\cite{25}, we define a word $S = " 11 \ldots 1 "$ and a set of words $F = \bigcup_{j=0}^{k-1} \{ " 11 \ldots 10 \}_{j} \}$ where $(1)0$ corresponds to (un)successful reception of a beacon. It means that a run of $k$ losses occurs when the sequence $\{" FF \ldots FS" \}_{j=0}^{\infty}$ is observed. Also, by occurrence a word in $F$, i.e., hitting a successful beacon reception, the process is resumed and the previous history related to lost beacons are dismissed. This behavior concludes a recursion on a successful trial as follows:

\[
P(x) = 0, \quad 0 < x < k
\]
\[
P(x = k) = p_1 P_{11}^{k-1}
\]
\[
P(x = k + 1) = p_0 P_{01} P_{11}^{k-1}
\]
\[
P(x) = P_{00} P(x - 1) + \sum_{i=2}^{k} P(x - i) P_{10} P_{01} P_{11}^{i-1} \quad , x > k + 1
\]

which bring the expected value of $x$ as:

\[
E[x] = \frac{(P_{01} + P_{10}) - p_1 P_{11}^{k-1} + (p_1 - P_{01}) P_{11}^{k}}{P_{01} P_{10} P_{11}^{k-1}} \quad (2.6)
\]

It means that network switches to another channel with the rate of $r_{sw} = (BI \cdot E[x])^{-1}$ times per second.

To answer the second question, let random variable $v$ be defined as the number of lost
beacons before detecting interference by observing a loss run of length \( k \). According to \cite{26}, \( v \) has the shifted geometric distribution of order \((k-1)\) with the following expected value:

\[
E[v] = \frac{1 - P_{11}^{k-1}}{(1 - P_{11})P_{11}^{k-1}}
\] (2.7)

it means that an end-device loses an average number of \( E[v] \) beacons and consequently misses \( BI \cdot E[v] \) seconds of channel time for data communication before BCRS is triggered.

The above discussion indicates that selection of \( k \) is critical both for avoiding excessive switching overheads and rapid reaction to crippling interference. For instance, \( k \) should not be much larger than \( E[\text{loss-train}] \) in (2.3), otherwise it is unlikely that the condition for BCRS activation is met.

### 2.6 Simulation Results and Discussions

In simulated coexistence scenario, consists of a Zigbee-based BAN with WLAN, we study 1) the extent to which medium access delay and maximum arrival rate are compromised by beaconing failure, 2) how promptly BCRS rescues an interfered BAN when the level of interference is measured as a function of beacon reception probability and 3) the proper setting for network configuration parameters to meet application service requirements.

Zigbee entities (NC and end-devices) work according to the IEEE 802.15.4 standard Beacon-Enabled mode with the transmission rate of 250 Kbps. The simulator is written in Python and simulations are performed on a dual core desktop computer. In this setup, NC updates its knowledge about the status of IEEE 802.15.4 channels every 15\( m\)sec, which is the finest obtainable time granularity for the simulation platform. As also confirmed in Python documentation, this is the minimum interval that can be implemented under a standard desktop operating system.
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The coexistent WLAN transits between exponentially distributed idle and busy states with parameters $\lambda$ and $\mu$. Various combinations of $\lambda$ and $\mu$ represent different WLAN traffic patterns that consequently expose Zigbee-based BAN subject to different levels of interference. Considering low-power and low data rate features of BANs, an end-device captures the medium for its transmission if and only if 1) the shared medium is free of WLAN transmissions, i.e. WLAN is in the idle state and 2) an end-device has received the latest beacon and consequently it is in synchronization with the NC. Transmission time of each Zigbee packet is set to 20 $msec$.

2.6.1 Medium Access Delay and BO Parameter

This part discusses that medium access delay and upper bound of the network arrival rate are functions of the BI's length or equivalently the BO parameter such that, in the same coexistence scenario, a BAN with larger BO experiences larger delays and supports lower arrival rates than a one with smaller BO. Medium access delay refers to an interval that a packet remains backlogged until it is dequeued and launched for transmission.

![Figure 2.6: Effect of BO parameter on medium access delay and maximum arrival rate](image)

Fig. 2.6 illustrates medium access delay under different values of BO for a set of exemplary shared channels. Results of an ideal case (named Without Beaconing), in which
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the chance of beacon loss is zero, are provided as reference to the lower bound of achievable medium access delay.

For every single setup, comparison with reference delays, i.e. perfect beaconing, clarifies that beacon loss issue may severely compromise medium access delay and restrict BAN arrival rate.

Comparison of reference delays on different setups indicates that increasing the beacon reception probability without enhancing reliability of data packets does not conclude to a desired level of network performance. To elaborate this statement, consider the significant increase in lower bound of medium access delays when WLAN air time increases from \( \mu^{-1} = 0.4 \) to \( \mu^{-1} = 0.8 \). According to this observation, instead of just protecting beacons by sending them on a less interfered channel or with a robust coding scheme, we suggest switching to a cleaner channel to improve the overall performance.

For queue stability, all generated packets in a cycle (see Fig. 2.2) should get service within the same cycle otherwise queue length goes to infinity. It means that for BAN with arrival rate of \( r_{BAN} \), those \( X_{ineligible}r_{BAN} \) packets generated and backlogged within the ineligible period of a cycle plus \( X_{eligible}r_{BAN} \) packets generated during the eligible period of that cycle should all be served throughout the eligible period of \( X_{eligible} \) seconds. Since the length of the eligible period is a function of \( BO \), for a reasonable medium access delay and support of specific arrival rates, \( BO \) is required to be configured properly.

Consider two BANs with \( BO = 4 \) and \( BO = 0 \) when WLAN traffic pattern is represented by \( \mu^{-1} = 0.7 \) and \( \lambda^{-1} = 0.3 \). According to (2.5), the BAN with \( BO = 4 \) periodically participates in contention for \( X_{eligible} = 105 \) msec and then it is excluded from data communications for \( X_{ineligible} = 573 \) msec. Given that this BAN wants to report events with the rate of \( r_{BAN} = 10 pk/sec \), its eligible period has room for transmission of only 5.2 packets out of those 6.8 packets generated every cycle. As a result, some packets
on average) remain backlogged which asymptotically lead to an unstable queue and an infinite medium access delay, as Fig. 2.6 shows. In contrast, for BAN with \( BO = 0 \), the eligible period is long enough to service all generated packets throughout the cycle and therefore, bounded delay under \( r_{BAN} = 10pk/sec \) is guaranteed.

### 2.6.2 Setting Zigbee and BCRS Configuration Parameters

This section discusses that for taking advantage of BCRS enhancement, network configuration parameters \((k\) and \(BO\)) should be set according to service requirements of the target application and traffic statistics \((\mu, \lambda)\) of the working channel.

1) **Meeting application service requirements when both \(k\) and \(BO\) are unknown**: Solving (2.5) and (2.6) subject to channel switching rate and delay requirements of the target application concludes the appropriate \(BO\) and \(k\). Suppose a coexistence scenario in which WLAN transmissions occupy half of the channel time \((P_{busy} = 0.5)\) and the average stay of WLAN in its busy state is \(\mu^{-1} = 0.7\) sec. In this coexistence situation, the NC wants to find proper configuration parameters to 1) not allow service interruption intervals longer than two seconds (i.e. \(X_{ineligible} < 2\) sec), and 2) limit channel switching rates to at most one time per minute (i.e. \(60\) sec \(\leq r_{SW}^{-1}\)).

For the explained coexistence scenario, numerical (from (2.5) and (2.6)) and simulation results for service interruptions and channel stay durations of the BAN under different settings of \(k\) and \(BO\) are represented in Fig. 2.7. Results indicate that \(BO = 5, K = 7\) is one possible solution to meet both specified application requirements.

2) **Meeting application service requirements when \(BO\) is fixed**: By applying a known \(BO\) parameter in (2.6), a proper \(k\) for meeting the switching rate constraint of the target application is calculated. Suppose NC sets the \(BO\) configuration parameter to \(BO = 6\). Also, the target application affords channel switching rates not greater than one time
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Figure 2.7: Service interruption intervals ($X_{ineligible}$) and channel stay duration ($r_{sw}^{-1} \mu$) for a coexistence scenario with $\mu^{-1} = 0.7$.

per minute (i.e. $60 \text{ sec} \leq r_{sw}^{-1} = BI.E[x]$). Given that BAN works on a channel with specifications $\mu^{-1} = 0.4 \text{ sec}$ and $P_{busy} = 0.5$, numerical and simulation results for various values of $k$ are illustrated in Fig. 2.8. Results show that one possible solution to meet that switching rate constraint is $k \geq 6$ which means that an end-device with $BO = 6$ and $k \geq 6$ stays on the mentioned working channel for at least one minute before it migrates to a cleaner channel. Fig. 2.8 also shows the total duration of losing synchronizations with the NC, i.e. $BI \cdot E[v]$, when an end-device is excluded from access to the working channel before BCRS is triggered.

2.7 Summary

Prevalence of low power and low complexity communication technologies, like IEEE 802.15.4, may contribute in realization of public m-health service with real-time monitoring capability. For such applications with timeliness and long term operability requirements, the synchronous Beacon-Enabled mode of the standard is the preferred mode in which bea-
coning strategy is applied for network synchronization. This chapter comprehensively, by experimental and analytical results, discussed that the coexistence nature of the ISM band jeopardizes beaconing performance which in turn compromises the delay requirement of an 802.15.4-based network. To mitigate service interruptions caused by the beacon corruption issue, a recovery scheme, called BCRS, is proposed for migration of an interfered network to a cleaner channel. Simulation results show that an enhancement of the standard with BCRS guarantees low-delay information exchanges if network parameters are configured based on a shared channel statistics.

Figure 2.8: BCRS behavior under different values of $k$ when $BO$ is constant
Chapter 3

Opportunistic Medium Access Control Layer Design for Body Area Networks

3.1 Introduction

Public m-health is a new medical service under intensive development, which provides unobtrusive monitoring of people’s health conditions from anywhere at any time to enable detection of deteriorating health conditions before severe discomfort or disability occur. A person wearing a BAN can freely move from home to office, street, shopping mall, etc. while his/her health condition is being continuously monitored and conveyed to a medical center. Indeed, m-health service will contribute to the goal of disease prevention and early diagnosis by allowing doctors and caregivers to have access to patients’ medical data continuously and in real-time.

Medical data typically consist of periodically-sampled body signals that have relatively low data rates. As a result, unlike other conventional wireless networks that are designed

This chapter is based on the following papers:


Chapter 3. Opportunistic Medium Access Control Layer Design for Body Area Networks

for capacity maximization, a BAN is not required to support a high throughput. In contrast, medical data should be reported to the gateway promptly and with a high PDR. Satisfaction of these requirements guarantees that sampled body signals are transmitted over a BAN to the gateway in real-time without compromise of data fidelity.

To continuously send a stream of data toward the gateway, body nodes have to have guaranteed access to the medium within a certain delay constraint. However, providing real-time connectivity over a BAN from everywhere and at anytime is challenging especially considering that body nodes are low-complexity devices that work in a very low power regime. To meet this challenge, the first factor that should be considered is the frequency band in which public m-health service is implemented.

The Federal Communications Commission (FCC) of the United States has dedicated vacant television band as the Wireless Medical Telemetry Service (WMTS) to protect medical devices from interference. However, WMTS is a regulated band confined to medical equipment within healthcare facilities. Thus, WMTS is unable to support everywhere monitoring for a seamless connectivity between a BAN and a medical center. Instead of licensed frequency bands, the license-free Medical Implant Communication Service (MICS), Ultra Wideband (UWB) and ISM bands are more suitable for use by low-cost devices for pervasive health monitoring. However, MICS is intended for communications with medicated devices implanted within the human body, whereas BANs for public m-health service generally employ on-body data transmissions [27].

ISM and UWB are suitable frequency bands that not only provide large bandwidths, but also are available everywhere to allow ubiquitous monitoring. However, BANs working in these license-free bands must share the medium with a dynamic set of coexisting wireless systems with diverse physical and MAC layer specifications, such as WLANs, Bluetooth and low-rate WPANs. These systems work independently of each other since there is no
central coordinator to manage all coexisting systems’ access to the shared medium. Thus, a BAN in competition with coexisting systems for spectrum access may not be able to promptly access the medium to send its data within the required delay constraint. To address this issue, we propose a coexistence management mechanism for BANs to improve their immunity to interference when accessing license-free bands.

The main contribution of this chapter is proposing a cognitive medium access control method called CBAS to enable ubiquitous real-time report of medical data from a BAN toward a care-center considering the low-complexity and very low power characteristics of body nodes. By opportunistic extraction of idle spaces from a pool of orthogonal channels, CBAS aims to:

- Dynamically adjust a BAN channel access pattern according to the current interference environment, and therefore improves the BAN visibility among coexistent networks.

- Reduce the queuing delay (interval between sampling and reporting of a body signal) by coping with dynamic service interruptions that result from a BAN operation in the license-free band.

- Guarantee low duty cycles for power savings in body nodes by placing most of the complexity at the gateway, which has much higher power and resource budgets.

The rest of the chapter is organized as follows: Related literature is briefly surveyed in Section 3.2. Section 3.3 provides system requirements and BAN architecture. Detailed description of CBAS and its characteristics with respect to addressing the coexistence challenge are discussed in Section 3.4. Section 3.5 models access of a BAN to a shared medium under CBAS and analyzes BAN performance in terms of delay and throughput. Performance evaluations are presented in Section 3.6. Section 3.7 summarizes this chapter.
3.2 Literature Review

In the context of BANs, several CSMA-based and time division multiple access (TDMA)-based MAC approaches have been proposed in the literature. These methods basically concentrate on energy and duty cycle constraints to minimize intra-network contention between body nodes, because they implicitly assume an interference-free medium for the BAN operation. However, this assumption may not be realistic when a BAN is operating in shared spectra under a variety of conditions.

IEEE 802.15.4 [6], a predominant standard for low-power and low-rate WPANs, is recommended by the IEEE 802.15.6 working group for BANs [7]. Under IEEE 802.15.4, working channel is statically selected by the network coordinator during the network initialization step. Two problems, resulting from specific MAC features of this standard, make real-time connectivity over BANs under question. These problems include beacon corruption and non-competitive time granularity. The former problem is resolved by the proposed recovery scheme discussed in Chapter 2. The latter arises from large back-off units of the 802.15.4 protocol and causes the WPAN to lose a noticeable portion of channel availabilities in contention with coexisting systems, like WLANs, that have smaller back-off units.

Yang Zhang et al. in [28] modified the frame structure of the 802.15.4 beacon-enabled mode to accommodate the requirements of both medical and consumer electronic applications. However, since this method is still based on the 802.15.4, it suffers from the same drawbacks as explained in [29].

Authors in [30] considered 802.11-based medical devices in WMTS band and proposed a Robust Adaptive Frequency Hopping scheme to improve communication reliability by dynamically adjusting channel hopping probabilities. However, 802.11-based devices incur heavy power consumption and may not be suitable for low-cost body sensors that should
operate for a long time on a set of batteries.

Moreover, authors in [31] experimentally investigated robustness of medical data transmission based on frequency hopping in a heterogeneous environment. Their results indicate that although medical companies envision frequency hopping as a promising candidate for wireless transmission, but this approach does not fulfill transmission reliability requirement (packet loss ratio less than 10%) of medical applications in a coexistent environment.

Authors in [32] introduce an interference-aware MAC scheme for e-health applications in a hospital environment. This scheme is implemented via two components: an inventory system and a Radio Access Controller (RAC). Regarding implementation of this proposal: 1) each service area should be equipped with those two components, 2) wireless standards employed by all coexisting systems need to be modified such that their access requests are sent to the RAC using the proposed request-to-send/clear-to-send (RTS/CTS) procedures and 3) wireless transceivers should be capable of changing their transmit power dynamically. However, all these modifications may not be practical especially for public m-health service that requires wide-area coverage.

A cognitive radio approach for telemedicine services employing secondary access to spectrum holes left vacant by primary users is considered in [33]. This is a beaconing scheme in which nodes periodically wake up at the start of each sensing period and continue listening on a channel until receiving a beacon. Such a network, as a secondary user, should confine its impact on primary user’s traffic to a specific disruption limit which is defined by the channel owner. However, nodes transmit according to the schedule they have received in the most recent beacon, regardless of the primary user’s activity. Therefore, the use of this approach in BANs for public m-health may not be appropriate due to potential service disruptions when the primary user becomes active, as well as interference from coexisting secondary systems.
As an example of TDMA approaches, authors in [34] and [35] follow the goal of reducing idle listening, collisions and overhearing by proposing TDMA structures. Note that a TDMA scheme relies on tight synchronization between nodes to provide collision-free access to the medium. Information about timeslots assigned to each node is carried by some control messages. Thus, the performance of those schemes is heavily constrained by transmission reliability of these messages. Moreover, in a multi-system coexistent environment, synchronization within a system does not prevent interference from non-cooperating collocated systems; even though a body node expects a free TDMA slot, its transmission may still collide with transmissions by other collocated systems. Authors in [36] proposed a rough BAN channel hopping scheme which is triggered by examination of the noise floor. However, operation and deployment of this idea have not been discussed.

Authors in [37] use channel information to adjust transmission parameters to mitigate fading effects around the human body. However, the proposed adaptive modulation does not address BAN throughput reduction due to coexistence and so real-time transmissions over a BAN in a shared medium may not be fulfilled.

This survey shows that there are gaps in the literature regarding the design of robust platforms for seamless transferring of medical data in a shared and non-cooperative medium. Our study in this chapter fills these gaps by proposing CBAS to improve the chance of body nodes to access a shared medium in the presence of coexisting systems.

3.3 System Architecture

3.3.1 System Requirements

M-health service improves social well-being and reduces health cost by diagnosing abnormalities in early stages. Based on this definition, an appropriate medium access scheme
needs to be designed for BANs, which addresses two basic requirements listed as follow:

1) Providing a low-delay platform for transmissions of medical data in the presence of coexistent systems while satisfying low-power and low-complexity requirements of body nodes.

Implementation of pervasive health monitoring for large groups of people requires a frequency spectrum that is available everywhere at any time. In this regard, the ISM and UWB bands are good options since they are not only always available, but also provide a pool of orthogonal channels. For instance, a BAN implemented according to the IEEE 802.15.4 standard may be configured to operate over any one of 16 orthogonal channels in the ISM band. Nevertheless, a BAN working in a license-free shared spectrum faces the coexistence problem. Thus, a robust MAC scheme should dynamically manage BAN channel access according to the current interference pattern in the shared medium. This adaptation needs to be accomplished under the constraints of low power and low processing capability of body nodes. We emphasize that for long-term continuous and pervasive monitoring, assuring low energy consumption is an important factor and so body nodes should work in a very low-power regime (less than 0.1 milliwatts). The range of these low power transmissions is limited to the body peripheral and so, inter-BAN interference would not be a concern in the context of public m-health service.

2) Capability to handle all BAN traffic categories (periodic, on-demand, emergency) satisfying their respective service requirements.

To address the above two requirements, we propose CBAS for a dynamic channel access management in a BAN. CBAS is a centralized approach where the gateway centrally makes decisions about 1) the BAN working frequency and 2) the times of packet transmissions in the BAN.
3.3.2 Architectural Design

The BAN architecture includes a gateway, usually positioned around the waist, and a number of body nodes, worn on different parts of the body. The gateway, as a hub, observes the occupancy of a pool of channels and exploits spectrum holes to cope with interference from coexisting systems, in contrast with existing BAN designs that confine the BAN operation to a single channel. BAN components are typically less than 2 meters from each other since they are positioned on a human body. Authors in [38] experimentally show that a BAN with a star topology achieves a PDR greater than 90% in diverse environments when body nodes operate with -10dBm transmission power, in the absence of interference. In the presence of collocated networks, especially those operating with much higher transmit power, it is reasonable to assume that all wireless links within a BAN are equally affected by interference and there is no differentiation between individual components or links regarding the level of interference experienced by them.

By considering the star topology [39], we can therefore focus on meeting the system-level challenge presented by coexisting systems, which is addressed in this chapter by our proposed CBAS medium access approach that improves the visibility of a BAN as a system in a shared medium. When body nodes operate with very low power (< -10dBm), one-hop connections between body nodes and the gateway may not achieve the required PDR, in which case a dynamic multi-hop scheduling is overlaid on top of CBAS to reach the PDR objective. This approach is discussed in Chapter 5.

Fig. 3.1 illustrates the configuration of a BAN. Each body node has its own unique identity (ID) and sampling rate. Note that only a small ID space is needed since a BAN includes a few body nodes. For power conservation, body nodes enter the low-power sleep mode when they are not exchanging data with the gateway. We consider that body nodes are equipped with passive Radio Frequency (RF) modules [40–42] that allow them to
receive commands from the gateway and process them when they are asleep.

