A Dynamic Channel Allocation Protocol for Medical Environment Under Multiple Base Stations

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***Abstract*—Health monitoring over wireless networks is at the same time increasingly popular and a challenging task. In fact, in a medical environment, the high density of wireless devices leads to an extensive amount of co-channel interferences, imposing risk to patients' life due to poor network performance (e.g. high latency and packet loss rate). In this work, we present a DynamiC distributed Channel Allocation (DCCA) protocol. DCCA takes into account the existence of co-located wireless body area networks (WBANs) and multiple base stations in a single medical environment. In other words, DCCA avoids co-channel interference and offers workload balancing among base stations by dynamically allocating channels based on a greedy solution to the graph-coloring problem. Simulation results from medical environment scenarios show that DCCA improves the quality of communication when compared with other representative frequency-allocation protocol. On average, DCCA increases 30% the network goodput and reduces 40% network latency.**

I. Introduction

Medical environments increasingly benefit from wireless networks, being able to integrate human body monitoring and data processing [8], [9]. Those systems, such as wireless body area networks (WBANs), are helpful in continuously monitoring patients' vital signs. WBANs comprise wireless sensors implanted over or inside the body. All captured data is sent to a base station by the body network coordinator (e.g. a smartphone), where specialized systems process patient data. Note that a wireless healthcare system presents hard QoS constrains, as low latency ($\leq$ 200 ms) [2] and low packet loss rate ($\leq$ 1%) [10]. Attaining these QoS requirements is essential to support healthcare, including the monitoring of patients' aging process and chronic diseases.

Given the growing critical role that wireless healthcare systems play for people's lives, reliable wireless communication is crucial. However, wireless communication is naturally prone to signal interferences that can easily compromise network performance [8], [9]. The wireless nature in communication makes them prone to signal interferences. The high density of devices and different wireless technologies also contribute to communication disturbances (e.g. co-channel interference). Co-located WBANs using the same channel, for instance, can cause performance degradation. Hence, these networks easily experience unreliable data communication, incurring into large delays, low throughput and waste of energy [1], [5].

Many research works focus on frequency allocation techniques to mitigate interferences among co-located WBANs. These techniques allow the network to allocate different channels for concurrent data transmission, avoiding interferences and degradation of the media access. Nevertheless, most of the proposed solutions assume the existence of a single base station to control the frequency allocation per geographic region. However, these solutions may cause an overload of the base station, compromising the QoS requirements for medical applications. In addition, their low scalability makes them less likely to be applied in practice.

In this paper, we present DCCA, a **D**ynami**C** **C**hannel **A**llocation protocol for wireless healthcare systems composed of multiple WBANs and base stations. DCCA offers workload balancing among base stations by dynamically allocating channels, avoiding WBAN channel interferences. More precisely, the protocol is founded on a greedy solution for the distributed graph coloring problem, in which each color represents an available communication channel. Interference among WBANs are avoided by mapping different colors (channels) to frequency-overlapping and co-located base stations. By the frequency balancing, DCCA intends to support the medical applications, reducing delay and increasing throughput. Differently from existing approaches [7], DCCA takes a step forward and considers the presence of multiple base stations, which greatly increases system scalability.

Simulation results show that DCCA presents better latency and goodput, as well as lower packet loss when compared to a representative frequency allocation protocol from the literature [7]. Our simulation results show an increase of 30% in goodput and a reduction of 40% in network latency. In sum, when using multiple base stations, DCCA is able to fully obey the delay and packet loss requested by medical applications, such as telemetry and infusion pumps.

This paper proceeds as follows. Section II overviews related work. Section III describes a wireless healthcare system for medical applications. Section IV presents the proposed DCCA protocol. Section V describes the simulation settings and results. Finally, Section VI concludes the paper and presents future works.

II. Related Work

This section presents main approaches that have addressed the wireless interference in medical environments. In general, those approaches aim to transfer the collected data in a short time, mostly based on the presence of multiple channels. Despite of the expected benefits on using multiple channels – as less interference once there is a larger number of available channels – channel allocation is still a challenging task.

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Kyasanur *et al.* [6] studied the applicability of multiple channels on a wireless *adhoc* network. The authors investigated how the number of channels and the number of radio interfaces impact on the network capacity. Their study showed that, even if the number of available interfaces is less than the number of channels, the network capacity is increased.