In our system design, the gateway is equipped with two radios, one supporting transmis-
sions based on the 802.15.4 WPAN physical layer, and the other supporting transmissions
at high power using IEEE 802.11. The gateway has access to a pool of $h$ orthogonal
channels and has the ability to instantaneously sense states of all channels in the channel
pool. In line with other work [22], channel sensing is assumed to be perfect. Since states
of channels are the same from the viewpoint of the gateway and body nodes, the gateway
explores available channels on behalf of body nodes. Therefore, if channel $x$ is perceived as
idle by the gateway, it is also idle in vicinity of all nodes and thus it can be reliably used for
communications between the gateway and a node. In this respect, the “hidden-terminal”
problem is not an issue as the same channel states are seen by all BAN components.

3.4 Centralized BAN Access Scheme

3.4.1 Justification Behind the CBAS

Since body nodes transmit in low power, they are usually unable to force high power inter-
ferers such as WLANs to respect traffic requirements of a BAN through channel sensing.
Thus, access of nodes is generally restricted to unused spaces of the spectrum that re-
main between transmissions of high-powered coexistent networks. These unused spaces are scattered over time because traffic of collocated systems generally does not have a predictable pattern. As a consequence, access of nodes to the shared medium is intermittently fragmented over time and faces unpredictable interruptions on a specific channel.

```
(a) CH1
(b) CH2
(c) CH3
(d) Virtual-CH
```

Figure 3.2: (a-b-c) Channel access pattern, (d) Virtual-CH resulted from the pool of \{CH1, CH2, CH3\}

To illustrate this problem, suppose there is a pool of three orthogonal channels, \{CH1, CH2, CH3\}, while collocated networks occupy them as shown in Fig. 3.2(a-b-c). BAN is tuned to CH1 and its access to the shared medium is excluded in the dashed parts of Fig.3.2(a). However, if at the time of service interruption on CH1, the BAN is tuned to another available channel (like CH2 or CH3), the capacity of the shared medium expands to un-shaded spaces of the Virtual-CH in Fig.3.2(d).

In a nutshell, a BAN that is statically assigned to work on a single channel all the time, like an 802.15.4-based BAN, loses a lot of chance for channel access because of the activities of coexistent systems and so medical data faces unpredictable delays before they get transmitted. However, by capturing idle spaces from a pool of channels, channel access opportunities are potentially enhanced and consequently BAN data experiences less queuing delays.

The proposed CBAS in the following part is designed to operate under the assumption that a dedicated CCH is available for exchange of control information such as channel
assignment broadcasts and access requests between the gateway and body nodes. In the 3-10 GHz UWB band, the CCH can be realized using a long spreading code to minimize interference from and to other coexisting systems [43]. In the 2.4 GHz ISM band, where interference from high power WLAN transmissions is dominant, the CCH can be implemented using the part of the spectrum that is not occupied by WLANs. For instance, channels 13 and 14 of IEEE 802.11 WLANs operating in the 2.4 GHz ISM band are not used by most WLAN devices in North America [23] due to transmit power restrictions. Therefore, WPAN channels 25 or 26 would be free of WLAN interference and can be used as the CCH. Although this choice protects the control channel from IEEE 802.11 WLAN interference, IEEE 802.15.1 or 802.15.4 WPANs may still interfere with the CCH. However, WPANs generally have much lower transmission power, so that interference from these systems is less of a concern. Thus in all cases, the realization of a dedicated CCH supporting highly reliable transmissions of control messages seems feasible.

3.4.2 CBAS

To meet delay requirements of a BAN in a shared medium, CBAS, formally presented in Procedure 3.1, is designed to operate as follow:

- During normal operations, the gateway continuously senses all channels in the pool of candidate channels to detect those that are unoccupied, as well as idle spaces that occur between transmissions of collocated networks in the occupied channels.

- Based on the traffic requirements and the sensed channel states, the gateway assigns the white-spaces as transmission slots to the body nodes. It is possible that more than one channel is perceived as idle by the gateway. If so, one of the available channels is chosen based on the specific channel selection strategy that the gateway follows. A channel selection scheme for QoS provisioning is discussed in Chapter 6.
As the other scheme, the gateway may choose and remain tuned to an idle channel until it becomes unavailable or degraded due to activities of coexisting systems. Alternatively, the gateway may choose a channel based on the history extracted from the quality of that channel within predefined intervals. In addition, an appropriate strategy considers that each WLAN channel has a width of four 802.15.4 channels and so, if the BAN is based on 802.15.4 channels, channels furthest-away from a busy channel are more suitable candidates since adjacent WPAN channels experience strongly correlated link qualities as experimentally investigated in [44].

- The gateway sends an RTS (as per the 802.11 protocol) on the WLAN channel that overlaps with the allocated channel using its 802.11 radio. The RTS specifies an appropriate reservation time, $T$, that represents the duration of a complete data transmission over the BAN. Afterward, the gateway allocates the extracted transmission slot to the next scheduled body node by sending a command on the CCH. The gateway, as a device with relaxed energy constraints, sends the command with a higher power so that it is delivered to all body nodes with a high probability of success (e.g., 99%). The command includes the ID of the target node plus information about the channel chosen for data transmission. Scheduling is done based on the knowledge of the gateway about sampling rates of nodes.

- The passive RF module of the target node, upon matching its ID to that in the command sent by the gateway over the CCH, wakes up the body node to process the command and begin packet transmission.

- The target body node switches to the assigned channel and exchanges data with the gateway on that channel. When data transmission is finished, the body node tunes its radio to the CCH and returns to the sleep mode. Note that channel switching cost
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Opportunistic Medium Access Control Layer Design for Body Area Networks

**Procedure 3.1 Centralized BAN Access Scheme**

1. Gateway continuously monitors availability of channels in the BAN channel pool and updates
   the list of available channels.
2. **Repeat:**
3.  **While** (list of available channels is not empty){
4.  Gateway selects one of the channels from the list, e.g., $CH_x$.
5.  Gateway selects one of the body nodes, as the target node, based on its specific scheduling
    algorithm.
6.  Gateway sets transmission duration, $T$, in an RTS message and sends it with high power
    over WLAN channel overlapping $CH_x$.
7.  Gateway sends a command of triple $<ID$ of the target node, $CH_x$, $T> \text{ on CCH.}$
8.  All body nodes except the target node ignore the command.
9.  The target body node tunes its radio to $CH_x$ and starts its transmission for $T$ seconds.
10. After $T$ seconds, the target node tunes its transceiver to CCH and goes to the sleep
    mode.  }

is not a problem since the widely used transceivers for short range and low power
WPANs, e.g., TI CC2420 and the more recent CC2500, have channel switching times
of only $300\mu \text{sec}$ and $90\mu \text{sec}$, respectively \[45\].

Due to the centralized operation of a BAN under the control of the gateway as described
above, only one body node exchanges data with the gateway over the assigned channel at
any time slot. Since nodes do not contend for data transmissions, and channel state sensing
is performed centrally by the gateway, the fact that some body nodes do not overhear the
transmissions of others, i.e., they are “hidden nodes” relative to other body nodes, does
not present a problem as long as all nodes can exchange data with the gateway.
3.4.3 Characteristics and Features of CBAS

This section presents some important characteristics and features of CBAS, especially with regard to how CBAS addresses the system requirements mentioned in Sec. 3.3.1.

1. **CBAS properly services all three categories of periodic, on-demand and emergency data.**

   For serving periodic data, gateway allocates extracted transmission opportunities to body nodes based on the nodes’ sampling rates. For serving on-demand traffic, when the gateway requires measurements from a specific body node, it simply assigns the first available white-space to that body node and commands it to initiate a transmission.

   In emergency situations, when a body node has collected sampled data that is out of range, it increases its sampling rate within a specific interval and informs the gateway by sending a request through the CCH. Once the gateway receives the emergency request and finds a transmission opportunity, it assigns the channel to the requesting body node faced with out-of-range data. By transmitting emergency data with a minimum delay, medical staff can address the situation right away before the patient’s condition worsens.

2. **CBAS addresses energy conservation requirement of BANs.**

   Since sensing of channels, finding available channels and assigning spectrum holes to body nodes are all performed by the gateway centrally, CBAS saves body nodes from energy-consuming procedures by concentrating all the complexities at the gateway side. Furthermore, by incorporating passive RF modules in the body nodes, they do not waste their precious energy on idle listening. Passive RF modules bring the benefit of energy harvesting and no quiescent power consumption from the battery when a body node is waiting for the next command. In other words, although a body node has no knowledge about when the gateway will transmit a command, it does not need to spend energy on listening to the CCH all the time. When a command arrives in the CCH, the passive RF
module recovers energy from the command to decode it and wakes up the body node to further process the command, if its ID matches that of the node. These features make CBAS an energy efficient access scheme that prolongs BAN life time.

3. CBAS protects low power transmissions of body nodes from being perceived as noise by collocated systems, mitigating the problem that body nodes are “hidden nodes” with respect to collocated systems.

WLANs are CSMA-based wireless systems that employ a CCA scheme to check the availability of the medium before capturing it. CCA is a conservative approach to reduce collisions between systems with access to the same shared medium. As it is likely that a BAN operates in a shared medium with coexistent CSMA-based systems, these systems are expected to defer their contention for capturing the shared medium when the BAN is active. This expectation is mostly satisfied by coexisting low power WPANs, such as those employing the IEEE 802.15.4 standard, as their transmission power levels are similar to that of the BAN. Thus, CCA works in a reciprocal manner and ongoing BAN transmissions are less likely to be interfered by low power WPANs. However, the problem of uneven channel perception occurs between the BAN and coexisting networks employing higher power levels [46]. The big difference in the BAN and coexisting network’s transmit power means that the high-power interferers’ CCA may sense a clear channel while a BAN transmission is in progress. In essence, all BAN nodes are hidden from the interfering system. This problem penalizes the BAN and makes energy-based CCAs insufficient for detecting channel occupancy and avoiding collision in a heterogeneous wireless environment.

Specifically, high transmit power levels plus high CCA thresholds of IEEE 802.11 WLANs seriously threaten low power BAN transmissions, which may be hidden from WLANs, i.e., treated by WLANs as noise and ignored. Consequently, the protection of
BAN packets from potentially coexisting 802.11 systems is necessary. To accomplish this, we exploit the possibility of implementing the gateway in contemporary portable computing devices supporting multiple radio interfaces, such as smart phones. When the gateway decides on the allocation of a specific available channel to a body node, it sends an RTS with high power on the overlapping WLAN channel according to the 802.11 standard before sending a command through the CCH. The RTS includes the expected duration of the data exchange between the gateway and the body node, which is specified as $T$ in Procedure 3.1. All 802.11 stations receiving the RTS, set their Network Allocation Vector (NAV) with the announced duration and defer their channel access for the NAV period. Consequently, the BAN transmission would be free of interference from coexisting WLANs.

4. **CBAS addresses the “hidden node” problem.**

Since CBAS share the license-free spectrum with coexisting systems by CCA or carrier-sensing capability, the presence of “hidden nodes” is an issue that needs to be discussed explicitly. There are three possible cases of “hidden nodes”, which are addressed by CBAS as follow:

- BAN nodes are hidden from each other: since CBAS operate under centralized control of the gateway, this case does not present a problem since the gateway has a good connection with all body nodes and so when a command is launched, only the target body node that has been addressed over the CCH responds to the command. Indeed, it is not possible that two body nodes simultaneously send data over an assigned channel and so the BAN never experiences this hidden node problem under CBAS.

- BAN nodes are hidden from outside networks: CBAS addresses this problem by employing multiple radios in the gateway. In CBAS, the gateway sends RTS frames to reserve channel time on behalf of the BAN, which keep the channel free of interference
from the moment that an RTS is transmitted till the target node finishes its data exchange. Thus, the BAN as one entity is no longer hidden from the outside network.

- Outside nodes are hidden from some BAN nodes but not others: BAN nodes are typically much closer to the gateway than outside nodes, so we may assume that all body nodes are subject to the same level of interference from (high-power) outside nodes. This is true considering the fact that WLANs are the main source of interference from coexisting systems in the ISM band. The same assumption is also used in [22] for a Bluetooth system coexisting with WLANs. Therefore this hidden node problem does not affect CBAS since the gateway senses the transmissions from outside nodes on behalf of all body nodes.

### 3.5 Theoretical Analysis

By extracting idle spaces from a group of orthogonal candidate channels, CBAS provides a Virtual-CH to the BAN with much expanded access availabilities as illustrated in Fig. 3.2(d). This part gives an analysis of the channel occupation statistics of the Virtual-CH and CBAS performance based on the following assumptions:

#### 3.5.1 Assumptions

- Low-rate and low-power transmissions of body nodes do not change access pattern of coexisting systems contending on a shared channel. This implicitly means that BAN operation is restricted to unused spaces that remain between transmissions of more powerful (in terms of data rate and energy) coexistent systems such as WLANs.

- Each candidate channel in the channel pool alternates between the busy state in which it is occupied by a coexistent system’s transmission, and the idle state when no coexistent system is accessing the channel. The BAN is restricted to accessing
candidate channels that are in the idle state.

- Transitions of a candidate channel $i$ between idle and busy states are modeled by a two state Markov Chain. A channel remains in busy (idle) state for a random length of time with negative exponential distributions with parameters $\mu$ ($\lambda$). This assumption is also used in [48]. Therefore, the probability that channel $i$ is found busy or idle at any time instant would be:

$$
P_{busy}^i = \frac{\lambda}{\lambda + \mu}, \quad P_{idle}^i = \frac{\mu}{\lambda + \mu}
$$

(3.1)

- The state transitions and statistical behaviors of the candidate channels are independent and identically distributed (i.i.d.). This implies that each candidate channel overlaps with a different set of coexistent systems.

- BAN packet length is $L$ Bytes and transmission rate is $R$ bits/sec. It leads to the packet air-time of $T = \frac{8L}{R}$ sec.

### 3.5.2 Evolution of Channel Pool Status

According to CBAS, BAN has access to a medium as long as one of $h$ candidate channels is found idle by the gateway and it loses its access when all $h$ candidate channels become busy due to activities of coexisting systems. Thus, the BAN’s operation is described by two states: the active and inactive states, between which the BAN transits from time to time. The inactive state occurs with probability $P_{inactive} = \prod_{i=1}^{h} P_{busy}^i$. In this state, the BAN operation is stalled and its service is interrupted since there is no channel available for capturing by the gateway. When at least one out of $h$ channels becomes idle, which occurs with probability $P_{active} = 1 - \prod_{i=1}^{h} P_{busy}^i$, the BAN transits to the active state and its service is resumed.
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To evaluate how the BAN’s operational state evolves under a pool of \( h \) candidate channels, we define process \( \{Y(t), t \geq 0\} \) and the BAN’s state space \( S = \{y|0 \leq y \leq h\} \). At time \( t \), process \( Y(t) \) is in state \( y \) if and only if the instantaneous number of idle channels is \( y \). Inactive periods are represented by the time intervals when the BAN is in state \( (y = 0) \); i.e., when all of the \( h \) channels are busy. Active periods include all remaining states with \( 0 < y \leq h \).

Suppose that the system is in a general state \( y \) while idle channel \( i \) remains idle for \( I_i \) time units, \( i = 1, ..., y \) and each busy channel \( j \) stays busy for \( B_j \) time units, \( j = 1, ..., (h - y) \). Since channels evolve independently, process \( Y(t) \) leaves state \( y \) as soon as one of \( h \) channels changes its status, i.e., a busy channel turns idle or an idle channel turns busy. Since the system is memoryless, the holding time in state \( y \) is determined by the minimum of \( y \) and \( h - y \) exponential random variables with parameters \( \lambda \) and \( \mu \) respectively, i.e. \( \min(I_1, ..., I_y, B_1, ..., B_{(h-y)}) \). As a result, the sojourn time of state \( y \) is an exponential random variable with parameter \( \lambda_y = y\lambda + (h - y)\mu \). Indeed, \( \lambda_y \) is the flow rate for the system out of state \( y \). After leaving state \( y \), the system evolves to:

1. state \((y + 1)\) where the number of idle channels increases by one. This transition from state \( y \) to \( y + 1 \) happens if \( \min(B_1, B_2, ..., B_{(h-y)}) < \min(I_1, I_2, ..., I_y) \) which occurs with probability \( P_{(y,y+1)} = \frac{(h-y)\mu}{y\lambda + (h-y)\mu} \). Or otherwise to

2. state \((y - 1)\) where the number of busy channels increases by one. This transition from state \( y \) to \( y - 1 \) happens if \( \min(I_1, I_2, ..., I_y) < \min(B_1, B_2, ..., B_{(h-y)}) \) which occurs with probability \( P_{(y,y-1)} = \frac{y\lambda}{y\lambda + (h-y)\mu} \).

According to this argument, there is a sequence of i.i.d. exponentially distributed random variables with parameters \( \{\lambda_y|y \in S\} \) that governs sojourn times of each state. To summarize, the evolution of a channel pool with \( h \) candidate channels is modeled by a
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CTMC. Proved in [49], parameter $\lambda_y P_{(y,y')}$ represents the flow rate of probability leaving state $y$ and heading toward $y'$. Consequently, $P_{(y,y+1)} \lambda_y$ and $P_{(y,y-1)} \lambda_y$ are transition rates directed toward state $y+1$ and $y-1$ respectively as illustrated in Fig. 3.3.

![Figure 3.3: Evolution of a pool of $h$ channels as a CTMC](image)

3.5.3 Active and Inactive Periods

Fig. 3.4 illustrates the availability of the Virtual-CH over time, which is composed of cycles where each cycle includes one inactive period followed by one active period. Clearly, the average duration of these two periods, represented by $X_{inactive}$ and $X_{active}$, determines how often BAN service is interrupted.

![Figure 3.4: Illustration of active and inactive periods](image)

To estimate $X_{active}$, note that from inactive period, i.e., state $(y = 0)$, the next transition is always to state $(y = 1)$. As a result, the expected hitting time of state $(y = 0)$ starting from the initial state $(y = 1)$ represents the average time between two consecutive inactive periods. To estimate this hitting time and consequently $X_{active}$, the following proposition from [49] is used.

**Proposition:**
Define the generator matrix $A$ of a CTMC by:

$$A_{ij} = \begin{cases} -\lambda_i & \text{if } i = j \\ \lambda_i P_{ij} & \text{if } i \neq j \end{cases}$$

where $P = (P_{ij})$ is the transition matrix.

Define matrix $B$ as:

$$B = (A_{ik}, i \neq j, k \neq j)$$

The column vector of expected hitting times of state $j$ starting from state $i \neq j$ can be calculated as:

$$t = (-B)^{-1} \mathbf{1}$$

where $\mathbf{1}$ is a column vector of 1’s.

By definition of $i$ and $j$ as states ($y = 1$) and ($y = 0$), the hitting time from $i$ to $j$ gives the average of active period, $X_{\text{active}}$, which is expanded from the moment that inactive period finishes until $Y(t)$ again transits to the consecutive inactive period. Inactive period includes only one state ($y = 0$) and the sojourn time of this state is exponentially distributed with parameter $\lambda_0 = h\mu$ which brings the average of inactive periods as

$$X_{\text{inactive}} = \frac{1}{h\mu}.$$  

Fig. 3.5 illustrates resultant $X_{\text{active}}$ and $X_{\text{inactive}}$ from the above derivations when $T = 15\text{msec}$. To model candidate channels with different channel access patterns, $\lambda$ in (3.1) is fixed and $\mu$ is varied over a wide range of values. On one hand the results give an insight into how often the Virtual-CH becomes unavailable and consequently BAN access to the medium is interrupted by collocated networks, and on the other hand they show
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how a smoother service with fewer fragmentation is offered to a BAN when the gateway opportunistically access a larger set of candidate channels.

For instance, when each candidate channel $i$ is characterized by $(\lambda^{-1} = 1, \mu^{-1} = 1)$, a BAN tuned to a single channel suffers from interruptions of 1 sec after a 1 sec active period, on average. These service interruptions are reduced to 0.15 sec after an expanded active period of 4 sec when the size of the channel pool is increased to four.

3.5.4 Upper Bound for BAN Arrival Rate under CBAS

The average throughput of a BAN ($\overline{b_{BAN}}$) is the average number of BAN packets serviced per unit time. $\overline{b_{BAN}}$ can be obtained as the ratio between the number of packets serviced over some time interval when this interval is very long. In a stable system, the average rate of arrivals should not exceed the average rate of departures in the long term. Therefore, the value of $\overline{b_{BAN}}$ indicates the maximum BAN arrival rate that can be supported under CBAS and a pool of $h$ channels with specification $P^i_{busy}, i \in \{1, 2, ..., h\}$.

The cyclic behavior of the Virtual-CH in the time domain as shown in Fig. 3.4 introduces a renewal process in which the cycles renew themselves over time. The duration of each cycle is represent by random variable $Z = X_{active} + X_{inactive}$. As a result of this modeling, $\overline{b_{BAN}}$ is estimated with the help of the Renewal-Reward Theorem [50] as follows.

Define:

- $R_j$ as the reward associated with cycle $Z_j$. $R_j$ is a sequence of i.i.d. random variables where $R_j$ is independent of $\{Z_i : i \neq j\}$ although $R_j$ may depend on $Z_j$.

- $M(t)$ as the number of cycles that have occurred by epoch $t \geq 0$.

- $C(t)$ as the cumulative reward by epoch $t$, i.e., $C(t) = \sum_{j=1}^{M(t)} R_j$ and $c(t) = E\{C(t)\}$. 

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Figure 3.5: \( \overline{X}_{\text{active}} \) and \( \overline{X}_{\text{active}} \) under a diverse setting of channels

\[ \lambda = 0.1 \]

\[ \lambda = 1 \]

\[ \lambda = 10 \]
Renewal-Reward Theorem says that when \( E[|R_j|] < \infty \) and \( E[Z_j] > 0 \),

\[
\lim_{t \to \infty} \frac{C(t)}{t} = \frac{E[R_j]}{E[Z_j]}, \quad \lim_{t \to \infty} \frac{c(t)}{t} = \frac{E[R_j]}{E[Z_j]}
\]

To apply the Renewal-Reward Theorem in the context of CBAS, suppose \( Z_j \) is the \( j \)th cycle and \( R_j \) is the number of BAN packets serviced in cycle \( Z_j \) while:

\[
E[R_j] = \frac{X_{active}}{T}, \quad E[Z_j] = X_{active} + X_{inactive}
\]

therefore, the number of serviced packets per unit time is the expected total number of packets serviced per cycle divided by the expected cycle length, i.e., \( \bar{b}_{BAN} = \frac{E[R_j]}{E[Z_j]} \). Results of \( \bar{b}_{BAN} \) in Fig. 3.6 indicate the upper bound of BAN arrival rate that can be serviced under CBAS when \( T = 15 \text{msec} \).

### 3.5.5 BAN Queuing-Delay Analysis

The above analysis is provided to answer how promptly BAN packets get service under CBAS and a pool of \( h \) channels with specification \( P_{busy}^i \). Or in other words, how large a channel pool is required to reach a specific level of delay and throughput for BAN packets.

This part answers this question by modeling the CBAS framework as an M/G/1 pre-emptive resume priority queue with two priority classes. Inactive periods represent durations that privileged packets (from high-power coexisting systems), i.e., class 1, with the highest priority are in transmissions. BAN packets have the lowest priority and are
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![Figure 3.6: Maximum achievable BAN throughput under CBAS](image)

Figure 3.6: Maximum achievable BAN throughput under CBAS

designated as class 2, which get service during active periods that no packet from class 1 exists. These two priority classes have the following specifications:

**Arrival rate of class 1** ($r_1$): to find the average arrival rate of class 1, two different approaches exist:

1) Since packets from class 1 arrive once per cycle, $r_1$ is estimated by $r_1 = \frac{1}{\tau_{active} + \tau_{inactive}}$.

2) Since $r_1$ is the rate of transition from active period to inactive period, we partition the state space of the CTMC to $A$ as the set of all states with at least one idle channel and $A^c$ as the only state ($y = 0$). The rate from inactive period ($A^c$) to active period ($A$) equals to $\eta(0) \times h\mu$ where $\eta(0) = P_{inactive}$ is the stationary distribution of state ($y = 0$). Also, for a positive irreducible Markov chain, the rate from $A$ to $A^c$ is equal to rate from $A^c$ to $A$ [30]. In this regard, the arrival rate of class 1 is expressed by:

$$r_1 = \text{rate from } A \text{ to } A^c = \text{rate from } A^c \text{ to } A = P_{inactive} \times h\mu$$

Both approaches yield the same value for $r_1$.

**Service time of class 1**: the first two moments of service time of class 1 are denoted.
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\[ E[X_1] = \frac{1}{h\mu} \quad \text{and} \quad E[X_1^2] = 2E[X_1]^2 \quad \text{because the sojourn time of the inactive period is exponentially distributed with parameter } h\mu. \] Finally, the percentage of time that channel is occupied by class 1 is \( \rho_1 = P_{\text{inactive}}. \)

**Arrival rate of class 2** \((r_2):\) BAN arrival rate is assumed to be Poisson with parameter \( r_2. \)

**Service time of class 2:** the service time distribution for BAN packets is assumed to be deterministic. Then the first and second moment of BAN service time is \( E[X_2] = T \) and \( E[X_2^2] = E[X_2]^2 = T^2. \) It provides \( \rho_2 = r_2T \) as the percentage of time that medium is occupied by BAN transmissions.

Now according to the M/G/1 preemptive queue formulas, the average of queuing-delay of BAN packets is approximated by:

\[
W_2 = \frac{E[X_2]}{1 - \rho_1} + \frac{r_1E[X_1^2] + r_2E[X_2^2]}{2(1 - \rho_1)(1 - \rho_1 - \rho_2)} \quad (3.2)
\]

The relation between \( W_2 \) and different settings of channels for \( T = 15\text{msec} \) is presented in Fig. 3.7. Consider for instance that BAN packets expire after 1sec. This constraint, \( W_2 < 1\text{sec}.;\)

- under \( P_{\text{busy}}^i = 0.6, h = 2 \) is met if BAN average arrival rate is bounded to \( r_2 < 28 \text{pk/sec}. \) This bound is relaxed to \( r_2 < 45 \text{pk/sec} \) when the channel pool size increases to \( h = 3. \)

- under \( P_{\text{busy}}^i = 0.8, h = 2 \) is not met. However, under a larger set of candidate channels, say \( h = 3, \) this requirement is satisfied for \( r_2 < 12 \text{pk/sec}. \)
3.6 Performance Evaluations

This section evaluates the maximum arrival rates and average BAN queuing-delays achieved under CBAS by simulations, and shows how accurately the analysis in Sec. 3.5 matches the simulation results.

3.6.1 Simulation Settings

We consider a BAN operating in a coexistence medium (like 2.4 GHz ISM band) while the gateway utilizes a subset of $h$ channels to service sampled medical data. Body nodes work according to the IEEE 802.15.4 PHY layer and their transmission rate is $R = 250$ Kbps. The simulator is written in Python and simulations are performed on a dual core desktop computer. In these sets of simulations, when an idle channel is found, the gateway reserves it for $T = 15msec$ and so the maximum length of a BAN packet is bounded to $L \leq 469$ Bytes. As also confirmed in Python documentations, this is the minimum interval that can be implemented under a standard desktop operating system. In other words, gateway updates its knowledge about the status of each candidate channel every $15msec$, which is
the finest obtainable time granularity for the simulation platform.

Each of \( h \) candidate channels transits between idle and busy states with time intervals that are exponentially distributed with parameters \( \lambda \) and \( \mu \). Busy durations represent intervals in which collocated systems like WLANs are in operation. The gateway captures the medium for BAN access when a channel is in the idle state. By changing \( \lambda \) and \( \mu \), BAN is subject to different levels of interference from coexistent networks.

It is worth repeating that as a result of the uneven channel perception issue [46], the effect of low-power interference (like WPAN transmissions) on a collocated WLAN is an increment of the WLAN packet error rate. It implies that BAN transmissions do not change the WLAN’s channel access rate [22] or equivalently \( \lambda \) and \( \mu \) as the parameters of a candidate channel.

## 3.6.2 Performance Metrics and Channel Pool Size

This part on one hand evaluates the accuracy of the theoretical results in Sec. 3.5.5 in modeling the system as a preemptive queue with two priority classes. On the other hand, it elaborates on how the channel pool size affects BAN performance metrics.

Fig.3.8 illustrates queuing-delays from simulations and (3.2) when each candidate channel \( i \) is characterized by \( (\lambda^{-1} = 0.5, \mu^{-1} = 0.5) \). To elaborate on this figure, suppose the average arrival rate is \( r_2 = 25 \) pk/sec while each BAN packet is at most 469 Bytes. Under this setting, the average queuing-delay significantly reduces from 4 sec to 80 msec when the size of the channel pool increase from \( h = 1 \) to \( h = 3 \). Results confirm that expanding the channel pool size allows a BAN to have higher sampling (arrival) rates and also offers a better service (lower packet delays) to a BAN.

The figure also shows that except for very high arrival rates, the theoretical and simulation results are very close, which show that the preemptive queuing model is a good
approximation to system behavior except when the system is heavily congested. As traffic requirements for different biomedical applications in Table 1.1 show, BANs typically do not operate under heavy traffic congestion due to latency requirements and so it is reasonable for system designers or the decision-making entity incorporating in the gateway to utilize the theoretical model to find the maximum BAN arrival rates (by estimating $b_{BAN}$) and BAN queuing-delays (from (3.2)) under different settings of channel pool.

Figure 3.8: Effect of the channel pool size on BAN packet delays, $\lambda^{-1} = \mu^{-1} = 0.5$

### 3.6.3 Channel Pool Size

This part illustrates the application of (3.2) to help the gateway decide on the appropriate size of the channel pool based on 1) the occupancy statistics of candidate channels and 2) BAN traffic requirements in terms of arrival rate and transmission deadlines.

For illustration, suppose the gateway is responsible to find white-spaces for its body nodes with average arrival rate $r_2 = 30$ pk/sec while each BAN packet expires after 2 sec. Note that in our simulation setting, 30 pk/sec is equivalent to at most 112.5 Kbit/sec. The gateway also estimates the average of idle and busy duration of candidate channels to $\lambda^{-1}$ and $\mu^{-1}$ sec. Subject to these traffic requirements and perceived channel statistics, the gateway applies (3.2) to find the minimum required size of the channel pool, i.e., $h$. Finding the minimum set is important since there is a tradeoff between the size of the
channel pool, BAN performance metrics (delay and throughput) and complexities imposed to the gateway by sensing a larger set of channels.

Solving $W_2 < 2\text{sec}$ given the settings of $(\lambda^{-1}, \mu^{-1})$ leads to the following results:

- $h = 1$ channel when the estimated setting is $(\lambda^{-1} = 0.6, \mu^{-1} = 0.4)$.
- $h = 2$ channels when the estimated setting is $(\lambda^{-1} = 0.4, \mu^{-1} = 0.6)$.
- $h = 3$ channels when the estimated setting is $(\lambda^{-1} = 0.3, \mu^{-1} = 0.7)$.
- $h = 4$ channels when the estimated setting is $(\lambda^{-1} = 0.2, \mu^{-1} = 0.8)$.

BAN queuing-delays for the above options are illustrated in Fig. 3.9. All these sets of channel pools provide a Virtual-CH with $P_{active} \sim 60\%-65\%$.

3.7 Summary

Public m-health is under active development for pervasive health monitoring to enable early disease detection and prediction. To support everywhere and any time observation of body vital signs, the use of license-exempt spectra is necessary. However, the shared nature of these bands leads to unpredictable service interruptions due to interference from coexisting systems that have higher transmission power and data rates than a BAN. In this chapter we have tried to address this challenge by taking advantage of a large channel pool that unlicensed ISM band and UWB support by proposing the CBAS, an opportunistic MAC where the cognitive gateway senses for free spectrum and assigns extracted white-spaces to body nodes for dissemination of monitored physiological signals. Performance analysis of a BAN under CBAS provided to illustrate how the channel pool size may be tailored according to the channel statistics, delay and throughput requirements of a BAN. Performance evaluations confirm that BAN service disruptions are significantly reduced.
when BAN is dynamically tuned to a set of channels while no processing overhead is imposed on low complexity body nodes. We believe that adoption of the proposed CBAS to improve BAN service robustness will take one big step forward toward the realization of public m-health.
Chapter 4

Feasibility of Dynamic Spectrum Access for Pervasive Monitoring in ISM Band

4.1 Introduction

Seamless report of medical data over a BAN demands a frequency band with no spatial or temporal access constraints. The unlicensed ISM band meets these requirements since this band not only provides large bandwidths, but also is available everywhere with little access constraints. However, the ISM frequency band is shared by wireless networks such as Bluetooth, low-rate/low-power WPANs and IEEE 802.11 WLANs. Differences among transmission power and S/I threshold of diverse wireless technologies lead to asymmetric mutual interference and unequal carrier sensing abilities. These uncoordinated parameters along with the lack of central authority to manage and schedule channel access result in different levels of medium access priority experienced by these heterogeneous networks.

For instance, in a WLAN/WPAN coexistence scenario, WPAN transmissions are vulnerable to corruption by coexisting WLAN transmissions while WLAN packets are generally not affected [19]. More aggressive MAC behavior, higher transmit power and finer

This chapter is based on the following paper:
timer granularity give WLAN an advantage over WPAN in a shared spectrum such that WPAN is handicapped by coexisting WLAN \[29\]. Typically, successful WPAN communications are confined to unused spaces (white-spaces) of the spectrum that remain between transmissions of WLANs. These spectrum holes are usually scattered over time and do not have a predictable pattern. Consequently, when new data arrive, a WPAN may not promptly access the medium and its communications suffer from large delays. To address this issue, an opportunistic MAC scheme for dynamic spectrum access is beneficial for low power devices operating in the ISM band. The idea is that devices in such networks use frequency agile radios to dynamically change their operating frequencies to where white-spaces are found in order to achieve a better communication performance (in terms of delay, packet delivery ratio, etc.), in the same manner as a cognitive radio network employing overlay dynamic spectrum access \[51, 54\].

To support this dynamic spectrum access capability, devices actively probe the entire spectrum and find white-spaces that are orthogonal to the existing transmissions in frequency and/or time. Utilization of white-spaces, occurring at different parts of the spectrum over time, allow low power WPANs to access the shared ISM band more promptly and achieve a lower transmission latency in the presence of more powerful networks such as WLANs \[11\].

The feasibility of applying such an opportunistic MAC scheme, based on dynamic spectrum access, for WPANs, depends on the answer to the following important question:

“How frequently white-spaces with sufficient bandwidth occur on the ISM band and whether this occurrence frequency is sufficient for real-time and low-latency access of the target application to the ISM band?”

The main contribution of this chapter is answering this question along with proposing a sensing algorithm that improves the robustness of white-space detection. The correspond-
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The discussion is organized in two parts:

1) Spectrum sensing over ISM band: A suitable spectrum sensing approach over the ISM band is required to detect locally available white-spaces as possible candidates for dynamic spectrum access. In Section 4.2, performance of two well-known spectrum sensing approaches are evaluated on a SDR platform on ISM band and then improvements over these approaches are proposed as the dual-spectrum-sensing strategy which offers more precise spectrum sensing results. In a SDR, major parts of the frequency scanning and signal processing tasks are performed by software instead of the application specific hardware. In this study, the open-sourced GNU Radio is used as the SDR platform, with the Universal Software Radio Peripheral (USRP) N200 incorporating the RFX2400 ISM band radio front-end, which work together to sample the entire 2.4 GHz spectrum and convert to digital data for processing by the GNU radio.

2) Detection of target white-spaces: The objective is to identify usable white-spaces in the ISM band that match the bandwidth requirements and traffic demands of a specific application. Since networks with diverse physical and MAC layer protocols share the ISM band, the set of running applications over time is dynamic which consequently leaves a highly fragmented available spectrum. As a result, although fine-grain usage traces of 20MHz to 6GHz spectrum range show that on average 54% of the spectrum is never used and 26% is only partially used, this information does not give the percentage of available fragments with the minimum contiguous bandwidth required by the application. We present field test results in Section 4.3 to evaluate the occurrence frequency of target white-spaces for a frequency agile WPAN. These tests involve running our proposed dual-spectrum-sensing strategy at different public places to identify target white-spaces and then investigate whether they occur frequent enough to guarantee a WPAN timely access to the ISM band. A target white-space is an unoccupied part of the spectrum that exceeds or
equals the minimum bandwidth required by the application.

4.2 Spectrum Sensing Strategy

In this section, two well-discussed spectrum sensing approaches, the power-threshold [58] and edge-sensing [59], are tested over the 2.4GHz ISM band. By considering deficiencies of these approaches, a set of enhancements are proposed to improve their functionality in a heterogeneous medium like the ISM band.

4.2.1 Power-threshold Spectrum Sensing

The power-threshold method compares the power at each narrow slice in the spectrum against a fixed threshold value. In parts of the spectrum in which the detected power is greater than the threshold, the spectrum is marked as occupied. Decision making based only on a fixed threshold makes this scheme easy to implement but unreliable from two aspects:

1) correctly identifying the start and the end of the occupied spectrum that usually are sharp rise/fall edges. For instance, in Fig.4.1, the method inefficiently detects only parts of the range from 2410MHz to 2420MHz as occupied.

2) properly handling high variations in power levels which causes the predication to swing between occupied/idle. In Fig.4.2, although spectrum is occupied from 2429MHz to 2443MHz, the method detects this range as idle → occupied → idle → occupied → idle. In these figures, the spectrum slices are 125KHz wide and data points are centered in slices.
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4.2.2 Edge-sensing

In the edge-sensing method [59], the power levels at consecutive slices in the frequency spectrum are checked. The difference between these slices is then compared against the edge-threshold. If the difference in power levels exceeds the edge-threshold, the algorithm predicts a rising edge which indicates the start of an occupied part of the spectrum. The increase in power of the spectrum could be due to either transmissions of a 2.4GHz device (WLAN/Bluetooth, etc.) or noise. The end of the occupied part of a spectrum, i.e., falling
edge, is detected by checking if the difference in power levels is smaller than the negative of the edge-threshold. Then, portion of the spectrum starting from the falling edge to the next rising edge is considered as a white-space. The accuracy of edge-sensing is affected by the following issue:

**Oblivious matching of a rising edge with the next falling edge:** the edge-sensing implicitly assumes a well-behaved spectrum and simply matches a rising edge with the next falling edge without performing any checks. Besides, the edge-sensing method does not accommodate any strategy to separate normal edges from abrupt variations in power levels that could be observed between consecutive slices. For instance in Fig.4.3, the method misinterprets power variation at \( \sim 2435\text{MHz} \) as a falling edge and consequently matches the rising edge at 2438MHz with this falling edge and therefore the spectrum in between (2435-2438MHz) is incorrectly classified as unoccupied even though it is actually occupied. This figure is obtained under the edge-threshold of 4dB.

![Plot of power vs freq and location of white spaces](image)

**Figure 4.3:** Oblivious matching of edges and no proper noise handling under the edge-sensing
4.2.3 Cluster-edge Spectrum Sensing

The cluster-edge method is our first improvement over the edge-sensing method. As clarified before, if the edge-sensing incorrectly detects a falling edge, it pairs this false edge with the latest rising edge without considering whether this pairing is correct or not. The cluster-edge method alleviates this deficiency by classifying edges as strong/weak and performing a selective match of rising and falling edges to detect occupied parts of the spectrum. Before explanation of the method, its terminology is provided:

*Cluster*: is a logical grouping of edges and contains similar edges at consecutive frequency slices in the spectrum. All the edges in a cluster have to be of a single type, i.e, rising or falling. A cluster is a potential candidate for a strong edge.

*Weak edges*: are all clusters that are not qualified to be strong edges. Strong edges always have priority over weak edges in selecting pairs of rising/falling edges, but weak rising and falling edges can be paired if there is no strong edge between the weak edges. Note that a strong edge represents a marked increase/decrease in power, which is more likely to be caused by Bluetooth/WLAN signals in the 2.4GHz ISM band, while weak edges are more likely to be caused by noise. Weak edges are identifiable in a portion of the spectrum that is not bounded by strong edges.

*Cluster-power-value*: is the overall power variation of the entire cluster. It is the cumulative sum of the changes in power for each edge in the cluster. For instance, in a cluster of two falling edges, if the changes in power for each edge are -4dB and -4.3dB, the cluster-power-value is -8.3dB.

*Cluster-power-threshold*: is the minimum (maximum) cluster-power-value to consider a cluster as a strong falling (rising) edge. Suppose that a cluster-power-threshold is 10dB. A cluster of rising edges with cluster size = 3 and change in power at each edge as 3dB (cluster-power-value = 9dB) would not be marked as a strong rising edge while a cluster
of size 2 and changes in power as -5dB and -5.5dB (cluster-power-value = -10.5dB) would be considered as a strong falling edge since its cluster-power-value = -10.5dB <-10dB.

Based on the above definitions, the cluster-edge sensing method classifies the spectrum as occupied/idle as shown in Procedure 4.1.