Lee *et al.* [7] proposed DCAA, a Dynamic Channel Adjustable Asynchronous Protocol. DCCA provides a frequency-hopping approach in order to assign communication channels between end nodes and a base station. The authors focused on cognitive radio interfaces and developed a protocol to meet medical applications demands. They presented a base station that continuously switch among available channels. When a client starts a communication process, it randomly chooses a channel and sends a request in blind. In case of a busy medium or the base station does not answer, the client skips that frequency and restarts the communication process. Otherwise, if the base station answers to the client request, both nodes exchange data accordingly. This approach simplifies the channel allocation and management. However, it may introduce relatively long delays and a huge overhead regarding the channel switching. In addition, DCAA may lead to the problem of deafness, in which a client initiates transmissions when the base station is tuned to another frequency, leading to a great waste of resources, e.g. energy and bandwidth.

Phunchongharn *et al.* [9] presented another wireless communication approach for medical applications based on cognitive radio. The authors proposed a system with multiple channels, nonetheless using a dedicated control channel and a single channel to data transmission. The transmission occurs in two stages. First, the control channel is employed for a handshaking protocol, in which the frequency and transmission power are negotiated. After this initial phase, the client receives a dedicated transmission channel. The main goal is to provide reliable transmissions to a hospital environment.

Doost-Mohammady and Chowdhury [4] presented a protocol following the Phunchongharn *et al.* [7]. The authors introduced a dedicated control channel, modifying its communication to enable wider bandwidths. Moreover, instead of a single data channel, the protocol uses multiple data channels. Finally, authors address the waste of energy under user's mobility and poor quality of service.

In all those works, the presence of multiple base stations is not considered. However, in the current medical environment, it is expected the presence of multiple and co-located base stations [2]. Due to the lack of communication among the base stations, one expects devices operating on the same frequency, leading to a high number of interferences. The higher the interference, the higher the goodput degradation and energy waste. This problem can be mitigated when base stations communicate with each other, coordinating among themselves the use of the frequencies and their allocation to the clients. Since it is required to ensure the synchronization among base stations, a new level of complexity exits.

Differently from the previous studies, this work presents a protocol that provides a safe transmission to the client in an environment composed of multiple base stations. Our protocol is founded on the strategies described in [4] and [7]. Since the base stations interact to avoid interferences, the proposed protocol can be used in large scale scenarios.

III. System Overview

Fig. 1 illustrates the system architecture we have considered in this work. The system comprises two main entities: base station and client (wireless body area network). The base station controls all clients and presents neither energy or processing constraints. The base station also represents the destination of the collected data, being also responsible for the analysis.

Each client (WBAN) comprises a set of sensor nodes located inside or on the body. Sensor nodes main task lies on monitoring vital signs. The WBAN also presents network coordinator, that acts as gateway, aggregating data from sensor nodes (intra-WBAN communication) and retransmitting them to a base station. Without loss of generality, we assume a single hop architecture, where data transfer occurs directly between clients and base station (inter-WBAN communication). Moreover, we assume an intra-WBAN communication without interferences.

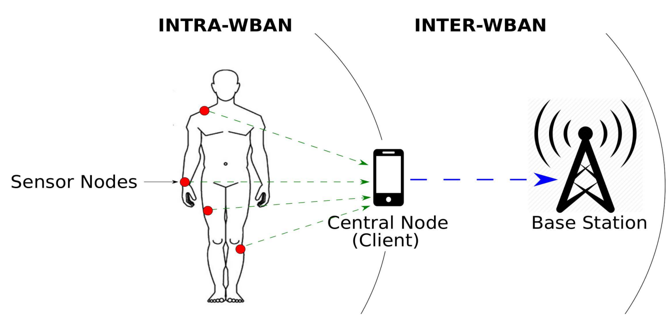


Figure 1: System Model.

The system works under two types of communication channels: a common control channel and a data channel, located in an unlicensed band of spectrum. As expected, the control channel is dedicated to the exchange of control messages between base station and clients. The data channel is employed to transfer data and acknowledgment packets.

Each base station keeps the control of the frequencies available to clients, performing a status-based approximation. The base station determines the status of the frequencies based on their allocation history. In general, the base station has full control of which frequencies are occupied and which are free. Thus, the base station is able to provide an exclusive channel access to data for a single communication, avoiding co-channel interference between clients.

In this work, we consider that a base station has two wireless network interfaces available. Base station uses one interface exclusively to tune the control channel, while the other tunes the data channel. Hence, the base station is able to transmit and receive data in both channels at the same time. The two interfaces also allow simultaneous transmission, where the overhead to the switch channels is diminished. The client, in turn, employs only one interface, that can transmit and receive data in both control and data channels, but exclusively. Finally, we assume a reliable communication channel interconnecting base stations. For example, base stations may be wired connected, ensuring a low communication latency and high throughput.