**Procedure 4.1 Cluster-edge Spectrum Sensing Strategy**

1: Obtain the edge data using the edge-sensing method, normally with a low edge-threshold.

2: Identify edge clusters from the edge data.

3: Identify if a cluster is a strong edge by comparing its cluster-power-value against the cluster-power-threshold.

4: Occupied part of the spectrum is predicted to lie between a strong rising edge-strong falling edge pair or between a weak rising edge-weak falling edge pair. Cross combinations (weak edge paired with a strong edge) are not considered in any cases.

5: Unoccupied parts of the spectrum are checked for their bandwidth and identified as target white-spaces if they meet the minimum bandwidth requirement.

The cluster-edge method provides a robust check to match rising and falling edges, which reduces the probability of misdetection due to noise in the occupied part of the spectrum. As illustrated in Fig. 4.4, the cluster-edge method properly detects occupied part in the range of 2428-2443MHz because it classifies the falling edge at 2438MHz as a weak edge which is not paired with the strong rising edge at 2428MHz. Edge-sensing pairs the falling edge at 2438MHz with the previous rising edge and incorrectly detects the end of the occupied spectrum at 2438MHz. The edge-threshold and the cluster-power-threshold are set to 3.6dB and 8dB respectively.
4.2.4 Convergence-cluster Spectrum Sensing

Although false edge detection happens with a much lower probability under the cluster-edge method than the edge-sensing but there is still a chance the cluster-edge misclassifies extreme noise variations as strong edges. Our next improvement, called the convergence-cluster method, deals with this issue by taking into account that occupied parts of the spectrum, marked between strong edges, should normally start and end at similar power values. The method introduces a constraint for identifying strong edge pairs, as opposed to unconditional strong edge pairing in the cluster-edge sensing. By considering following terms, the convergence-cluster spectrum sensing is explained in Procedure 4.2.

*Cluster-start-value:* is the power at the lowest frequency in the cluster.

*Cluster-end-value:* is the power at the highest frequency in the cluster. For instance in a cluster of rising edges with cluster size of 4, if the power at consecutive points in the cluster is -60dB, -56.5dB, -53.2dB, -50.0dB, (say, at frequencies 2430, 2430.125, 2430.25 and 2430.375MHz) then the cluster-start-value is -60dB (i.e. the power at 2430 MHz, the lowest frequency) and the cluster-end-value is -50dB (i.e. the power at 2430.375MHz, the highest frequency).
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Match-value: for a pair of strong rising and falling edges, it is the absolute difference between the cluster-start-value of the strong rising edge and the cluster-end-value for the strong falling edge. If the cluster-start-value of the strong rising edge is -59dB, and the cluster-end-value of the strong falling edge is -56dB, the match-value is 3dB.

Convergence-value: is the maximum permissible edge match-value for a strong rising edge-strong falling edge pair to be considered valid. If the match-value is greater than the convergence-value, the strong edge pairing is not considered.

Procedure 4.2 Convergence-cluster Spectrum Sensing Strategy

1: Obtain the edge data, including its classification into strong/weak edges, by using the cluster-edge sensing method.

2: For each strong edge, find the cluster-start-value and cluster-end-value.

3: To find part of the spectrum marked between strong edges do the following:
   (a) Calculate the edge match-value for that strong edge pair.

   (b) Compare the match-value with the convergence-value to check if the considered strong edge pairing is valid.

   (c) If the strong edge pair is valid, mark the spectrum between the strong edge pair as occupied.

   (d) If the strong edge pair is not valid, check pairing of the next strong falling edge with the current strong edge.

As illustrated in Fig. 4.5, the additional constraint of comparing the match-value with the convergence-value reduces the chance that noise in the occupied part of the spectrum and between strong edges is misclassified as a strong edge. Convergence-cluster method correctly detects the occupied part of the spectrum from 2429MHz to 2444MHz while the cluster-edge predicts 2441MHz as the end of the occupied part. A false strong falling edge
at 2441MHz detected by the cluster-edge method is ignored by the convergence-cluster since the match-value of this falling edge and the strong rising edge at 2429MHz is larger than the convergence-value (set to 5dB). The convergence-cluster method thus provides reliable detection even in the presence of noise by avoiding a false strong edge being paired with a genuine strong edge.

Figure 4.5: Noise handling by the convergence-cluster method

However, the convergence-cluster, like the cluster-edge method, is specifically designed to identify a sharp rise/fall in power and hence fails to detect gradually varying power in the spectrum (from 2420MHz to 2430MHz) as pictured in Fig. 4.6. The convergence-value is set to 5dB.

4.2.5 Dual-spectrum-sensing

The dual-spectrum-sensing, as our ultimate proposal for the spectrum sensing, is the combination of the convergence-cluster and the power-threshold methods. As observed earlier, the convergence-cluster is suitable to properly detect occupied parts of the spectrum that start with sharp rise edges and end with sharp fall edges but deficient in identifying occupied parts of the spectrum with gradually varying power; on the other hand, the
Figure 4.6: Deficiency of the convergence-cluster method in detecting the gradually increasing power

power-threshold strategy is deficient in identifying start/end of the occupied parts of the spectrum as illustrated in Fig. 4.1. The dual-spectrum-sensing, by combining these two methods, copes with deficiencies of these individual methods and provides the most robust results. As exemplified in Fig. 4.7, the dual-spectrum-sensing properly detects a gradual rise/fall in power (by applying the power-threshold method) in addition to the sharp rise/fall in power (by applying the convergence-cluster method). Procedure 4.3 presents how spectrum classification under the dual-spectrum-sensing performs.

Procedure 4.3 Dual-spectrum-sensing Strategy

1: Obtain the occupied parts of the spectrum by applying the convergence-cluster spectrum sensing strategy.

2: Over the unoccupied parts of the spectrum apply the power-threshold method, i.e. check the power at each frequency against the power-threshold and mark occupied the frequencies at which the power is greater than the power-threshold.

3: For the unoccupied part of the spectrum, the white-spaces having the minimum required bandwidth are identified as target white-spaces.
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4.3 Field Tests

With the dual-spectrum-sensing strategy which is able to reliably identify spectrum holes, the focus is shifted to verifying target (usable) white-spaces for a specific network. An SDR platform consisting of a laptop as the host computer running Ubuntu and GNU Radio software, connected to the USRP N200, is set up to extract white-spaces, with at least 2MHz bandwidth, based on the dual-spectrum-sensing strategy.

For a frequency agile radio, medium access delay is directly determined by occurrence frequency of target white-spaces. To find how promptly an 802.15.4-based frequency agile radio with dynamic spectrum access capability finds white-spaces to access the medium, the SDR platform is taken to different public locations and a number of tests are carried out so as to obtain an idea about the average spectrum usage statistics in a particular area. In each test, USRP N200 captures multiple snapshots of ISM band, then spectrum sensing results are fed to a script written in Matlab and then some parameters are extracted and averaged. Ideally a snapshot is supposed to be instantaneous, however, due to practical considerations, there is some delay. The evaluated parameters are:

- The average number of target white-spaces occurred per snapshot of the spectrum

Figure 4.7: Dual-spectrum-sensing and detection of occupied parts
The average bandwidth of identified target white-spaces per snapshot

Statistics in Fig. 4.8 indicate that even in the areas with the greatest expected use of competing WLAN/Bluetooth signals, white-spaces with at least 2MHz bandwidth do exist and occupy a non-negligible percentage of the whole spectrum. It means that if WPAN has the capability to scan the entire 2.4GHz instantaneously, it can promptly find a white-space to access the ISM band when it has new data to send. These results show that a frequency agile WPAN with dynamic spectrum access capability is suitable for industrial and monitoring applications with low-latency service requirements. Field tests are carried out at different locations in Vancouver, BC.

Figure 4.8: Statistics about white-spaces with at least 2MHz bandwidth over the ISM band

It is worthwhile to emphasize that reports, like [56], only provide general statistics about the available/occupied percentage of the ISM band but no information about the usable percentage of the spectrum is derived from them. Note that a spectrum hole is usable by a frequency agile radio only if it meets the minimum contiguous bandwidth required by the application [60].
4.4 Summary

The ISM band is a heterogeneous environment shared among networks with diverse physical and MAC layer specifications. Opportunistic access allows networks to have more reliable and timely transmissions specifically in coexistence with more powerful networks like WLAN. For opportunistic access, a frequency agile radio with dynamic spectrum access capability captures spectrum holes, with the minimum contiguous bandwidth required by the application, to access the spectrum. In this chapter, we have proposed the dual-spectrum-sensing strategy to detect idle parts of the spectrum even in a heterogeneous medium like ISM band where various shapes of power spectral densities coexist. Based on measurements performed in public places, we have presented results that show the superiority of our dual-spectrum-sensing strategy over the well-discussed edge-sensing [59] strategy in detecting idle parts of the spectrum. We have presented statistics based on our measurements, which show the good availability of white-spaces that are sufficiently wide for IEEE 802.15.4-based WPANs with dynamic spectrum access capability to significantly improve their chance to opportunistically access the ISM band spectrum.
Chapter 5

Cross-Layer Design for Reliable Transmissions over Body Area Networks

5.1 Introduction

A BAN includes a small number of on-body sensor nodes for sensing of physiological data, such as EEG, ECG and EMG data, which are collected by a gateway and forwarded to a medical center over the existing telecommunication infrastructure for interpretation by a care-giver and detection of emergency conditions. Gateways may be implemented in commonly available mobile devices such as smart phones, and they are subject to a less stringent constraint on power consumption and processing resources than body nodes. As an enabling component, BAN facilitates m-health service by eliminating wires between body nodes and the gateway to realize an unobtrusive platform for monitoring a patient’s health status.

Although the arrangement of body nodes and the gateway resembles a simple master-
slave architecture, movements of limbs and very low-power transmissions of body nodes result in a completely dynamic BAN topology that is determined by the relative positions and orientations of body nodes toward the gateway and instantaneous quality of the wireless links. Under such a time-varying topology, reliable delivery of medical data from body nodes to the gateway is challenging and requires a network layer that is aware of the wireless channel variations around the subject’s body at the time of a transmission.

The main contribution of this chapter is proposing a topology-related network layer design to make ambulatory health monitoring via BAN more reliable and robust. In this platform, the MAC layer provides the network layer with local information about the quality of on-body links. Information from the MAC layer is implicitly used by the network-layer to identify the most reliable links in a distributed manner and consequently take into account the channel fluctuations of on-body links into BAN scheduling. This opportunistic scheduling, by capturing of high quality on-body links, reduces the tension between PDR and delays. This proposal is built on top of our CBAS framework, a receiver-initiated MAC scheme that improves the visibility of a BAN in a coexistent environment where diverse networks with various physical and MAC protocols share the radio spectrum. The design enhances CBAS by incorporating a network layer scheme that provides a reliable platform with high PDR for medical data transmissions while minimizing the need for multi-hop cooperative transmissions; thus packet delay is less compromised to achieve higher PDRs.

The rest of the chapter is organized as follows. The next section reviews related works in the area. CBAS, a gateway-initiated MAC scheme that enables body nodes to access the shared medium opportunistically, is briefly explained in Section 5.3. Section 5.4 proposes the topology-adaptive network layer that is overlaid on top of CBAS to improve the PDR of sampled data using cross-layer enhancements. To give an insight about the efficiency of our proposal, Section 5.5 presents the results of extensive experimental evaluations.
Section 5.6 summarizes the chapter.

## 5.2 Literature Review

It has been extensively reported that the data reliability and energy requirements of low-power BANs cannot be addressed only at the physical layer by increasing transmit power or improving receiver sensitivity. Consequently, the designs of the MAC and network layers need to contribute to these goals \[61–63\]. If the dynamic topology of a BAN is considered in scheduling and packets are transmitted on wireless links with a high quality, it is more probable that packets are directly received by the gateway rather than relayed by intermediate body nodes. It reduces the demands for utilisation of the shared medium and also reduces packet delivery delays.

In this regard, some previous work on BAN has studied the utilization of control packets sent periodically in the BAN to pursue body posture trends and determine link status. For instance, authors in \[64\] developed an on-body store-and-forward packet routing algorithm for a BAN with partitioned topology. Each body node maintains a neighbor table by sending periodic HELLO messages to track its local link connectivity. At any given time, a body node checks if any of its direct neighbors has a higher connectivity likelihood to the gateway. It ensures that the body node forwards its packet to a node that is most likely to successfully deliver the packet to the destination node. However, this work leaves a number of unanswered questions, such as how timely a body node finds access to the shared medium to launch HELLO packets periodically, how much energy a body node loses due to transmissions of control messages and maintaining its neighbor table, and how PDR and delays are affected if HELLO messages are not transmitted in a timely manner.

In an effort to predict the dynamics of BAN links, a flipping strategy is proposed in \[65\]. It is a TDMA approach where the scheduling order of body nodes in each round
depends on the results of the previous round. Under the flipping strategy, body nodes that successfully delivered their packet in the previous round are scheduled first, followed by unsuccessful nodes. In the proposal in [66], the gateway computes a quality factor for its incoming links. To update its knowledge about the status of on-body links and track their dynamics, the gateway needs to receive at least one data packet from each node every round. This strategy forces body nodes to frequently send packets even though they may not have sampled data to send.

Authors in [67] claim that human movements cause periodic signal strength fluctuations. Their goal is scheduling packets on the peaks of signal strength fluctuations with the help of periodic probe packets based on the Received Signal Strength (RSS) values. The gateway derives the phase and period of RSS fluctuations from that information to predict a time-duration in which transmission from a body node may yield a high RSS. In another work, a history based approach called the Window Mean with Exponentially Weighted Moving Average is used for capturing the long-term stability and quality of each radio link [68].

Also, cooperative communications and relaying, as a promising remedy for networks with time-variant channels, has gained attention from the research community. Two different approaches, namely deterministic relay selection and combined path and double-hop cooperation, have been proposed in [69] and evaluated in [70]; however, problems related to dynamic relay selection and timings for transmission of relayed packets remain as open implementation issues. Note that to consider intermittent link-up and link-down situations of on-body links, relay selection should adapt to the instantaneous topology of a BAN.

There are two issues that the reviewed approaches have not addressed:

1) They implicitly assume that channel is always available for transmissions of data or control packets to extrapolate posture changes based on feedbacks obtained from those packets. However, tracking body posture in this way is not reliable since periodic access to
the medium is not guaranteed when a BAN works in the presence of coexistent networks.

2) Irregularities of body movements even in semi-periodic postures like walking and intermittent link (dis)connectivity even within a posture make learning-based approaches less effective. To cope with unpredictable body changes, an on-line scheduling mechanism based on immediate on-body link qualities is preferable.

5.3 Cross Layer Design: Medium Access

Low latency is a requirement of m-health services, aimed at prediction and prevention of life threatening health conditions before they occur. For instance, ambulatory monitoring of the motor signals of a patient with PD allows the effectiveness of the medication to be determined and alerts the care-giver to adjust the medication dosages as needed. BAN is useful for PD patient monitoring only if motion data are delivered to the gateway with a low latency. Transmission latency is mainly determined by the delay experienced by the MAC layer in capturing the medium to transfer data. Medium access schemes for BANs mostly employ CSMA/CA and TDMA approaches.

Because of the master-slave architecture and presence of a gateway as a resourceful component, TDMA-based approaches may seem as good candidates for BANs to achieve the desired energy efficiency, as dedicated time-slots avoid medium access contentions among body nodes and the wastage of transmission energy. However, pervasive monitoring requires a BAN to work in a shared medium where multiple networks with various physical and MAC layer protocols work independently. The lack of coordination among these independent networks in an unlicensed band threatens the transmission of body nodes with interference in the allocated time-slots, since these allocations are not respected by the coexisting systems. Therefore, a BAN should contend with other collocated networks to access the shared medium. However, even though CSMA/CA is employed by many net-
works to access this shared medium, high power networks such as WLANs may not sense the low power BAN transmissions and thus interfere with ongoing BAN transmissions. Such interference restricts access of body nodes to unused spaces of the spectrum that remain between transmissions of high-powered coexistent networks. Unused spaces are scattered randomly over time because traffic of collocated wireless systems generally does not have a predictable pattern. As a consequence, access of body nodes to the shared medium is intermittently fragmented over time and faces unpredictable interruptions.

To 1) capture the energy conserving feature of TDMA-based approaches even in an unsupervised heterogeneous medium, like ISM band in which various networks work independently, and 2) resolve the large access delays that a BAN faces in contention with high-power and high data-rate networks, we have proposed an opportunistic gateway-initiated MAC scheme called CBAS in Chapter 3. The idea is that the gateway actively probes a wide part of the spectrum, finds white-spaces and initiates a connection that is orthogonal to the existing transmissions in frequency and/or time. This approach enables reliable operation of a BAN in a coexistence medium and provides interference-free transmission-slots for body nodes.

The feasibility of this idea is based on spectrum usage measurements that have been made previously. Fine-grain usage traces of 20MHz to 6GHz spectrum range [56] show that on average 54% of the spectrum is never used and 26% is only partially used. Also, ISM band channel utilization traces from real life environments [57] show that although the ISM band is heavily crowded by WLAN access points, WLAN network traffic is highly bursty and leaves white-spaces between transmissions. Moreover, BANs have low bandwidth requirements such that for a BAN implemented based on the IEEE 802.15.4 physical layer, a 2MHz channel is enough for a packet transmission. In the rest, an unused part of the spectrum with at least 2MHz width is called a target white-space for BAN transmissions.
Chapter 5. Cross-Layer Design for Reliable Transmissions over Body Area Networks

in which transmission slots can be derived.

Experiments on BAN communications have been conducted, which led to following observations regarding CBAS:

Observation 1) The BAN does not operate over a single channel but instead benefits from white-spaces occurring over a wide part of the spectrum. This opens up transmission opportunities for the BAN, improves its visibility in the shared environment and offers low-latency transmissions in the coexistence medium. Based on the comprehensively discussed results in Sec. 4.3, even in the areas with the greatest expected use of competing WLAN/Bluetooth signals, white-spaces of bandwidth greater than 2MHz do exist and occupy a non-negligible percentage of the whole spectrum. This indicates that the inherent assumption made in the design of CBAS is realistic. Therefore, if the gateway has the capability to scan the entire 2.4GHz ISM band, extracting spectrum holes to schedule body node transmissions would likely be successful most of the time.

Observation 2) When the channel condition is poor, the gateway may not be a single-hop neighbor of the target body node and consequently a packet transmitted by the body node may not reach the gateway, the assigned transmission-slot is wasted and PDR reduces. To determine the severity of this problem, experimental results from measurements of on-body links during walking activities are represented by Finite State Machines (FSM). Positions of body nodes and the experimental setup is explained in Sec. 5.5.1. The gateway, located on the belt, transmits commands every 50msec toward a specific body node. The target node records the Signal-to-Noise Ratio (SNR) and Link Quality Indication (LQI) of the received command and transmits a packet in response to that command. The gateway, on the other side, records whether it has received a packet corresponding to that command or not. Per the suggestion in [71], the target node estimates the quality of its wireless links as the distance, DIS, from the origin based on the value of (SNR,
Table 5.1: On-body links' statistics during walking movement

<table>
<thead>
<tr>
<th>Node</th>
<th>R.Ankle</th>
<th>R.Knee</th>
<th>R.Wrist</th>
<th>R.Shoulder</th>
<th>L.Shoulder</th>
<th>R.Thigh</th>
</tr>
</thead>
<tbody>
<tr>
<td>State</td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>α</td>
<td>15%</td>
<td>84%</td>
<td>1%</td>
<td>3%</td>
<td>87%</td>
<td>10%</td>
</tr>
<tr>
<td>β</td>
<td>7%</td>
<td>27%</td>
<td>91%</td>
<td>9%</td>
<td>34%</td>
<td>82%</td>
</tr>
</tbody>
</table>

LQI), i.e., \(DIS = \sqrt{(SNR^2 + LQI^2)}\). The calculated DISs are partitioned into three non-overlapped states A, B and C as: \(\{DIS <= Th_1\} \in A, \{Th_1 < DIS <= Th_2\} \in B\) and \(\{Th_2 < DIS\} \in C\). To set the thresholds, PDR vs DIS relationship for each node-gateway link is derived and the areas with the lowest and highest PDRs are located (approximately) as state A and state C respectively. This relationship for the node on the right-wrist is illustrated in Fig. 5.1 and thresholds are set to \(Th1 = 105.7, Th2 = 111.9\).

By mapping every single DIS value to a specific state, the link behavior is characterized by two parameters \(\alpha\) and \(\beta\) in Table 5.1 and the corresponding FSM is derived. The former parameter is the percentage of time that a node stays in the corresponding state and the latter is the percentage of packets successfully delivered to the gateway in that state.

According to Table 5.1 there are moments that a body node experiences good PDRs, i.e., node is in state C. Therefore, in assignment of commands to body nodes the instantaneous situation of on-body links between body nodes and the gateway should be considered such that at each random packet transmission instance, the highest priority should be given to body nodes in state C, followed by nodes in state B, and the lowest priority to nodes in state A, in order to improve the chance of successful packet transmissions. It is further observed that some nodes are found in state C so rarely that even under an optimal scheduling that captures all moments that these nodes stay in state C, they cannot reach a high PDR unless a very low sampling rate is used. These nodes require cooperation of other body nodes to deliver their packets to the gateway. For instance, the R.Ankle node has a 91% successful packet delivery ratio just 1% of times and so most of its packets are dropped unless they are relayed by some intermediate nodes to finally reach the gateway.


5.4 Cross Layer Design: Scheduling

Reliable delivery of periodically sampled sensory data is mandatory for BANs employed for m-health due to the potentially serious consequence of failures. Fulfillment of this reliability criterion requires an adaptive network layer that is tolerant of highly dynamic changes in the BAN topology with body nodes employing very low power transmissions.

To improve the reliability of packet delivery in a BAN, our network layer design incorporates knowledge of channel fluctuations in scheduling of body nodes to take advantage of high quality wireless links. Link quality information is provided by CBAS in the underlying MAC layer for cross-layer performance enhancement. The dynamic scheduling mechanism proposed in this chapter is motivated by the following observations:

1) Channel measurements over BANs [72] show that the predominant fading effect is slow flat fading, although in some cases frequency-selective fading is observed. Also, experimental results indicate that BAN channels are symmetric [61] [73].
2) Under CBAS, when a white-space with at least 2MHz bandwidth is extracted, a command is launched and then transmission starts. In fact, a command precedes each data packet transmission. The information provided by command receptions enables real-time determination of the link quality.

3) Investigations in [67] show that the signal strength amplitudes of on-body links are typically long lasting (100’s of msec), when compared to the transmission times of packets (a few msec).

As a consequence, if the RSS value of the received command indicates a good channel from the gateway, the quality of the uplink channel (from a body node toward the gateway) should be fine for packet transmission.

5.4.1 Dynamic Single-Hop Scheduling

Our cross-layer design for BAN scheduling consists of two phases. First, the gateway extracts transmission opportunities from the shared medium and announces them to body nodes by launching commands. In this way, nodes are not involved in contention with other collocating networks for access to the shared medium. Similar to TDMA approaches, the gateway provides interference-free transmission slots for BAN communications. In the second phase, body nodes contend with each other to capture the slots announced by the gateway. When nodes receive a command from the gateway, they use the RSS to compute their back-off windows. Body nodes autonomously set their back-off windows based on two factors: 1) The estimated link quality based on the RSS of the received command such that a node with a higher quality link towards the gateway sets a smaller window and consequently finds a better chance to capture the announced transmission slot. 2) Their history in capturing previous slots, in order to provide fairness in the scheduling scheme. In fact, the role of the gateway is limited to the first phase in finding and reserving spectrum
holes and announcing these slots to body nodes. The gateway does not get involved in assigning transmission slots to specific body nodes; in this sense the scheduling mechanism is a distributed one. Based on the following notations, the proposed dynamic scheduling mechanism is presented in Procedure 5.1 and elaborated as follow:

- \( P_G \): Gateway’s power for transmission of commands.
- \( \gamma_{(G \rightarrow i)} \): Command’s RSS perceived by node \( i \).
- \( \gamma_G \): Gateway’s RSS threshold for decoding a packet.
- \( P_{th} \): Power threshold.
- \( P_{(i \rightarrow G)} \): Minimum power required by node \( i \) to send a packet to the gateway.
- \( T_{TX} \): Duration of data exchange between the gateway and a node.

By reception of a command, node \( i \) extracts the RSS value, \( \gamma_{(G \rightarrow i)} \), and calculates the total channel attenuation as \( Y = P_G - \gamma_{(G \rightarrow i)} \). By considering flat fading and symmetric characteristics of a BAN channel, node \( i \) infers that its transmission to the gateway will be subject to an attenuation of about \( Y \) dbm if it sends a packet to the gateway over the announced channel (Line 7).

Since the reception threshold of the gateway is \( \gamma_G \), node \( i \) calculates the minimum power required for a successful packet reception as \( P_{(i \rightarrow G)} = \gamma_G + Y \). It means that in the current BAN topology, node \( i \)'s packet is received successfully by the gateway if transmission power of node \( i \) would be at least \( P_{(i \rightarrow G)} \) (Line 8).

If \( P_{(i \rightarrow G)} \) exceeds the \( P_{th} \), node \( i \) finds a very poor link quality toward the gateway and abstains from the current round of channel access (Line 12). Otherwise, it calculates its weight for packet transmission as (Line 10):

\[
Weight_i = (1 - \frac{P_{th}}{|P_{th} - P_{(i \rightarrow G)}|}) \cdot (1 - \frac{X_i}{K}) \tag{5.1}
\]

In (5.1), factor \( f_1 = (1 - \frac{P_{th}}{|P_{th} - P_{(i \rightarrow G)}|}) \) represents the relative reliability of the wireless link from node \( i \) toward the gateway because a better link quality, i.e., smaller \( P_{(i \rightarrow G)} \), yields a
Procedure 5.1 Dynamic Single-Hop Scheduling over CBAS

1: Gateway continuously monitors the shared medium to find white-spaces with sufficient length.
2: Repeat:
   3: While (a target white-space is available) {
   4:   Gateway picks an available white-space, e.g., $CH_x$.
   5:   Gateway sets an RTS with $T_{TX}$ and sends it through the overlapped WLAN channel to reserve the space.
   6:   Gateway sends a command of $<CH_x, T_{TX}>$ on the CCH.
   7:   By receiving the command, body node $i$ calculates its channel attenuation as $Y = P_G - \gamma_{(G\rightarrow i)}$.
   8:   Node $i$ calculates its minimum required power as $P_{(i\rightarrow G)} = \gamma_G + Y$.
   9:   If (!($P_{(i\rightarrow G)} > P_{th}$ || node $i$’s queue is empty)) then
   10:      Node $i$ calculates its $Weight_i$ and sets its back-off window.
   11:   Else
   12:      Node $i$ does not participate in contention.
   13:   By receiving the win-packet, node $i$ leaves the back-off.
   14:   At the end of the back-off window, node $i$ sends a win-packet through the CCH, tunes to $CH_x$ and wakes up by powering its radio to initiate a transmission on $CH_x$.
   15:   After $T_{TX}$, the winner tunes its transceiver to the CCH and goes to sleep. }

higher value for this factor. Factor $f_2 = (1 - \frac{X_i}{K})$ provides a fair distribution of transmission opportunities between body nodes. Body nodes have a sliding window with length $K$ to keep the history (bitmap) of their $K$ previous transmission opportunities. $X_i$ represents the number of times that node $i$ has responded to previous $K$ commands by initiating a packet transmission. Thus, node $i$ with a higher $X_i$ has a smaller chance to capture the current transmission slot. Then, $Weight_i$ is applied to calculate the back-off window of
node $i$ as:

$$\text{Back-off-window}_i = f(\text{weight}_i) \cdot \theta$$

(5.2)

where $\theta$ is the maximum contention window selected based on the BAN time granularity.

Node $i$ sets an interrupt to be expired after $\text{Back-off-window}_i$. Finally, a node with the highest $\text{Weight}$ sets the smallest back-off window and captures the transmission slot.

The first node that completes its back-off window sends a very short packet ($\text{win-packet}$) through the CCH, via its passive RF module, to inform other nodes about its decision to initiate a transmission. It then wakes up from the sleep mode by activating its main radio (Line 14). Since the $\text{win-packet}$ is very short, a robust channel coding can be used to increase the chance of a successful reception under a low SNR, without unduly increasing the overhead. This ensures that the body nodes at the extremities can successfully send their $\text{win-packets}$ to the gateway. To minimize the chance of collision and to make sure that all body nodes are informed about occupation of the current slot, the gateway sends a high power packet on the CCH immediately after reception of the $\text{win-packet}$ to prevent other nodes from starting a transmission. When the passive RF module of a body node that is backing off is triggered by a $\text{win-packet}$, the node leaves the contention by terminating its back-off process (Line 13).

Note that by applying power control schemes like [74], a body node equipped with a radio that support dynamic transmit power control may adjust its transmit power based on its immediate link quality (SNR) toward the gateway. For example, a body node $i$ that wins the contention for capturing the command and works with the default power of $P_{\text{def}}$, may adjust its power before initiating its transmission as follow:
If \((P_{i\rightarrow G} - P_{\text{def}}) > TH\) then

Node \(i\) increases its transmission power.

Else

Node \(i\) operates with the default power \(P_{\text{def}}\).

\(TH\) should be set carefully to avoid unnecessary power increments. In this way, while a node still enjoys the relaying feature of the proposal to improve its PDR, it increases the chance of direct packet transmissions by increasing its transmit power level. Therefore, our cross-layer design simultaneously benefit from adaptive scheduling and adaptive transmission power management which are both critical in the context of ultra-low power BANs.

5.4.2 Dynamic Multi-Hop Scheduling

Although dynamic single-hop scheduling improves PDR of all body nodes by opportunistic capturing of high quality links at each scheduling instance, there are some nodes at the extremities, e.g., the ankle node, which usually experience poor link qualities toward the gateway and still suffer from low PDRs. To address those cases via multi-hop transmissions, the single-hop procedure is modified such that body nodes listen to the allocated channel when they receive the win-packet. Thus, the current neighbors of the source node receive a copy of the data packet and may work as a relay for that node. When this transmission is not acknowledged by the gateway, a neighbor of that body node that has a copy of this packet relays the packet to the gateway to improve the chance of successful packet reception at the gateway.

For multi-hop enabled BAN operation, it is assumed that each packet includes the “ID”, “Seq”, “Source” fields. Also, each node aims at maximizing its own PDR before helping other nodes to improve their PDRs by relaying their packets. In this regard, each
node has two queues: the DataQ queue for its own packets and the MsgQ queue for the
relayed packets. When it wants to transmit a packet, it gives a higher priority to its own
queue and only when DataQ is empty, a packet from MsgQ is dequeued. This behavior
is justified when we consider that a relayed packet has already captured a transmission-
slot but a packet in the DataQ has not been given a transmission opportunity yet. The
dynamic multi-hop scheduling, illustrated in Procedure 5.2, is elaborated as follows:

Procedure 5.2 Dynamic Multi-Hop Scheduling over CBAS

1: Gateway continuously monitors the shared medium to find white-spaces with sufficient
length.
2: Repeat:
3: While (a target white-space is available) {
4: Gateway picks an available white-space, e.g., \( CH_x \).
5: Gateway sets an RTS with \( T_{TX} \) and sends it through the overlapped WLAN channel to
reserve the space.
6: Gateway piggybacks an acknowledgment for the latest packet that it has received.
7: Gateway sends a command of \(< CH_x, T_{TX} >\) on the CCH.
8: By receiving the command, node \( i \) calculates its channel attenuation as \( Y = P_G - \gamma_{(G \rightarrow i)} \).
9: Node \( i \) calculates its minimum required power as \( P_{(i \rightarrow G)} = \gamma_G + Y \).
10: If \(! (P_{(i \rightarrow G)} > P_{th} || \text{ node } i \text{'s queue is empty})\) then
11: Node \( i \) calculates its \( Weight_i \) and sets its back-off window.
12: Else
13: Node \( i \) does not participate in contention.
14: By receiving the win-packet, node \( i \) leaves the back-off procedure, switches to \( CH_x \), wakes
up by powering its radio to listen to \( CH_x \).
15: At the end of the back-off window, node \( i \) sends a win-packet through the CCH, tunes to
\( CH_x \) and wakes up by powering its radio to initiate a transmission on \( CH_x \).
16: After \( T_{TX} \), the winner tunes its transceiver to the CCH and goes to sleep. }

The gateway piggybacks contents of the “Seq” and ‘Source” fields of the latest success-
fully received packet on the command. When the command is sent, all body nodes that have a copy of the acknowledged packet remove it from their buffers to avoid duplicate transmissions (Line 6). For instance, suppose node \( y \) generates a packet with “Seq=k”, which is transmitted with “Source=y, Seq=k”. Assume that the gateway does not receive this packet but neighbor \( x \) does. At some point, node \( x \) wins the contention while its DataQ is empty and the next packet in its MsgQ is the one with “Source=y, Seq=k”. In this case, fields of the packet are filled as “ID=x, Source=y, Seq=k”.

Note that (5.1) still works fine for the multi-hop case and gives more chances to relaying nodes since 1) nodes with an empty queue do not try to capture the medium and leave the opportunities for others, 2) implementation of the sliding window and recording the history of participations automatically distributes commands between body nodes.

Except the node that wins the contention and captures the channel, all remained body nodes are awoken by receiving the win-packet to listen to the channel for \( \delta \) seconds to figure out whether they are neighbors of the transmitter or not. \( \delta \) is a small duration required for reception of a few bits. If a body node finds itself as a neighbor of a transmitter, it continues listening to the channel for \( T_{TX} \) seconds to receive the whole packet and then goes back to sleep. Otherwise, it stops listening, switches to the CCH and goes to sleep since it does not find itself as the current neighbor of the transmitter (Line 14). In this way, neighbors of the target body node receive a copy of a transmitted packet.

Although neighbors of a specific body node are not unique and change in the course of the BAN operation, there is no need for explicit coordination between several nodes for relay selection. In fact, body nodes implicitly find their link connectivity pattern with others and their role as a relay based on the immediate BAN topology, unlike other BAN multi-hop proposals in the literature like [75].

Note that the acknowledgment piggybacked on the gateway command serves to prevent
duplicate transmissions because multiple neighbors may receive and attempt to forward a copy of the transmitted packet. This procedure allows body nodes to discard a packet that has already reached the gateway via others nodes.

5.4.3 Duty Cycle and Energy Consumption Analysis

Duty Cycle (DC) is defined as the fraction of time that radio is ON for receiving, transmitting or idle listening. Equipping with passive RF module, as a wake-up circuit tuned to CCH, allows a body node to sleep (i.e., turn off its main radio) until it is required to participate in data communications (to receive or transmit a packet) \[41\]. As a result, a body node is either in active mode or sleep mode and so no energy is wasted to idly listen to the channel to receive commands or win-packets.

Under the proposed dynamic scheduling schemes, DC of a body node is defined as the total of node’s ON period during a sliding window of length \(K\) divided by the window duration. By assuming that the gateway launches commends every \(\Delta\) unit-time and body nodes all have the same packet size, lower and upper bounds of DC are analyzed as follow.

The longest sleep interval \((SI_{up})\) and consequently the lower bound of DC \((DC_{low})\) is achieved when a body node wakes up only for transmission of its own packet which is equivalent to applying the dynamic single-hop scheduling. If a body node decides to participate in contention (Line 9 of Procedure [5.1], it may either 1) be triggered by a win-packet and consequently respects the winner of contention by disabling its back-off interrupt or 2) be notified by expiration of its own back-off window and consequently captures the transmission opportunity by powering its main circuit, initiates a transmission for \(T_{TX}\) and then goes back to sleep until it again wins the contention. Defining \(T_{trans}\) as the average time for transition between modes, we have:
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\[ DC_{\text{low}} = \frac{k_1(T_{TX} + T_{\text{trans}})}{K\Delta}, \quad 1 \leq k_1 \leq K \]  
\[ SI^{\text{up}} = \frac{K\Delta}{k_1} - (T_{TX} + T_{\text{trans}}) \]  

The shortest sleep interval \((SI_{\text{low}})\) and consequently the upper bound of DC \((DC^{\text{up}})\) is achieved when a body node decides to be part of contention as long as it has a pending packet even if it is a relayed one in its MsgQ. After setting its back-off window, the body node faces one of these cases: case 1) it wins the contention, sends a win-packet as a wake-up signal, wakes up by switching to the active mode and starts a transmission for \(T_{TX}\); case 2) it does not win the contention but finds the winner in its neighbor range, listens to channel for \(T_{TX}\) and gets a copy of the winner’s packet for later relaying. For both cases the radio’s ON period terminates after \(T_{TX} + T_{\text{trans}}\); case 3) it is triggered by the win-packet and powers its main circuit to listen in a hope of receiving the winner’s packet. However, it does not hear the packet and terminates its ON duration after \(\delta + T_{\text{trans}}\) seconds. \(\delta\) is a small duration required for reception of a few bits. At the end of each case, the body node goes back to sleep until one of these cases happens again. Defining \(k_1, k_2\) and \(k_3\) as the number of times that case 1, case 2 and case 3 happen over a window of \(K\) commands \((k_1 + k_2 + k_3 \leq K)\): 

\[ DC^{\text{up}} = \frac{(k_1 + k_2)(T_{TX} + T_{\text{trans}}) + k_3(\delta + T_{\text{trans}})}{K\Delta} \]  
\[ SI_{\text{low}} = \frac{K\Delta}{k_1 + k_2 + k_3} - (T_{TX} + T_{\text{trans}}) \]  

Defining \(I_{tx}, I_{rx}, I_{idle}\) and \(I_{\text{trans}}\) as the radio’s current drawn for transmitting, receiving, idle-listening and mode transition, energy consumption of a node per window of \(K\)
commands is also bounded by $E_{\text{low}}$ and $E^{\text{up}}$ as follow:

$$E_{\text{low}} = k_1 [T_{TX} I_{tx} + T_{\text{trans}} I_{\text{trans}}] \cdot V_{\text{bat}}$$  \hspace{1cm} (5.7)$$

$$E^{\text{up}} = [k_1 T_{TX} I_{tx} + k_2 T_{TX} I_{rx} + k_3 \delta I_{\text{idle}} + (k_1 + k_2 + k_3) T_{\text{trans}} I_{\text{trans}}] \cdot V_{\text{bat}}$$  \hspace{1cm} (5.8)$$

where $V_{\text{bat}}$ is the voltage level of the battery.

A direct tie between radio’s DC and energy consumption highlights the importance of DC management approaches. In this regard, authors in [76] have experimentally investigated that network’s lifetime may boost drastically under a proper management of body nodes’ DC. They report that providing the built-in low-power mode for TinyOS sensor platforms decreases the average power consumption even more than five times. Besides common proposals, like packing packets and sending them as a single one, our cross layer design has a flexibility to manage its DC by controlling over $k_1$, $k_2$ and $k_3$. Note that preference of a body node for packet relaying determines its actual DC which is a value in a range of $DC_{\text{low}}$ and $DC_{\text{up}}$. Applying certain policies or conditions for management of a node’s preference helps the node control its ON duration by adjusting $k_1$, $k_2$ and $k_3$ and deciding whether it wants to have a DC close to $DC_{\text{low}}$ or $DC_{\text{up}}$. For clarification, suppose a body node is set not to participate in relaying if its remaining power is below a specific level. When this condition is met, wake-up rate will only be based on the node’s arrival rate. Therefore, $k_1$ reduces, $k_2 = k_3 = 0$ and node’s DC and power consumption drop to $DC_{\text{low}}$ and $E_{\text{low}}$, respectively by compromising the network’s reliability. It is worth noting that the node’s preference for packet relaying has a direct impact on the network PDR and the delay of relayed packets. The more the number of potential relaying body nodes, the bigger the set of possible relaying paths and the higher the chance that a packet is relayed over a better link. It results in larger network PDR, smaller hopping-delays and consequently smaller overall delays.
5.5 Performance Evaluation

Our cross-layer design is implemented in NesC and overlaid on the 802.15.4 physical layer. The nominal experimental setup includes six TelosB motes and a gateway, located on different body segments of a female subject as Fig. 5.2 shows. To ensure that the subject’s body shape influences the directivity of body nodes and the gateway, no cushion is used between clothes and nodes. Each trial includes 10 minutes walking at a speed of 1.7 steps per second down a corridor. We emphasize that despite our desire for evaluating different algorithms under literally the same configuration, the inherent dynamism in nodes’ placement and orientation, limb movements and RF signal blockages do not allow connectivities and link qualities to be exactly replicated. Similar to settings in [64], nodes generate a packet every 1200msec, and so overall the BAN transfers a new packet every 200msec. Each packet has 31Bytes and its transmission takes $T_{TX} = 1$msec. In the experiments, dummy data are sent in packets, although in practice each packet may carry either raw or pre-processed (e.g., compressed) sensory data. Note that sensors (like accelerometers and ECG) are usually operated with sampling frequencies of hundreds of Hz, so that some data reduction or compression approaches, like feature extraction from the raw data, may be required since transmissions of raw data consume too much battery energy and reduce the lifetime of body nodes.