IV. Dynamic Channel Allocation Protocol

This section presents DCCA, a DynamiC Channel Allocation protocol. It provides a distributed channel allocation among base stations thus avoiding interferences among co-located and multiple WBANs. In sum, a set of base stations split among them the available channels. Each base station communicates to each other and assign available channels to clients, avoiding co-channel interference and contributing to system overall workload balancing.

More precisely, the channel allocation is modelled as a graph coloring problem, in which a color represents a channel, and the same color cannot be assigned to two adjacent nodes in the graph. Founded on a solution to the graph coloring problem, DCCA dynamically manages, in a distributed way, the channel allocations, avoiding interferences among multiple base stations. The multiple base stations work collaboratively to allocate the frequencies.

For the protocol, the medium access follows two distinct phases: **control** and **data transmission**. During the control phase, the client in need of transmitting data uses the control channel to negotiate with the base station and allocate a data channel. Data transmission starts after the data channel is negotiated and then that channel is employed. This approach avoids the deafness problem, i.e. when the transmitter and the receiver are tuned to different channels.

A. Channel Allocation and Access

Fig. 2 provides the protocol message sequence. In order to keep track of each channel status, the base station uses basically three data structures. The first is a free channel list (FCL). FCL lists all available channels that a base station may use. The second data structure is a channel usage list (CUL), which represents all channels already allocated on that base station. And the third data structure is a blocked channel list (BCL) that keeps control over which channels are blocked and how many base stations have blocked a given channel.

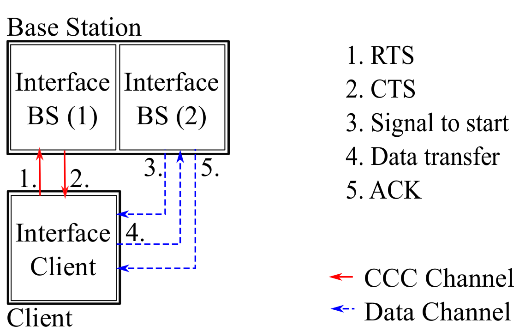


Figure 2: Channel allocation protocol message sequence

The **Control Phase** starts when a client sends a request RTS (*message 1 in Fig. 2*) to the closest base station through the control channel. This phase is characterized by clients wishing to transmit their collected healthcare-related data. Clients perform an initial contact with a base station in order to decide in which channel data transmission should occur. DCCA does not consider any kind of service differentiation, thus all clients access the control channel with equivalent rights following the CSMA/CA access control protocol.

Base stations have a fixed control interface, which is employed to communicate through the control channel. When a request is received by the base station via its control channel, it looks for an available channel in its FCL. The main task of the FCL is to keep control about which channels might still be allocated. If the base station fails on finding a free channel (when the FCL is empty), it sends a message indicating that it is no longer possible to allocate any new channel for transmission (NCTS). The client, when receiving a NCTS, waits a fixed random time before requesting again.

When the base station is able to find a free channel, it removes this channel from the FCL and inserts it into the CUL, indicating that the channel is going to be used. The base station broadcasts to its neighbors (other base stations) the selected channel to avoid allocations that may cause interference. This last action requires a synchronization among base stations, detailed in the next subsection.

After being added to the CUL, the chosen channel information is sent to the client via CTS (*message 2 in Fig. 2*). After receiving the CTS, the client knows that a data channel has been successfully allocated. The client then sends a confirmation message to the base station via control channel and tunes into the channel indicated in the CTS. After tuning into the data channel, the client waits for a message indicating the start of transmission, closing the control phase.

The **Data Transmission Phase** starts when an element is added to the CUL. As all channels present in CUL have a customer waiting for a transmission signal, the second interface, also known as data interface, uses the CUL as a tuning queue. By adding a channel to the CUL, the data interface starts tuning. In each tuned channel, the base station sends a signal to start the transmission (*message 3 in Fig. 2*). The clients tuned in the same channel receive the signal and start the data transmission (*message 4 in Fig. 2*). After receiving the data, the base station sends an acknowledgment packet to the client (*message 5 in Fig. 2*). When sending a client an acknowledgment packet, the channel employed for the transmission is removed from CUL and added to the FCL. Then, it is announced as free to other base stations (details in the next subsection). When the CUL is empty, the data interface is in an idle mode. If the CUL still has elements, the data interface restarts the transmission phase. The base station has the ability to communicate simultaneously with two clients: while the control interface includes channels in the CUL, the data interface removes channels from it.