5.5.1 Experimental Setup

For long term monitoring, assuring low energy consumption of nodes is important. In this regard and similar to [36], TelosB motes are set to transmit with a low power level 2 (PA-LEVEL=2), which is approximately $P_{def} = -42$dbm. Note that the CC2420 radio is configurable to 32 different power levels from 0 to 31. Working with such a low power makes the power wastage less of a concern even when the body node experiences a good-
quality link. Also, when a body node experiences a poor link, the low reliability problem is addressed by the relaying feature of the proposal instead of increasing the node’s transmit power. As a result and despite a fixed setting for the power, both power wastage and low reliability problems are addressed properly.

![Figure 5.2: Placement of body nodes in the experimental setup](image)

Battery life is usually less of an issue with the gateway, which is located around the subject’s waist; the gateway is set up to operate with a transmit power of $-10$ dbm (PA-LEVEL=11). Observations verify that, in our experimental setup, this transmit power is sufficient for the gateway to successfully deliver 99.9% of commands to all nodes. The CC2420 radio of each TelosB mote has an RSS Indicator (RSSI) register that records the RSS of the latest packet received by the mote, which is utilized in the proposed scheduling mechanisms.

Since vital signs are delay sensitive and body nodes have a limited buffer capacity, when a packet is sent, it is totally removed from the transmitter queue and so a body node never retransmits its own packet again to avoid extra delay on its successive sampled data. However under a multi-hop platform, this packet may find more transmission opportunities,
if it is relayed by other nodes.

5.5.2 Performance Criteria

Real-time assessing of the patient’s health status, predicting and managing the possible risks via ambulatory monitoring is infeasible unless sampled vital signs are delivered to the gateway with a specific level of reliability and timeliness. Therefore, a good protocol design for BANs should guarantee a high PDR without jeopardizing the delay. PDR is defined as the percentage of data packets originated by body nodes, which are successfully received by the gateway.

The delay metric indicates how timely sampled data get service and includes queuing-delay and hopping-delay. The former is an interval that packet remains backlogged on the sensor node until its transmission from the source node begins. From this moment until reception of the packet by the gateway is called hopping-delay. As an instance of a medical application, to detect and distinguish activities of a PD patient and consequently make (near) real-time falling alerts, a maximum detection delay of 2sec should be met [77].

Due to long-term pervasive monitoring objective, a successful MAC or network layer design for a BAN should maximize the durations that the radio of each node is powered down or minimize the ON period of each radio as much as possible. In this regard, the last evaluated metrics are duty-cycle and energy consumption of body nodes.

Note that launching a command by the gateway causes a packet transmission by a node. Consequently shortening the command intervals also shortens the intervals that data packets remain back-logged. In the rest of this chapter, the command-interval, $\Delta$, indicates how often the gateway transmits commands. To have high PDRs, the implicit assumption is that the number of commands is at least as large as the total number of generated packets in the network such that every single packet has a chance of being
transmitted to the gateway.

5.5.3 Dynamic Scheduling

Fig. 5.3 illustrates the results from five trials of dynamic single-hop scheduling with $\Delta = 200$ msec where parameters of (5.1) are set to $(P_{th} = -20$dbm$ , K = 6)$ and node $i$ uses $Back-off-window_i = (1 - Weight^2_i).150$ to set its back-off window. Note that node $i$ always transmits its packets with $P_{def} = -42$dbm and $P_{(i\rightarrow G)}$ is only used for setting the back-off interval according to (5.2).

![Dynamic Single-Hop Scheduling (\(\Delta = 200 \text{ msec}\))](image)

Figure 5.3: PDR under dynamic single-hop scheduling

Fig.5.4 shows results of dynamic multi-hop scheduling. To service additional loads imposed by relayed packets, commands are transmitted every 150msec which is more frequent than that in the single-hop case. By setting $K = 8$ in (5.1), a node sets its window by considering the number of times it has captured the previous $K = 8$ transmission opportunities.

These experimental results bring the following observations:

1) Regarding the trend of hopping-delay under multi-hop scheduling shown in Fig. 5.5 note that as long as a body node has a back-logged packet in its DataQ, it ignores waiting packets in its MsgQ. This packet differentiation policy causes relayed packets to
experience larger hopping-delays and hence larger overall delays. Therefore, for nodes with lower single-hop PDRs, larger hopping-delays are expected since those nodes have a larger number of packets that do not directly reach the gateway but instead are relayed by intermediate nodes. For instance, Fig. 5.3 shows that more than 70% of the R.Ankle node’s packets reach the gateway with the help of other nodes in a multi-hop fashion. Each of these packets stays in the MsgQ of some intermediate nodes until one of these nodes captures a command while its DataQ is empty and relays the packet.

2) As confirmed by results in Fig. 5.5, a node with a less reliable connectivity experiences larger queuing-delays. Factor $f_1 = (1 - \frac{P_{th}}{P_{th} - P_{(i\rightarrow G)}})$ in (5.1) is a function of gateway-node link’s quality and so under the same value for factor $f_2 = (1 - \frac{X_i}{\bar{X}})$, a node with a relatively better connectivity toward the gateway has a smaller $P_{(i\rightarrow G)}$ and sets a
smaller back-off window in comparison to a node that receives commands with a higher attenuation. It explains why queuing-delay for the R.Ankle node is much higher than that for the R.Thigh node.

3) Regarding PDRs, comparison of single-hop and multi-hop approaches confirms that a high PDR for all body nodes is not achieved unless multi-hop transmissions are supported. Under the single-hop scheme, less than 30% of the packets generated by the R.Ankle node (Node 1) reach the gateway, while the multi-hop scheme improves this value to 97%. Note that this improvement is achieved at the cost of extraction of more transmission-slots (commands) from the shared spectrum. In the single-hop case, the gateway launches commands every 200msec based on the total packet generation rate of body nodes (5 packets/sec) while for the multi-hop case this value is reduced to 150msec to provide a 33% increase in total transmission opportunities for the packets generated in the BAN, to accommodate packets that need to be relayed.

4) Regarding PDRs under dynamic multi-hop scheduling, although the reported PDR for node \( i \) is a function of the BAN topology, for every envisioned topology, the result is lower bound by PDR of node \( i \) under dynamic single-hop scheduling. The reason is that if node \( i \) has either very few logical neighbors or neighbors with low-quality links toward the gateway, node \( i \) does not benefit much from relaying. In the worst case this reduces to the dynamic single-hop PDR in which relaying is not supported. To validate this statement, PDRs of a set of nodes over different BAN topologies are reported in Table 5.2 to exemplify how the size and placement of other body nodes affect reported PDRs. For a better understanding of the effect of relaying on PDRs, note that dynamic single-hop PDRs of R.Ankle, L.Knee, R.Thigh, L-Wrist are 30%, 46%, 78% and 81%, respectively.

The goal of this section is to justify that our on-the-fly BAN scheduling scheme results in substantial improvements in PDRs without unreasonably sacrificing delays or imposing
computational overhead for tracking the body posture over time. Clearly, implementation of a more precise formula than (5.1) can better accommodate specific characteristics of body nodes. For instance, in a BAN with non-homogeneous nodes responsible for monitoring diverse physical and physiological parameters, specific traffic demands of each body node should be considered in the formula for calculating back-off windows.

Table 5.2: BAN topology and dynamic multi-hop scheduling performance

<table>
<thead>
<tr>
<th>PDR</th>
<th>R.Ankle</th>
<th>L.Knee</th>
<th>R.Thigh</th>
<th>L.Wrist</th>
<th>∆</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topology1</td>
<td>42%</td>
<td>48%</td>
<td>92%</td>
<td>90%</td>
<td>451_msec</td>
</tr>
<tr>
<td>Topology2</td>
<td>74%</td>
<td>77%</td>
<td>92%</td>
<td>90%</td>
<td>300_msec</td>
</tr>
<tr>
<td>Topology3</td>
<td>89%</td>
<td>86%</td>
<td>97%</td>
<td>90%</td>
<td>224_msec</td>
</tr>
</tbody>
</table>

5.5.4 Benchmarks

As benchmarks for evaluating the performance of our proposal, the following network layer approaches are implemented and tested under the setup explained in Sec. 5.5.1.

Static single-hop: is a TDMA approach in which the gateway announces the static scheduling pattern of body nodes at the start of each frame. This naive scheme provides the worst case results since it is completely blind to the BAN topology. For a fair comparison with dynamic single-hop scheduling, the TDMA frame length, i.e., scheduling round, is set to 1200msec with six slots per frame. Note that the static single-hop scheduling is equivalent to the IEEE 802.15.4 Beacon-Enabled mode in any implementations like TKN15.4 MAC developed at TU Berlin [78]. The Beacon-Enabled mode of the standard is preferred over the non-beacon mode for BANs because it offers the possibility of bandwidth reservation by allocating time slots, called Guaranteed Time Slots (GTSs), to guarantee an exclusive and contention-free access of a device to the channel during its GTS(s). Accord-
ing to the standard, GTS supports only single-hop communication between the coordinator and a device. Therefore, a BAN under IEEE 802.15.4 MAC operates as follow: a body node configures its GTS request to indicate its traffic requirement and then the 802.15.4-based gateway undertakes GTS allocation. The gateway announces GTS allocations in beacons that are periodically transmitted at the start of each frame. When a body node reaches its allocated slot, it wakes up to initiate a single-hop communication with the gateway. Thus the presented results for single-hop scheduling would be equivalent to that of any implementation of IEEE 802.15.4 Beacon-Enabled mode with GTS reservation, such as the TKN15.4 MAC developed at TU Berlin [78].

On-Demand Listening and Forwarding (ODLF) [66]: is a multi-hop TDMA approach where the gateway computes a parameter, called the quality factor, for all links based on their packet reception history. The gateway compares the link quality factors with a threshold to recognize the nodes that probably need to send their packets by multi-hops and then distributes a list of these nodes to the network. Body nodes listen to time-slots not only dedicated to them but also those assigned to nodes announced in the list. To have a reasonable comparison with the proposed dynamic multi-hop approach, in our ODLF implementation, we assume only one packet is transmitted in each slot. To take into account of the relaying load of nodes, the TDMA frame includes eight slots, which leaves two slots for supporting relayed packets. To distribute extra slots among nodes, packets have a “Weight” field which is filled by the total number of back-logged packets received from neighbor nodes; those that were part of the list. When the gateway receives a packet, it finds the latest “Weight” of the sending node and employs this information in assignment of extra slots to body nodes. If a node does not have a packet to transmit in its allocated slot, it sends a dummy packet.
5.5.5 Analysis of Results

Tables 5.3 and 5.4 summarize all the results and configuration parameters while figures 5.6 and 5.7 display them graphically to ease visualization and comparisons.

**PDR under single-hop approaches:** Results confirm that without any additional cost for tracking or prediction of the BAN topology, our single-hop topology-related scheduling achieves noticeably better PDRs compared to the static single-hop approach. Since all transmissions are single hop, both approaches operate under the same number of transmission opportunities equal to the total number of generated packets in the network. Results also point to the fact that single-hop communications are ill-suited to the BAN topology and considering a master-salve architecture for BANs is not realistic.

**Delay under single-hop approaches:** Under the static approach, queuing delays for all body nodes are approximately the same since it is the offset between generation of a packet in a 1200msec cycle and allocated slot to that node. Under dynamic scheduling, queuing-delay is related to the average back-off window of that node, which in turn is a function of the node’s average link quality. Hopping-delays for both approaches are similar (∼ 20msec) because all packets are transmitted in one-hop.

**PDR under multi-hop approaches:** Comparisons of PDRs obtained from ODLF and dynamic multi-hop approach show that under the same number of transmission opportunities, our dynamic multi-hop approach yields better results because it accounts for the immediate quality of links in scheduling to achieve more successful transmissions and minimize the number of packets that needs to be relayed by other nodes. This discussion suggests that ODLF can also achieve a higher PDR if more transmission opportunities are provided. To test this argument, the ODLF scenario is tested again with frames of 12 slots in which 6 slots are left for relaying packets. In this case, a PDR of 90% is reached for all body nodes but this improvement costs two times more transmission opportunities than
the actual BAN traffic rate. Taking a look at the average number of slots responding with dummy packets over five trials, (9.8, 6.8, 10.1, 5.2, 6.2, 9.2 for nodes 1, 2, . . . , 6 respectively) justifies that the least 12 slots per frame is required if ODLF targets PDRs higher than 90%. The end result is that ODLF may not be able to support as many body nodes or as high a sampling rate compared with our dynamic multi-hop approach. We emphasize that hardware limitations and dynamic transmission patterns of coexistence systems sharing the medium limit the number of commands that the gateway may launch over each time period. Practically it means that the number of commands available for packet relaying is not very high such that only a portion of the packets in MsgQ of body nodes find a chance to be relayed. Therefore, the more successful scheduling scheme yields a higher PDR despite a smaller number of extra commands for relaying.

*Delay under multi-hop approaches:* While supporting multi-hop transmission promisingly improves PDRs of low-power BANs, this is achieved at the cost of a larger average end-to-end packet delay. Therefore, the more efficient algorithm is the one that yields a better trade-off between PDR and delay. Delays for ODLF under $\Delta = 150$ msec are not reported since they were all higher than 2 sec, which is not acceptable for most biomedical applications.

Finally, comparisons of results are concluded in the two following observations:

1) *Dynamic scheduling provides robust data transfer in the presence of irregularities of body movements*

While dynamic scheduling allows on-the-fly scheduling of body nodes, TDMA approaches like ODLF schedules with a granularity of a round and ahead of actual transmissions of body nodes. However, per-round scheduling is not sensitive enough to connectivity changes and limb movements and does not provide frequent updates about quality of on-body links because of the following two reasons: 1) from the moment that a body node
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finishes its transmission in round \( t \) till the start of its next transmission in round \( t + 1 \), connectivity of a body node and the gateway may undergo dynamic changes, 2) if the sampling frequency of a body node is less than the frequency of slot allocation, the body node may not always have data to send in its allocated slot and so the gateway cannot update its knowledge about the node’s link quality. Under each of the explained situations, the gateway’s knowledge about link quality becomes obsolete which consequently degrades the quality of scheduling decisions. A remedy for both cases is forcing body nodes to send packets more often, even as dummy ones when they do not have data for transmissions, just to let the gateway track the link quality more precisely. However this is not feasible for long term pervasive monitoring that is required to support low data rates, low power consumptions of body nodes and irregularities of body movements.

2) Dynamic scheduling supports more single-hop transmissions and alleviates issues related to extraction of white-spaces out of a shared medium.

Comparison of PDRs confirm that static or per-round scheduling approaches waste lots of transmissions slots by not incorporating instantaneous node-gateway link quality in slot allocations while our proposed dynamic approaches effectively captures high quality on-body links to increase the number of successful packet transmissions. We emphasize that finding spectrum access opportunities subject to the BAN’s prompt medium access constraint is a challenging problem, due to the coexistence problem that we have comprehensively investigated in [51]. Therefore, the proposed cross-layer design is more robust and offers a higher reliability since it can meet the BAN’s data transfer requirements using a smaller number of transmission opportunities.
Figure 5.6: Comparison of PDR for proposed scheduling schemes

Figure 5.7: Comparison of delay for proposed scheduling schemes

Table 5.3: PDR comparison of scheduling schemes

<table>
<thead>
<tr>
<th>PDR</th>
<th>R.Ansle</th>
<th>R.Wrist</th>
<th>R.Shoulder</th>
<th>R.Knee</th>
<th>L.Shoulder</th>
<th>R.Thigh</th>
<th>Δ</th>
<th># commands / 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static Single-Hop</td>
<td>12%</td>
<td>50%</td>
<td>44%</td>
<td>39%</td>
<td>86%</td>
<td>74%</td>
<td>200msec</td>
<td>1505</td>
</tr>
<tr>
<td>Static Single-Hop</td>
<td>68%</td>
<td>63%</td>
<td>71%</td>
<td>75%</td>
<td>88%</td>
<td>89%</td>
<td>150msec</td>
<td>1998</td>
</tr>
<tr>
<td>ODLF</td>
<td>65%</td>
<td>90%</td>
<td>91%</td>
<td>95%</td>
<td>93%</td>
<td>99%</td>
<td>100msec</td>
<td>3002</td>
</tr>
<tr>
<td>Dynamic Single-Hop</td>
<td>30%</td>
<td>68%</td>
<td>62%</td>
<td>71%</td>
<td>97%</td>
<td>78%</td>
<td>200msec</td>
<td>1505</td>
</tr>
<tr>
<td>Dynamic Multi-Hop</td>
<td>97%</td>
<td>98%</td>
<td>97%</td>
<td>99%</td>
<td>95%</td>
<td>99%</td>
<td>150msec</td>
<td>1998</td>
</tr>
</tbody>
</table>

Table 5.4: Delay comparison of scheduling schemes

<table>
<thead>
<tr>
<th>Delay (msec)</th>
<th>R.Ansle</th>
<th>R.Wrist</th>
<th>R.Shoulder</th>
<th>R.Knee</th>
<th>L.Shoulder</th>
<th>R.Thigh</th>
<th>Δ</th>
<th># commands / 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static Single-Hop</td>
<td>645.28</td>
<td>622.4</td>
<td>531.33</td>
<td>627.22</td>
<td>564.24</td>
<td>610.92</td>
<td>200msec</td>
<td>1505</td>
</tr>
<tr>
<td>Static Single-Hop</td>
<td>228.76</td>
<td>231.96</td>
<td>276.69</td>
<td>206.9</td>
<td>288.23</td>
<td>244.81</td>
<td>100msec</td>
<td>3002</td>
</tr>
<tr>
<td>ODLF</td>
<td>1498.8</td>
<td>1121.9</td>
<td>1049.5</td>
<td>1210.85</td>
<td>548.1</td>
<td>598.5</td>
<td>100msec</td>
<td>3002</td>
</tr>
<tr>
<td>Dynamic Single-Hop</td>
<td>899.84</td>
<td>501.05</td>
<td>421.53</td>
<td>442.38</td>
<td>380.46</td>
<td>285.88</td>
<td>200msec</td>
<td>1505</td>
</tr>
<tr>
<td>Dynamic Multi-Hop</td>
<td>1415</td>
<td>978.6</td>
<td>838.7</td>
<td>821.9</td>
<td>399.3</td>
<td>608.7</td>
<td>150msec</td>
<td>1998</td>
</tr>
</tbody>
</table>
5.5.6 Relaying and BAN Topology

When a body node has more logical neighbors, its pending packet for relaying is found in MsgQ of more body nodes since a copy of this packet is received by a bigger set of neighbors. This situation potentially increases the chance of duplicate relaying since the same packet may be relayed via multiple relaying nodes before it finally reaches the gateway. Here we examine whether duplicate relaying is a major issue in a BAN with more nodes or not.

In this regard, a base topology consists of body nodes on L.Ankle, L.Knee, L.Thigh, L.Wrist is considered and then in the course of four steps, a similar chain of nodes are added on the right side of the body to gradually improve the chance of relaying for packets generated by nodes in the base topology. To have comparable results, the ratio between the number of commands and the total number of generated packets in the network, called $\rho$, is kept constant as follows. If there are $y$ body nodes in the BAN and each node generates $x$ packets in the course of a trial, then the gateway launches a total number of $\rho \cdot x \cdot y$ commands. This value increases to $\rho \cdot x \cdot (y+1)$ when a new body node is added. Therefore, the average transmission share of each body node remains fixed to $\rho \cdot x$ under all topologies.

As clarified before, coexistence of a BAN with powerful networks like WLAN limits the rate of commands launched by the gateway, which noticeably reduces the number of opportunities left for relaying purpose. Consequently, the goal of high PDRs for body nodes should be achieved under small values of $\rho$, which are very close to but higher than one. Our experimental results illustrate that with $\rho = 1.33$, PDR higher than 90% is achievable for all body nodes in the base topology. Given the following definitions:

- $c_i^j$: number of times that node $j$ relays packets of node $i$
- $\sum_{\forall j \neq i} c_i^j$: number of times that packets of node $i$ are relayed
- $\sigma$: difference between the number of commands and the total number of generated packets
Experimental results in Table 5.5 (each reported value is the average over 10 trials lasting five minutes each) reveal the following. When BAN topology with $y$ nodes changes to the one with $(y+1)$ nodes, the number of chances given to node $i$’s packets for relaying, i.e. $\sum_{\forall j \neq i} c_j^i$, remains approximately unchanged even though the number of logical neighbors for node $i$ increases. This confirms that duplicate relaying is not a significant issue when BAN has more nodes. If duplicate relaying is frequent, $\sum_{\forall j \neq i} c_j^i$ increases for node $i$ especially for a node with very low single-hop PDR like R.Ankle that most of its packets reach the gateway via relaying. The reasons behind this observation are as follow:

1) **Available opportunities for relaying are limited:** When the size of a BAN topology increases, the number of pending packets for relaying is larger but the number of opportunities that a body node has for transmission is fix (equal to $\rho \cdot x$). As a result, a relaying node does not find more chances to completely service its MsgQ although it potentially has a larger number of pending packets for relaying.