B. Synchronization among base stations

This subsection presents the base station distributed synchronization protocol. This synchronization occurs when: a) a base station receives a RTS; b) a successful data transmission has occurred, after an acknowledgment packet is sent to the client. As mentioned before, DCCA is based on the traditional graph coloring problem. That problem consists in coloring nodes of a graph so that adjacent nodes have different colors. Similarly, in frequency-allocation problems stated in this work, the goal is to ensure that adjacent base stations do not operate simultaneously in the same frequency.

Given a graph $G = (V, E)$ in which V represents all base stations in the system. The set of edges E indicates which base stations are adjacent. For the channel allocation, a color represents an available channel. Thus, since the coloring problem is solved, a setting for channel allocation among adjacent base stations is found and can be employed to avoid co-channel interference.

However, for the proper functioning of DCCA, some changes are made in the traditional graph coloring problem. First, a neutral color is added. The neutral color is the only color allowed to be used by two adjacent nodes. In DCCA, the neutral color represents idle base stations. The presence of multiple colors in a node is allowed. As stated previously, base stations can allocate more than one frequency through the CUL list. Thus, at this graph-coloring problem, nodes may have multiple colors. Briefly, a vertex may have various colors simultaneously, provided that no adjacent nodes have any of these colors. In DCCA, the CUL indicates which frequencies are allocated. Assuming that CUL starts empty, the graph starts with all nodes having only the neutral color.

The DCCA protocol follows two basic operations: channel allocation and channel release. The channel allocation occurs when the base station receives an RTS. Once a successful search for an available channel in the FCL list is performed, the base station sends a BLOCK blocking package containing the selected channel to every adjacent base station.

When a base station receives a blocking package, it increments the number of clients trying to allocate this channel in the BCL list. The BCL list starts with all channels information setup to zero. Besides the increment in the BCL list, the receiver base station performs a search for the channel in the FCL list. If found, the channel is removed from the list. The channel release procedure follows just the inverse of allocation operation. Performed after a successful transmission, the base station sends a release packet FREE with the channel used for the transmission. The base stations that receive the FREE package decrease the value of the received channel in the BCL list. If the channel count reaches 0, the channel is placed back in the FCL list and may be allocated again in future transmissions.

It is important to note that the synchronization among base stations occurs multiple times throughout the process and DCCA protocol does not guarantee optimal solution. Due to this characteristic, the DCCA does not offer a stable final solution, but various ones, trying to attend the current scenario of transmission and charging in the base stations. The adopted greedy strategy presents a simple, yet effective solution to avoid that adjacent base stations use the same channel simultaneously. As the base stations communicate with each other, they do not allow that multiple clients cause interference with each other. Furthermore, as the number of available frequencies is relatively low, the greedy strategy is computationally cost-effective, allowing DCCA to provide interference-free transmission, regardless of the number of adjacent base stations.

V. System Evaluation

A. Evaluation Methodology

We evaluate DCAA by simulating realistic medical environment scenarios using the Castalia [3]. Castalia is a network simulation tool based on OMNeT++ which can be used by researchers to test their distributed algorithms and/or protocols in a realistic wireless channel and radio model. We consider that each WBAN communicates to a central point using a Zigbee CC2420 radio[1] which operates in the 2.4 Ghz range. This radio can operate in up to 16 different channels at 20 MHz. In the simulations, we have fixed each channel bandwidth to 250 kbps. Moreover, we have varied the number of available channels (4, 8, and 16) to analyze the DCCA protocol overhead.

The simulations follow two realistic medical scenarios: a crowded emergency department and a calm radiology room. Both scenarios are described in Baker *et al.* [2]. We considered a 30 square meters room, with a fixed base station. We have distributed patients along the room following a uniform distribution. As expected, the scenarios have their own particularities. Table I summarizes the following characteristics for each medical application: emergency department and radiology room environments client number, required bandwidth and packet size.

Medical Application	Emergency Clients	Radiology Clients	Packet/s	Packet Size (kb)
Diagnostic	3	1	5	5.1
Telemetry	12	9	5	2.6
Infusion pump	10	10	1	1.0

Table I: Medical Applications and data load.