2) **Fair distribution of commands between all contending body nodes:** Because of the sliding window incorporated in our back-off mechanism, the new added node captures its own share of commands for transmissions no matter it has a good or bad quality link toward the gateway. As a result, those extra $\sigma$ commands for relaying are distributed among one more node.

3) **Packets in DataQ have priority over those in MsgQ:** When a node has more neighbors, its packets are found in MsgQ of more neighbors but these packets are completely disregarded as long as a potential relaying node has a non-empty DataQ.

4) **When a BAN has more nodes, the number of neighbors with good-quality links toward the gateway is higher:** When a body node has more neighbors, the chance that its packet is relayed sooner via a neighbor with a good-quality link and removed from MsgQ of all candidate relaying nodes is higher. This reduces the average number of transmissions
Chapter 5. Cross-Layer Design for Reliable Transmissions over Body Area Networks

Figure 5.8: Contribution of body nodes in relaying packets of L.Ankle

Table 5.5: Distribution of relaying opportunities between body nodes

<table>
<thead>
<tr>
<th>Topology</th>
<th>$\sum_{j\neq i} c^j_i$</th>
<th>L.Ankle</th>
<th>R.Ankle</th>
<th>L.Knee</th>
<th>R.Knee</th>
<th>L.Thigh</th>
<th>R.Thigh</th>
<th>L.Wrist</th>
<th>R.Wrist</th>
<th>$\sigma$</th>
<th>$\Delta$</th>
<th>$\rho$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topology1</td>
<td>151.25</td>
<td>131.84</td>
<td>115.42</td>
<td>15.09</td>
<td>43.89</td>
<td>342</td>
<td>1.33</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Topology2</td>
<td>121.02</td>
<td>147.11</td>
<td>110.45</td>
<td>76.75</td>
<td>9.68</td>
<td>34.0</td>
<td>34.53</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Topology3</td>
<td>141.77</td>
<td>149.82</td>
<td>118.88</td>
<td>80.81</td>
<td>16.87</td>
<td>26.93</td>
<td>40.12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Topology4</td>
<td>146.24</td>
<td>170.15</td>
<td>126.41</td>
<td>85.38</td>
<td>14.41</td>
<td>29.26</td>
<td>46.05</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Topology5</td>
<td>145.94</td>
<td>157.29</td>
<td>126.41</td>
<td>85.38</td>
<td>14.41</td>
<td>29.26</td>
<td>46.05</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

required by a relayed packet to reach the gateway.

5) **Having more neighbors does not always improve the chance of relaying:** Contribution of a specific body node in relaying other nodes’ packets is a function of its link quality. Nodes with low-quality links usually deal with transmissions of their own packets and rarely participate in packet relaying while higher quality links get more involved in relaying. Therefore, even though the added body node receives most of the packets transmitted in its neighborhood, it may find little opportunities to relay these packets. For instance, R.Ankle receives most of L.Ankle’s packets but its contribution in relaying packets of L.Ankle is only $\frac{c^{R.Ankle}_{L.Ankle}}{\sum_{j\neq i} c^j_i} = 6\%$ under Topology4 as illustrated in Fig. 5.8.
5.5.7 Duty Cycle and Energy Consumption

Figs. 5.9a-5.9b illustrate lower and upper bounds of duty cycle and energy consumptions based on parameters $k_1$, $k_2$ and $k_3$ extracted from experiments. Table 5.6 represents the breakdown of these parameters. The average energy consumptions are calculated based on $V_{bat} = 3V$ and the CC2420 radio parameters of $I_{trans} = 8mA$, $I_{tx} < 8.5mA$ (for PA-LEVEL=2), $I_{rx} = 19.7mA$, $I_{idle} = 18.8mA$ and $T_{trans} = 0.58msec$. Observations show that a better connectivity with the gateway and being in the neighborhood of a bigger set of nodes make a node more ready to work as a relay and introduce larger $DC^{up}$ and $E^{up}$ for that node, like R.Thigh (Node 6 in Fig. 5.2).

For ODLF, providing that a body node is assigned $k_1$ slots, its ON duration and energy consumption over a TDMA frame of $K$ slots are calculated as $(k_1 + |\psi|)(T_{TX} + T_{trans})$ and $E_{ODLF} = [T_{TX}(k_1I_{tx} + |\psi|I_{rx}) + (k_1 + |\psi|)T_{trans}I_{trans}]V_{bat}$, respectively where $|\psi|$ is the average size of the gateway’s requested set for overhearing. $|\psi|$ is a network parameter and depends on the overall link quality of body nodes toward the gateway. The applied placement of nodes in this set of experiments brings $|\psi| = 3.7$ for the ODLF.

Since the passive RF module adds only a negligible energy cost, results in Fig. 5.9b are concentrated on the main radio’s energy consumption for transmission, reception and idle-listening. Based on the reference implementation of the wake-up circuit in [33], the average transmission time of a 2 bytes wake-up signal (command or win-packet) is 21.2msec. Considering that the TelosB microcontroller consumes 340µA at 3V in its active mode, the energy spent for receiving a wake-up signal turns out to be 21.6µJ. Also, the current drawn by this circuit and its operating power consumption in the sleep mode are 4.176µA and 12.528mW, respectively.

Justified by the reported results, opportunistic scheduling has some advantages, in terms of not only PDR but also an energy consumption, over per-round scheduling schemes.
like ODLF because per-packet scheduling, provided by our proposal, shortens the radio ON durations required for packet relaying by supporting a larger number of direct communication links with the gateway.

![Graphs showing duty cycle and power consumption](image)

Figure 5.9: a) Comparison of duty cycles, b) Comparison of power consumptions

<table>
<thead>
<tr>
<th></th>
<th>$D_{C_{up}}$</th>
<th>$SI_{low}$</th>
<th>ODLF $k_1$</th>
<th>$SI_{ODLF}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-Ankle</td>
<td>1.5</td>
<td>1.5</td>
<td>2.3</td>
<td>235 msec</td>
</tr>
<tr>
<td>R.Wrist</td>
<td>1.4</td>
<td>1.4</td>
<td>2.8</td>
<td>220 msec</td>
</tr>
<tr>
<td>R.Shoulder</td>
<td>1.7</td>
<td>1.9</td>
<td>2.2</td>
<td>215 msec</td>
</tr>
<tr>
<td>R.Knee</td>
<td>1.8</td>
<td>2.4</td>
<td>1.9</td>
<td>206 msec</td>
</tr>
<tr>
<td>L.Shoulder</td>
<td>1.3</td>
<td>0.8</td>
<td>0.8</td>
<td>425 msec</td>
</tr>
<tr>
<td>R.Thigh</td>
<td>2.0</td>
<td>2.1</td>
<td>2.8</td>
<td>180 msec</td>
</tr>
</tbody>
</table>

### 5.6 Summary

Ambulatory health monitoring using BANs enables care-givers to diagnose a patient’s condition, predict ongoing risks and adjust treatments and medication dosage on a real-time and continuous basis. Therefore, any late or corrupted (lost) data may put the patient’s health at risk. In this chapter, we proposed a cross-layer design for BANs to provide a prompt and reliable platform for transmissions of sensory data to the gateway at
any time over a BAN. Our design includes a dynamic scheduling approach that is built on top of the CBAS, the gateway-initiated MAC scheme discussed in Chapter 3. CBAS, by opportunistic extraction of white-spaces from the whole frequency band, provides a high availability of access opportunities for the BAN to promptly access the shared medium. In this proposal, the MAC layer feeds the network layer with instantaneous conditions of on-body links to make implementation of a light-weight BAN dynamic scheduling feasible. Our topology-adaptive network layer design improves the chance of successful one-hop packet transmissions thus reducing the demands for packet relaying, while enabling cooperative multi-hop transmissions for body nodes with poor connectivity to the gateway, with little overhead for maintaining network connectivity or end-to-end routing paths. Our discussion in this chapter is backed by extensive experimental results to thoroughly demonstrate the efficiency of our cross layer design in supporting real-time and reliable connectivity over a BAN compared with existing approaches.
Chapter 6

Distributed QoS-aware Channel Selection Strategy for Body Area Networks

6.1 Introduction

Operation of BANs in close vicinity demands a QoS-aware platform to address various traffic requirements of patients. Traffic from patients in more critical condition should be served earlier than that from patients in a safer condition. For instance, an injured person is required to be served with a higher priority than a healthy person. Overlooking this multi priority requirements can cause life-critical issues especially when the overall capacity is not sufficient to support the total transmission bandwidth requested by the all collocated BANs. In a QoS-aware platform, the gateway, as a resource manager of a BAN, takes the traffic intensity of other BANs into consideration when it wants to capture a channel. Therefore, the applied channel selection strategy in the gateway should be self-regulating (fair) and load-aware such that not only inter-BAN interference is kept low but also radio resources (available spectrum holes) are distributed between BANs proportional to their traffic demands and QoS requirements.

This chapter is based on the following paper:
Chapter 6. Distributed QoS-aware Channel Selection Strategy for Body Area Networks

As a practical example, consider an environment where three BANs coexist while a common pool of four candidate channels, with the corresponding mean availabilities of $CH_1 \sim 0.9/CH_2 \sim 0.7/CH_3 \sim 0.5/CH_4 \sim 0.2$, is available for their operation. Also, BANs, worn on the body of different persons, are categorized into different classes of priorities based on the health condition of the respective person. Suppose BAN1 is carried by a person who has recently passed a surgery, BAN2 is worn on a body of a person with a chronic disease like diabetes and finally BAN3 is on a body of a healthy person. In comparison and in terms of the throughput and delay, BAN1 has the most strict QoS requirements and BAN2 requires a higher level of service than BAN3. In this situation and to provide a better service for these BANs, the rank-optimal choice of channels for BAN1, BAN2 and BAN3 would be CH1, CH2 and CH3 respectively. These three channels have the three highest mean availabilities in the channel pool.

As comprehensively discussed in Chapter 3, an opportunistic gateway-initiated MAC scheme resolves the large access delays that a BAN faces in contention with high-power and high data-rate networks. In this platform, the gateway, as a Secondary User (SU), actively probes a wide part of the spectrum, finds white-spaces that appear between transmissions of more powerful networks, which are considered as Primary Users (PU) of the shared medium, and initiates a connection that is orthogonal to the existing transmissions in frequency and/or time. This way, a BAN takes advantage of the possible empty spaces in the spectrum to have low delay medium access and interference-free transmission-slots. Thus, it is crucial for the gateway to make optimal decisions about which part of the spectrum to sense at different times. This gives rise to the trade-off between exploration: sensing new channels in the hope of obtaining better availability and exploitation: ensuring a successful transmission in the current time.

When multiple SUs coexist, there is a competition for access to the channel with the
highest mean availability. As a result, 1) collision is likely since multiple SUs may select the same channel. Note that SUs do not explicitly exchange information about their observations and channel selection strategy to avoid excessive channel selection cost, 2) QoS requirements of SUs are disregarded although they may have different ranks/priorities. However, handling of this coexistence problem is possible when SUs cooperatively seek their own unique rank-optimal channels and confine their operation on the rest of sub-optimal ones. This approach not only provides a better level of QoS but also reduces the chance of collisions.

The main contribution of this chapter is proposing a learning strategy, called \( k^{th}-MAB \), for distributed channel selection in cognitive radio networks. This strategy helps QoS provisioning such that competing SUs cooperatively converge to their rank-optimal channels while channel availability statistics are initially unknown. \( k^{th}-MAB \) is inspired from the classic Multi-Armed Bandit (MAB) problem but it converges to the \( k^{th} \) best channel. The rank-optimal channel for each user is identified based on the user’s QoS requirements. By this convergence, SUs receive services proportional to their QoS requirements while collision probability reduces a lot since SUs eventually work on orthogonal channels.

The rest of the chapter is organized as follow: a brief review about proposed distributed channel selection strategies in the literature is provided in Section 6.2. The MAB problem for finding the best channel in cognitive networks and two of the most cited solutions for this problem are reviewed in Section 6.3. Our distributed rank-based channel-selection strategy, \( k^{th}-MAB \), is proposed in Section 6.4. Performance evaluation and summary of the chapter are covered in Section 6.5 and Section 6.6 respectively.
6.2 Literature Review

Autonomous management and distribution of radio resources between collocated networks require SUs to have self-learning ability to constantly adapt their action strategy according to the network dynamism. It means that an effective solution for finding the rank-optimal channel should be model-free and coordination-free without a need for detailed modeling of the environment.

As a promising strategy, Q-learning is widely suggested to integrate context information and intelligence into dynamic channel selection. For instance, by applying the eRL- MAC strategy proposed in [79], SUs converge to a joint action that provides a better network wide performance. However, eRL- MAC limits the number of agents undergoing exploration within a neighborhood to only one SU to avoid instability in the learned channel mean availabilities. For this, an SU must announce its state, i.e. the start and termination of its exploration phase, to its neighbor agents. This requirement contradicts with the underlying assumption that SUs do not distribute any information regarding their strategy or observations.

Investigations justify that separation of exploration and exploitation phases is very inefficient. In fact, exploring the available spectrum pool by accessing all resources with equal probability, regardless of the information gained thru exploration result in high levels of interference [80]. In this regard, authors in [81] proposed the “Weight-drive” exploration to utilize the historical information gained in exploration to influence action selection, thereby achieving a more efficient exploration phase.

Authors in [82] have considered the problem of finding rank-optimal channels under two cases based on whether SUs have prior information about their ranks or not. For the first case, they proposed distributed learning under pre-allocation called $\rho_{PRE}$ which is a modified version of the $\epsilon - greedy$ strategy in [83]. In trial $n$ and under $\rho_{PRE}$ policy, an
SU with rank \( k \), selects a uniformly random channel with probability \( \epsilon_n = \min(1, \beta/n) \) and selects the channel with \( k^{th} \) highest sample mean with probability \( 1 - \epsilon_n \).

However, since the obtained observations about channel status (absence/presence of a PU) are stochastic, it might happen that during the first trials the optimal channel always gives low rewards. This situation makes the sample-mean of this channel smaller than that of the other channels. Hence an algorithm that only uses sample-means, like \( \epsilon - \text{greedy} \), might get stuck by not choosing the optimal channel any more. Upper Confidence Bound (UCB) policies in general prevent this problem by using the confidence bound on the mean rewards [84].

UCB policies are a category of learning strategies that successfully merge the exploration and exploitation phases by taking into account the knowledge gained in exploration to guarantee a specific level of accuracy about the learned criteria. The study in [85] applies a variant of the UCB policy to ensure fairness among SUs with the same level of QoS demand. The proposed Time Division Fair Sharing (TDFS) structure properly helps an SU to find the ordering of channels such that all competing SUs get approximately the same share from the \( U \)-best available channels and consequently reach the same maximum achievable throughput.

### 6.3 Finding the Best Channel

MAB problem in the context of cognitive radio networks is formulated as an exploration vs exploitation dilemma for choosing the best channel by selecting one out of \( M \) possible channels in each trial \( t \in 1, ..., n \). For the chosen channel \( i \) in trial \( t \), reward \( x_i^{(t)} \) is drawn from some fixed but unknown distributions while the rewards for other channels excluding channel \( i \) are not revealed. The appropriate strategy for the MAB problem pursues the goal of maximizing the total reward up to an observation period \( n \), i.e. \( \sum_{i=1}^{M} \sum_{t=1}^{n} x_i^{(t)} \).
where the upper bound of expected reward is obtained by the channel with the highest availability. The difference between this upper bound and the achieved total reward is defined as the \textit{regret}. The amount of regret determines the efficiency of the selection strategy in finding the best channel \cite{86}.

The exploration/exploitation trade-off is reflected on one hand by the necessity for trying all channels and on the other hand by the regret suffered by trying a non-optimal channel. Too little exploration might make a sub-optimal alternative look better than the optimal one because of random fluctuations, while too much exploration prevents the algorithm from applying the optimal solution often enough which also results in a large regret. Here, two categories of policies for solving the MAB problem are explained in the context of channel selection in cognitive radio networks.

\subsection*{6.3.1 Epsilon-Greedy Policy}

The general idea is that an SU does a lot of experiments by selecting different channels to estimate their availability ratios and eventually converge to the best one. At each trial, the \(\epsilon - greedy\) policy selects with probability \(1 - \epsilon\) the channel with the highest average reward and with probability \(\epsilon\) a randomly chosen channel. It shows that with a finite probability \(\epsilon\), an SU does not select the best channel and instead finds an opportunity to explore other channels to find a better estimation about their sample means. The obvious improvement is to let \(\epsilon\) go to zero in the course of each trial when the channel reward estimations become more accurate \cite{83}.

\subsection*{6.3.2 Upper Confidence Bound Policy}

\textbf{UCB1 policy}

UCB1 policy chooses channel \(i^{(t)}\) in trial \(t\) as:
Chapter 6. Distributed QoS-aware Channel Selection Strategy for Body Area Networks

\[ i^{(t)} = \arg \max_{i \in M} \left( \bar{x}_i^{(t)} + \sqrt{\frac{2\log(n)}{n_i^{(t)}}} \right) \]  

(6.1)

where, \( n \) is the number of trials done so far, \( \bar{x}_i^{(t)} \) is the current average reward estimated for channel \( i \) and \( n_i^{(t)} \) is the number of times that channel \( i \) has been played till trial \( n \). If \( R_i \) is defined as the true expected reward of channel \( i \), the second term in (6.1) corresponds to the confidence interval that both the true and average rewards fall in with high probability, i.e.,

\[ (\bar{x}_i^{(t)} - \sqrt{\frac{2\log(n)}{n_i^{(t)}}}) \leq R_i \leq (\bar{x}_i^{(t)} + \sqrt{\frac{2\log(n)}{n_i^{(t)}}}). \]

With UCB1, a trial is regarded as an exploitation if channel \( i \) is chosen because of its large value of \( \bar{x}_i^{(t)} \) and as an exploration if \( \sqrt{\frac{2\log(n)}{n_i^{(t)}}} \) is large. Since the second term decreases rapidly with each choice of channel \( i \), the number of exploration trials is limited. Thus, the use of UCB1 automatically trades off between explorations and exploitations.

**UCB-V Policy**

UCB-V is a variant of the basic algorithm for the stochastic MAB problem that takes into account the empirical variance of different channels [87, 88]. In fact, UCB-V improves UCB1 by using variance estimates in its bias factor as follow:

\[ i^{(t)} = \arg \max_{i \in M} \left( \bar{x}_i^{(t)} + \sqrt{\frac{(\bar{x}_i^{(t)} - (\bar{x}_i^{(t)})^2)c\log(n)}{n_i^{(t)}}} + \frac{c\log(n)}{n_i^{(t)}} \right) \]  

(6.2)

where we are free to adjust \( \epsilon \) and \( c \).
6.4 Finding the $k^{th}$ Best Channel

6.4.1 System Model

We assume that time is slotted and channel $i$ is occupied with probability $1 - \mu_i$ by PUs at each time-slot. There is a set of $U$ users grabbing free time-slots from $M$ ($U < M$) independent and orthogonal channels on the premise of not interfering with the operation of licensed PUs. Like [82], we assume each SU has a prior information about its own unique rank amongst the rest of $U-1$ users and greedily seeks free time-slots because it always has packets for transmission. Without loss of generality and for the sake of notational simplicity, suppose channels are ordered by their mean availability ratios, i.e., $\mu_1 > \mu_2 > ... > \mu_M$. Also, SUs are ordered according to their ranks, i.e., $SU_k$ and $SU_q$ have the $k^{th}$ and $q^{th}$ highest ranks where $k, q \in \{1, ..., U\}$ and $SU_k$’s rank is higher than that of $SU_q$ if $k < q$. We assume that the $U$ largest mean availabilities are distinct.

Here, users should learn channel mean availabilities, $\mu_i, i \in \{1, ..., M\}$, in a distributed manner and in a finite observation period. SUs target convergence to an appropriate channel while they do not exchange information on their observations and on the other hand they implement the pre-allocated rankings. Thus, the optimal channel selection strategy bounds the operation of $SU_k$ on the channel with the true expected reward $\mu_k$. Note that two terms, time-slot and trial, will be used interchangeably in the rest.

At the beginning of a time-slot, user $k$ selects a channel, say $i$, and keeps the number of selections of this channel on $T_{k,i}$. User $k$ then senses the selected channel $i$ to find if PU has occupied this slot or not and keeps the history of sensing results regarding channel $i$ in $X_{k,i}$. In fact, $X_{k,i}$ represents the number of times that channel $i$ is found free of PU operation. User $k$ approximates the mean availability of channel $i$ as $\hat{\mu}_i = \frac{X_{k,i}}{T_{k,i}}$. Then in the next time-slot, user $k$ applies the channel selection strategy and considers previous
observations in the form of $\hat{\mu}_i \in \{1, ..., M\}$ to pick a channel for sampling.

Finding a free channel indicates that a time-slot is free of PU transmissions but, it does not guarantee that $SU_k$ is the sole transmitter of that trial. In fact, collision is likely since multiple SUs may select a common channel. However, an SU, by learning its rank-optimal channel, confines its operation on the sub-optimal channels which consequently reduces the chance of collision in the course of trials. To estimate the achievable throughput, user $k$ keeps the number of successful transmissions based on the received acknowledgment packets received on channel $i$ in $Z_{k,i}$. This system model is borrowed from [82] since results related to our proposal are compared with those presented in this paper.

SU ranking assignment is out of the scope of this study however, a possible approach could be as follow. A gateway, as the BAN arbitrator, is able to determine its own location and the location of other BANs. This capability helps gateway to find the possibility of inter-BAN interference problem. Moreover, each gateway has a status, like what people have in the Facebook, to represent QoS requirements of its corresponding body nodes. It allows a BAN to become aware of the status of collocated BANs in its close region. Thus, the gateway categorizes BANs into different groups based on their need for medical treatments and estimates its own rank. Hence after, the gateway applies the proposed $k^{th}$-$MAB$ policy to consider priority information of other BANs when it wants to capture one of the perceived available channels.

### 6.4.2 $k^{th}$-$MAB$ Policy

In this section, the $k^{th}$-$MAB$ policy as a distributed rank-optimal channel selection strategy is proposed. The structure of this policy for $SU_k$ with the $k^{th}$ highest rank consists of 1) $k$ different lists initialized by channel estimations $\hat{\mu}_i \in \{1, ..., M\}$ and, 2) periodic frames while each frame includes $k$ consecutive time-slots. $SU_k$ employs these $k$ lists to find
the order of $k$-best channels and finally converge to its own rank-optimal channel. To make channel selection procedure more tractable, we explain the $k^{th}$-MAB policy with an example and then provide its formal description in Procedure

Consider $SU_3$ with the third highest rank among all collocated users. $SU_3$ works in frames of three time-slots and employs $list_1$, $list_2$ and $list_3$ to find the three out of $M$ channels with the highest mean availabilities and smoothly converge to the third one. For this reason, $SU_3$ samples each channel $i$, $i \in \{1, ..., M\}$, once and collects the following results as $X_{3,i} = 1(0)$ and $T_{3,i} = 1$ after the first $M$ time-slots. Note that $X_{3,i} = 1$ indicates that $SU_k$ found channel $i$ free of PU at the time of sampling. Then at the $(M+1)^{th}$ time-slot, $SU_3$ initializes $list_1$, $list_2$ and $list_3$ with $\hat{\mu}_i = \frac{X_{3,i}}{T_{3,i}}$ and starts its work in frames of three time-slots as follow:

**Step 1:** In the first time-slot, with probability $P_{\text{switch}}$ the best channel of $list_1$ is estimated, say channel $i$, based on the UCB-V policy. Then, 1) $X_{3,i}$ and $T_{3,i}$ are updated and a better estimation for $\hat{\mu}_i$ is obtained and 2) All entries of $list_1$ except the one related to the selected channel $i$ are assigned to $list_2$. As a consequence, $list_2$ includes information about the $M$-1 lowest rank channels and not about the estimated best channel $i$. Otherwise, i.e., with probability $1-P_{\text{switch}}$, the best channel of $list_3$ is sampled and its relevant parameters $X_{3,i}$, $T_{3,i}$ and $\hat{\mu}_i$ are updated. Note $P_{\text{switch}} \sim \min(1, \frac{\beta}{\sqrt{n}})$, where $n$ represents the number of trials done so far.

**Step 2:** In the second time-slot, the best channel of $list_2$ is estimated, say channel $i$, based on the UCB-V policy and with probability $P_{\text{switch}}$. Then, 1) $X_{3,i}$ and $T_{3,i}$ are updated and a better estimation for $\hat{\mu}_i$ is obtained and 2) All entries of $list_2$ except the one related to the selected channel $i$ is copied to $list_3$. Thus, $list_3$ does not have information about the estimated first and second best channels and only includes those related to the
$M-2$ lowest rank channels. Otherwise, i.e., with probability $1-P_{\text{switch}}$, the best channel of list$_3$ is estimated and sampled.

**Step 3:** In the third time-slot, the best channel of list$_3$ is estimated, say channel $i$, based on the UCB-V policy, $X_{3,i}$ and $T_{3,i}$ are updated and a better estimation for $\hat{\mu}_i$ is obtained. The next time-slot would be the start of the next frame and all above three steps are repeated.

Note that in the first and the second time-slot of a frame, UCB-V is applied to list$_3$ with probability $1-P_{\text{switch}}$. This allows SU$_3$ to smoothly settle down in the third best channel because the probability of selecting sub-optimal channels, $P_{\text{switch}}$, reduces and reaches zero in the course of trials. The value of $\beta$ in $P_{\text{switch}}$ defines the convergence rate and represents the trade-off between exploitation and exploration. In fact $k^{th}$-MAB combines UCB and $\epsilon-greedy$ policies for finding the $k^{th}$-best channel instead of the channel with the highest mean availability.

In Procedure 6.1, \(\setminus\) is the notation for an excluding operation and $B(\alpha)$ means Bernoulli distribution with parameter $\alpha$.

### 6.5 Performance Evaluation

In this section, the performance of the $k^{th}$-MAB policy in resolving contentions among SUs with different QoS requirements is evaluated. Corresponding results related to the $\rho^{\text{PRE}}$ strategy are also provided for comparisons. To the best of our knowledge, the $\rho^{\text{PRE}}$ is the only available policy in the literature that tackles the problem of rank-optimal channel selection under pre-allocated ranks. The efficiency of our proposal is demonstrated by extensive numerical results while analytical evaluations are postponed to the future work.
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Procedure 6.1 $k^{th}$-MAB policy for $SU_k$ with the $k^{th}$ highest rank

1: **Init**
2: Select channel $i, i \in \{1, ..., M\}$ once and update $X_{k,i}$ and $T_{k,i}$
3: Consider $k$ separate lists and initialize them with $\hat{\mu}_i = \frac{X_{k,i}}{T_{k,i}}$
4: Set $n = M$

5: **In each trial** $n > M$

6: $n = n + 1$
7: $h = (n \mod k) + 1$
8: $Y_{\text{switch}} = B(\min(1, \beta \sqrt{n}))$

9: If $Y_{\text{switch}} = 0$ or $h = k$:
10: Apply UCB-V to $\text{list}_k$
11: Select the best channel, say $i$, and update $\hat{\mu}_i$.

12: **Else**
13: If $h = 1$:
14: Apply UCB-V to $\text{list}_1$
15: Select the best channel, say $i$, and update $\hat{\mu}_i$
16: $\text{list}_2 = \text{list}_1 \setminus i$

17: Else if $h = 2$:
18: Apply UCB-V to $\text{list}_2$
19: Select the best channel, say $i$, and update $\hat{\mu}_i$
20: $\text{list}_3 = \text{list}_2 \setminus i$

21: ... 

22: Else if $h = k - 1$:
23: Apply UCB-V to $\text{list}_{(k-1)}$
24: Select the best channel, say $i$, and update $\hat{\mu}_i$
25: $\text{list}_k = \text{list}_{(k-1)} \setminus i$

In the presence of a centralized arbitrator, $SU_k$ is *centrally assigned* to work on the channel with the $k^{th}$ highest mean availability, say channel $h$ with $\mu_h$ which is called the rank-optimal channel for $SU_k$. Assignment of SUs to those orthogonal channels makes collision occurrence unlikely and guarantees the maximum average throughput $\mu_h$ for $SU_k$. 

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Figure 6.1: Convergence rate to the optimal channel vs. the number of trials under $k^{th}$-MAB and $\rho^{PRE}$ policies

However, without such an optimal allocation, users may not choose the appropriate channels and experience collisions in the course of trials for finding their rank-optimal channel. Thus, results related to the centralized case are considered as a reference to compare the efficiency of different channel selection schemes. In this regard, three comparison criteria are introduced as follow:

1) $rank_{opt}^k$: Under the given channel selection policy, $rank_{opt}^k = \frac{T_{k,h}}{\sum_{i=1}^{M} T_{k,i}}$ gives an es-
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Figure 6.2: The normalized regret vs. the number of trials under $k^{th}$-MAB and $\rho^{PRE}$ policies
timate of the percentage of time that $SU_k$ transmits on its rank-optimal channel and represents the efficiency of the given policy in bounding the operation of $SU_k$ to channel $h$. Note that under a centralized allocation policy, $SU_k$ always works on the channel $h$.

2) $\text{regret}_k^n$: Under the centralized allocation policy, the maximum achievable throughput for $SU_k$ after $n$ trials is $n\mu_h$ while its actual throughput under any policy is $\sum_{i=1}^{M} Z_{k,i}$. The difference of these two values, i.e., $\text{regret}_k^n = n\mu_h - \sum_{i=1}^{M} Z_{k,i}$, indicates how much
3) Throughput: Under the presence of a centralized arbitrator, the average throughput of $SU_k$ is $\mu_h$ which reduces to $\frac{\sum_{i=1}^{M} Z_{k,i}}{\sum_{i=1}^{M} T_{k,i}}$ under a decentralized channel selection strategy. This value estimates the percentage of successful packet transmissions.

In the following evaluations, we consider that a pool of $M = 5$ orthogonal channels with mean availabilities characterized by the following Bernoulli distributions, $CH1 \sim B(.8)$, $CH2 \sim B(.6)$, $CH3 \sim B(.4)$, $CH4 \sim B(.2)$, $CH5 \sim B(.1)$ is available for SUs. Fig. 6.1, Fig. 6.2 and Fig. 6.3 show the results for $k^{th}$-MAB and $\rho^{PRE}$ channel selection policies. Each column of these three figures corresponds to a specific number of coexistence SUs, e.g., $U=3$, and illustrates comparable results. Suppose SUs are ordered according to their ranks as $SU_0 > SU_1 > SU_2 > SU_3$. Under this ordering, the rank-optimal channels for $SU_0$, $SU_1$, $SU_2$ and $SU_3$ are CH1, CH2, CH3 and CH4, respectively. Also, $\beta$ in $P_{\text{switch}}$ is set
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to 3. The $\rho^{PRE}$ policy is evaluated for different values of $\beta$ and it is empirically estimated that $\beta = 200$ is one of the values that gives comparable results to $k^{th}$-MAB. However, results related to $\beta = 1000$ are also provided in Fig. 6.1. To make the comparison easier, a vertical line corresponds to 90% of the final value, is added to each graph.

6.5.1 Convergence to the Rank-Optimal Channel

Fig. 6.1 represents the results for $rank^k_{opt}$. This criterion indicates how fast a learning strategy converges to the rank-optimal channel. For the case of $U=2$ and under the $k^{th}$-MAB policy, $SU_1$ with the lowest priority does 85% of its transmission on its desired channel, i.e., CH2, after 2000 trials but the similar situation happens around the 7000$^{th}$ trial under the $\rho^{PRE}_{\beta=200}$ policy. For $U=3$, $SU_0$ with the highest rank transmits almost all of its packets on CH1 after 4000 trials but under the $\rho^{PRE}$ policy, its convergence rate to CH1 is bounded to 90%. All results indicate that the $k^{th}$-MAB is a more efficient policy than the $\rho^{PRE}$ especially when the observation period is short.

Note that under a higher convergence rate, SUs settle down in their desired channels sooner and so the number of collisions would be lower which consequently brings higher average throughput. Moreover, the requirement for selecting the rank-optimal channel in a short observation period becomes a more important issue when the operation environment of a SU frequently changes. For clarification, consider a moving person with a BAN worn on his body. The gateway of that BAN may find a new set of available channels for its operation when that person commutes among different places like home, street and office. Thus, a practical policy should find the rank-optimal channel in a reasonably short time before the BAN experiences a new environment.
6.5.2 Normalized Regret

Fig. 6.2 represents the normalized regret up to time-slot \( t \), i.e., \( \frac{\text{regret}_k}{\log(t)} \) for \( 0 < t < 10000 \). This is an indication of how close the channel selection strategy works to the centralized scheme. Comparisons of results for all three cases of \( U=2, U=3 \) and \( U=4 \) indicate that:

1. At each arbitrary trial \( t \), SUs under the \( k^{th}\)-MAB policy suffer lower regrets than \( \rho^{PRE} \).

2. SUs with higher ranks suffer larger regrets than those with lower ranks, i.e., \( \text{regret}_0 > \text{regret}_1 > \text{regret}_2 > \text{regret}_3 \). To explain why \( SU_0 \) experiences the highest regret, consider that each \( SU_k \) wants to find the k-best channels in order. Thus, all \( U \) secondary users try to find and sample the channel with the highest mean availability, i.e., CH1, in the first time-slot of their own periodic frames until \( P_{\text{switch}} \) degrades enough. This results in the highest number of collisions on CH1 which is the rank-optimal channel of \( SU_0 \). However, only SUs with the lowest \( U-1 \) ranks, i.e., all SUs except \( SU_0 \), need to find the second best channel. Consequently, CH2 experiences a lower number of collisions than CH1 resulting in \( SU_1 \) having less regret than \( SU_0 \).

6.5.3 Throughput

Fig. 6.3 represents \( \text{Throughput}_0 \sim 0.73, \text{Throughput}_1 \sim 0.55 \) and \( \text{Throughput}_2 \sim 0.37 \) under both policies. These results empirically prove convergence of SUs to their rank-optimal channels since each SU achieves the average throughput proportional to the mean availability of its rank-optimal channels, i.e., \( \frac{\text{Throughput}_k}{\mu_h} \). By considering the rank ordering of SUs, observation of \( \text{Throughput}_0 > \text{Throughput}_1 > \text{Throughput}_2 > \text{Throughput}_3 \) confirms order optimality in terms of the achievable throughput. Note that although both policies offer approximately the same average throughput, all SUs reach
90% of their throughput around the 2000\textsuperscript{th} trial under the \( k^{th} \)-MAB policy while the same situation happens around the 4000\textsuperscript{th} trial under \( \rho_{\beta=200}^{PRE} \).

### 6.6 Summary

In this chapter, we have proposed a distributed channel selection strategy, the \( k^{th} \)-MAB, to resolve contentions of competing SUs with diverse QoS demands. Subject to predetermined information about their ranks, SUs aim to converge to a channel with the same position in terms of availability-ordering as of the SU’s rank. This kind of convergence lead SUs to work on orthogonal channels and consequently get the average throughput proportional to the mean availability of their rank-optimal channels and cooperatively respect QoS requirements of each other. Applying the proposed \( k^{th} \)-MAB strategy at the BAN gateway provides a QoS-aware shared medium for collocated BANs such that BANs get services proportional to their service requirement.
Chapter 7

Conclusions and Future Work

7.1 Research Contributions

In this chapter, we summarize the results and highlight the contributions of this thesis.

• In Chapter 2, we analytically and experimentally have studied whether the synchronous IEEE 802.15.4 Beacon-Enabled mode is a viable MAC scheme for BANs. We have formulated how the coexistence problem in a shared frequency band affects the beaconing functionality, network synchronization and consequently medium access delay. We have found that loss of beacons and subsequent service interruption intervals handicap the BAN in support of delay-strict m-health applications. We have proposed a recovery scheme, called BCRS, to provide a more available medium and a less fragmented access for an 802.15.4-based BAN. We concluded that for addressing every-time and everywhere monitoring features of m-health service and expanding the set of traffics, that BAN may address their requirements, a MAC scheme specialized to unique characteristics of a BAN and a human body is required.

• In Chapter 3, we have proposed a frequency-agile MAC design, called CBAS, for handling the coexistence problem in a shared environment to support prompt access to the medium for a BAN. We have studied that CBAS provides a real-time platform for transmission of sampled vital signs over a BAN by opportunistic extraction of white-spaces from a pool of orthogonal channels. We have analyzed BAN
performance under CBAS by modeling the system as a preemptive-resume priority queue to show how much BAN service requirements, specifically queuing delay and throughput, are satisfied when CBAS is applied. We concluded that CBAS enables every-where every-time monitoring features of m-health service despite a dynamic set of coexisting networks.

• In Chapter 4, we practically have investigated whether an opportunistic MAC scheme, like CBAS, meets the BAN requirement for prompt medium access over a license-exempt frequency band. We have proposed a robust spectrum sensing strategy to detect occupied/idle parts of the channel without making any assumption about the possible radio technologies, modulation schemes or power spectral densities. We have run field tests in the 2.4GHz ISM band to examine the occurrence frequency of white-spaces with enough bandwidth to accommodate BAN transmissions. These tests involved running our proposed dual-spectrum-sensing strategy at different public places to investigate how an opportunistic MAC access helps a BAN to improve its timely access to a shared medium. According to field test results, ample white-spaces exist to enable BAN prompt access to the ISM band. It means that continuous and real-time report of medical data over 2.4GHz ISM band is practically feasible if a BAN is equipped with dynamic spectrum access capability.

• In Chapter 5, we have proposed a topology-adaptive network layer design to incorporate instantaneous link connectivities over a BAN into its scheduling to improve network reliability. We verified that under the proposed fair per-packet distributed scheduling scheme, body nodes participate in communication pertinent to their link qualities toward the gateway and the amount of backlogged traffic that they have. Our extensive experimental results, under various positioning of extremely low-power TelosB wireless devices, confirm that integration of MAC information, provided im-
plicitly by CBAS, into the network layer establishes a reliable communication platform for BANs without stressing the BAN power budget for body posture tracking. We concluded that building a per-packet scheduling scheme on top the CBAS platform handles the reliable packet delivery feature of m-health service despite the BAN dynamic topology. It means that our proposed cross MAC and network layers design makes a big step forward in realization of pervasive health monitoring.

- In Chapter 6 we have enhanced our opportunistic medium access scheme idea with QoS provisioning feature to support diverse service requirements of collocated BANs. We have proposed a learning strategy, called $k^{th}$-$MAB$, for a distributed channel selection to provide a self-regulating (fair) and load-aware platform for coexisting frequency-agile BANs. We verified, over simulation results, that adopting $k^{th}$-$MAB$ not only reduces inter-BAN interference by confining a BAN operation on its rank optimal channel, but also distributes radio resources (available spectrum holes) between BANs proportional to their QoS requirements.

### 7.2 Suggestions for Future Work

In the following, we consider several possibilities for extension of the current work.

1. **Joint QoS provisioning and throughput maximization for non-greedy traffics:** In Chapter 6 we focused on QoS provisioning when contending SUs are always seeking spectrum holes for their transmissions. It means that a SU chooses a channel in every single time slot and fully occupies spectrum holes arising on its rank-optimal channel because of its greedy traffic. We plan to extend our work for the non-greedy case in which channel availability of the desired channel is more than SU’s traffic demand and SU may not have a packet for transmission in all emerging spectrum
holes. In a modified algorithm, lower-rank SUs capture leftover channels with higher ranks to reach a better level of QoS in terms of average throughput.

2. **Updating the BAN channel pool in the course of time:** Considering the processing capability of a commonly available hand-held device, as the BAN gateway, the number of channels that can be sensed simultaneously is limited. It means that selecting the channel pool members out of a set of possible WPAN channels is an important decision which directly affects CBAS performance. To protect BAN from service degradation, decision making should be adaptive with dynamics of an interfering environment through updating the channel pool members in the course of time. We believe that studying such a channel decision making approach adds more value to our cross MAC-network layer design.

3. **Hardware implementation of BCRS:** In Chapter 2 we proposed BCRS as an amendment to the IEEE 802.15.4 to avoid large ineligible periods and consequently excessive medium access delays that WPAN may experience because of the beacon corruption issue. We plan to modify the 802.15.4 MAC layer implementation of multiple TelosB motes based on the proposed BCRS. This testbed help us to experimentally examine how this amendment may enhance WPAN access opportunities in different coexistence scenarios.

4. **Analysis of $k^{th}$-MAB policy:** Because of using the combination of UCB-V and $\epsilon$-greedy approaches for finding the K-th best channel, we assure that the minimum regret for the $k^{th}$-MAB policy, proposed in Chapter 6, grows with time at the logarithmic order subject to the proper setting of $\beta$. However, to investigate how regret scales with respect to the number of users and channels, we plan to extend this work with thorough analysis of the $k^{th}$-MAB approach.
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