In simulations, each client generates a data stream to the base station according to the parameters described in Table I. Clients are initialized sequentially every two seconds. The simulation finishes at the same time for all clients. Each simulation time is 16 minutes, from which we discard the initial minute in order to disconsider the warm-up period. Simulation results refer to 30 simulations rounds with 95% confidence intervals.

The following metrics are employed while evaluating MAC layer protocols:

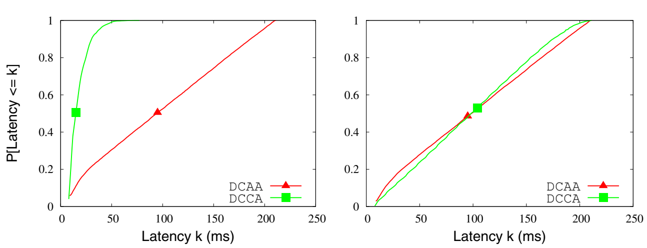
[1] http://www.ti.com/lit/ds/symlink/cc2420.pdf

- *Latency*: the amount of time a packet of data takes to get from a client to base station, including propagation, serialization, transmission time, and queuing delays.
- *Goodput:* the ratio between delivered amount of useful data and the latency. Useful data does not consider protocol overhead and retransmitted segments. Goodput is calculated as: *Goodput = Data Size / Latency*.
- *Packet loss rate:* the percentage of packets that has been incorrectly received or discarded by timeout. We consider a timeout limit of 200 ms to meet medical applications requirements [2]. Also note that packet loss rate should be as low as 0.01 [10].

The simulation code as well as the random number generator seed, used during this work, are available at: *http://www.4nerd.net/dcca*.

B. Numerical Results

We first compare our protocol (DCCA) to a Dynamic Channel Adjustable Asynchronous Protocol (DCAA) [7]. For both scenarios – a **radiology room** and an **emergency department** – we deployed a single fixed base station with 4 available channels. Fig. 3 presents cumulative distribution functions (CDFs) of DCCA data transmission latency, compared to a system using DCAA. Note that, on a calm radiology room – Fig. 3 (a) –, our protocol clearly outperforms the DCAA. In fact, DCCA is able to deliver all packets within a time limit of 130 ms. The DCAA however does not reach such marks, presenting about 30% of data transmissions with latency values larger than 130 ms. According to the medical environment latency constrains, DCAA presents up to 14% of packet loss.

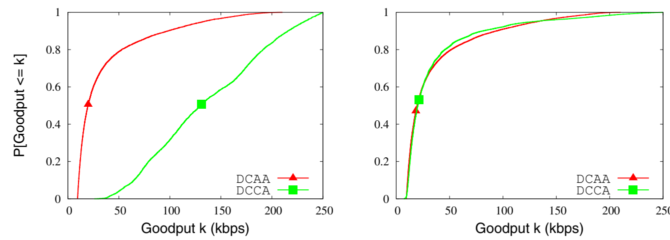


(a) Radiology (b) Emergency

Figure 3: System overall latency.

In a high-load scenario, as an Emergency department, both protocols present notable worse performance, when compared to the radiology room. Moreover, both protocols present quite similar latencies. In this case, less than 60% of transmissions present latencies values lower than 130 ms. However, DCAA presents practically twice packet loss, when compared to our protocol. While the first presents up to 30% of packet loss, the DCCA presents about 16%. It is important to note that, under the presence of a single base station, our protocol is far from achieving the requirements of medical applications, which demands no more than 0.1% of packet loss.

DCCA also enhances system overall goodput. In special, in a calm radiology room, as shown in Fig. 4 (a), DCCA presents almost 4 times better performance than DCAA. In fact, DCCA goodput confidence interval, for a 95% of confidence level is [134,977 : 137,452] kbps, while confidence interval for DCAA is only [36.473: 37.764] kbps. As occurs to latency, in a high-loaded scenario, both protocols present similar performance (about 36 kpbs). Although, we recall that DCAA presents a larger number of packet loss.



(a) Radiology (b) Emergency

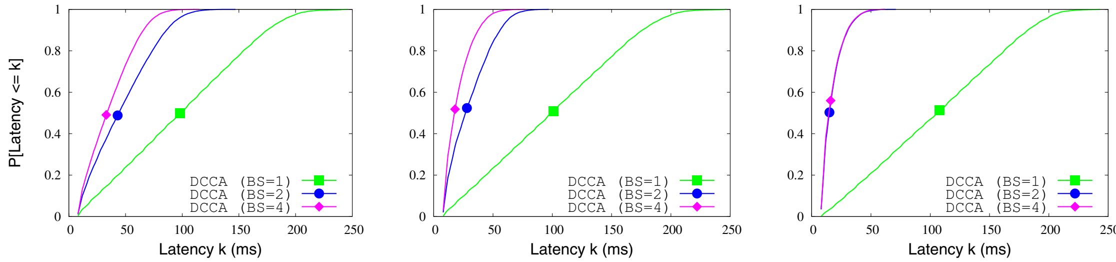
Figure 4: System overall goodput.

Hence, according to the previous results, we note that the proposed protocol DCCA enhances the communication system in a low-loaded scenario. In a high-loaded scenario, the gains are considerable when compared to DCAA, although they are still far from medical applications demands. In fact, previous results do not evidence a key element of our protocol: the presence of multiple base stations in the same region.

Figs. 5 and 6 present the system overall latency and goodput cumulative distribution function, when varying the number of base stations and available communication channels. In this case, we have considered only the emergency department scenario, once a single base station attended the calm radiology scenario requirements.

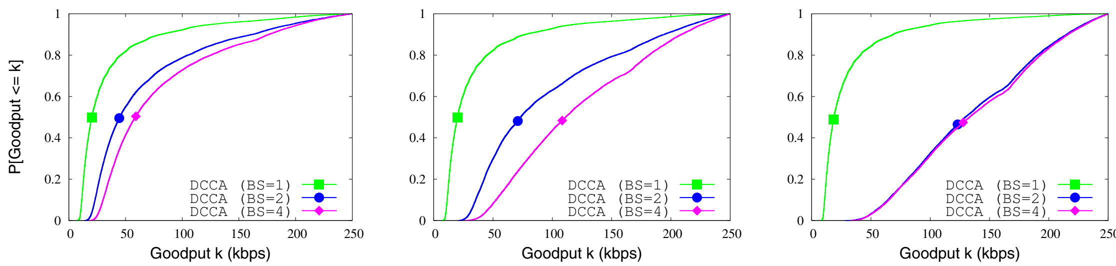
According to these figures, the higher the number of base stations and the number of available channels, the better will be both system overall latency and goodput. Precisely, as shown on Fig. 5, a higher number of base stations leads to a considerable latency reduction, for any number of available channels. It is interesting to note that, when we increase the number of base stations, we also increase the number of clients transmitting their data simultaneously, thereby leading to a greater packet flow. In fact, as shown on Figure 6, for all number of available channels, system overall goodput increases in a similar way as latency reduces.

The number of available channels also influences system latency and goodput in a positive way. Despite the gain that both factors bring, we note that the increase in the number of channels presents less impact on the performance than the number of stations. Intuitively, as the number of stations increase, it was expected the division of loads between them. On the other hand, even with the existence of multiple channels, the initial protocol phase is not parallelizable, what limits the gains inside the same station. However, the most consistent gains have been reached by the addition of new base stations. Regardless the number of available channels, the presence of a single base station does not achieve medical applications latency and packet loss requirements. For instance, under the presence of a single base station, our protocol presents up to



(a) 4 Channels (b) 8 Channels (c) 16 Channels

Figure 5: System overall latency.



(a) 4 Channels (b) 8 Channels (c) 16 Channels

Figure 6: System overall goodput.

16% of data packet loss, regardless of the number of channels. However, we guarantee the delivery of all packets to the base station with latencies values lower than 200 ms, by adding a second base station.

Note that, for the workload we use, the presence of two base stations produces a better improvement, when compared to a system with a single base station. In fact, when using two or four base stations, the difference on latency and goodput is small. Especially for a system with 16 available channels, this difference – for both metrics – can be negligible.

VI. Conclusion

In this paper, we have presented DCCA, a dynamic channel allocation MAC layer protocol for WBANs which addresses communication disturbances – as co-channel interference – by dynamically managing and allocating wireless channels to WBANs. We evaluated the protocol by simulating under two realistic medical environment scenarios, varying from a radiology department to a crowded emergency room. For both scenarios, DCCA enhances the communication between WBANs and access points. Under the presence of a single access point, DCCA is able to reduce overall mean system latency by 40%. Moreover, DCCA increases mean goodput by 30%. Even in a crowded scenario, packet loss became negligible under the presence of multiple access points. As a future work, we intend to adopt LTE standard (e.g. LTE-U) for communication instead of using CSMA/CA. Moreover, we will address power management on WBANs in order to save battery life. Finally, we intend to increase the data rate communication by combining several available channels.

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