Handovers and Interference Mitigation in Healthcare Environments

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***Abstract*— In this article, we consider candidate wireless technologies such as IEEE 802.11b and IEEE 802.15.4 that can support medical and healthcare informatics applications. The main questions that we try to answer are: (1) is there any potential for significant interference when these wireless technologies are present? (2) what are potential solutions to mitigate it? We consider a handover technique for IEEE 802.11b devices as an effective way to mitigate interference and improve performance. We propose the use of packet loss and retransmissions at the MAC layer in order to trigger a WLAN access point handover. Performance for scenarios of interest is measured in terms of packet loss, packet retransmissions, and delay jitter.**

I. Introduction

Recently, the emergence of families of standards for wireless personal area network (WPAN) and wireless local area network (WLAN) communication in the unlicensed bands, has focused the attention on the problem of spectrum crowding and ways to better share the available spectrum and mitigate interference. To date, most interference mitigation techniques have been primarily concerned with frequency hopping systems such as the Bluetooth specifications [1] interfering with direct sequence spread spectrum systems such as WLAN [2]. The range of solutions investigated vary from collaborative mechanisms where both technologies are implemented on the same system [3] to non-collaborative schemes such adpative frequency hopping, packet schedulings [4][5], and packet encapsulation [6].

Solving the interference problem between direct sequence spread spectrum systems has not been as popular mainly because these systems can be (manually) configured to operate on distinct center channels and therefore their signals do not have to overlap. While properly configuring a wireless system at deployment time remains an important step towards a solution, it should not be considered as the only strategy for interference mitigation. There are many reasons why manual configuration alone is not sufficient to completely eliminate the interference problem. To give a few examples here, we observe that a typical deployment of wireless systems happens gradually over time where more systems are added on an as-needed basis. Therefore, it is not likely that a complete channel allocation system can be devised initially. In most cases, the channel allocation map has to be revisited every time more devices are deployed, which is impractical. Also, given the sheer number of devices that need to be added, it is not always possible to completely isolate their operation on non-overlapping channels.

Our objectives in this paper are to introduce connection handovers as a dynamic channel re-allocation technique for mitigating interference between direct sequence spread spectrum devices. Therefore, we select two different direct sequence spread spectrum technologies, namely, WLAN and the low-rate WPAN defined in [7] operating in the context of a healthcare environment. Our choice for the environment is primarily motivated by the presence in healthcare of a variety of wireless technologies supporting different medical applications and by the need for these technologies to operate simultaneously and without interference. We note that in this critical environment, data loss may have life and death implications and therefore interference is not desirable. Finally, observe that although the healthcare environment constitutes an interesting context for our study, the solutions proposed in this article are not unique to the healthcare scenario studied and can be applied in a wide range of situations.

Our solution is based on the ability for WLAN devices to dynamically sense the interference on the medium, recognize the need to look for other access points in the area that are operating on a different center channel, and execute a handover for the connection. Our contributions in this article are two-fold. First, we recommend performing handovers as a means for mitigating interference between overlapping direct sequence spread spectrum devices. Second, we propose the use of MAC layer measurements, namely, the packet loss and the number of packets retransmitted as measures to detect interference and initiate a handover.

The remainder of this paper is organized as follows. In section II, we introduce the applications and the healthcare scenario considered and assess the interference problem between WLAN and low-rate WPAN systems. In section III, we propose a handover mechanism for WLAN as a means to mitigate interference. Section IV evaluates the handover mechanism proposed and discusses the performance improvements obtained. Concluding remarks are offered in section V.

II. Wireless Technologies in Support of Healthcare Applications

In the healthcare environment, there is a wide range of applications that span the entire gamut of data rate and power requirements. On one hand, there are medical device specific applications that consume little bandwidth such as monitors used to collect a patient's vital signs and probes deployed on a patient's body. On the other hand, there are other real-time applications such as video streams generated by camera monitors and remote-controlled robots used in surgical interventions that are bandwidth hungry. For this type of real-time applications, although their bandwidth requirement is different, their delay and packet loss requirements are more comparable. Basically, packet delay variation should be kept to a minimum and packet loss is not tolerated. At the other end of the spectrum, lies non-real time applications for healthcare informatics, such as Internet access and database queries. This diversity in the applications and their requirements calls for considering different network technologies, for example, low-rate medical applications can use sensor network technologies, while broadband access can use high-speed network technologies. Our objective in this section is to focus on an example scenario for the use of different wireless technologies in the same healthcare environment and explore any side-effects resulting from their interaction.

A. Low-rate WPAN versus WLAN

We focus our efforts on two wireless technologies, namely, the emerging low-rate WPAN technology as specified in the IEEE 802.15.4 standard [7], and the WLAN technology specified by the IEEE 802.11b [2]. These two technologies alone sweep the entire power/data rate spectrum. Low-rate WPAN supports short range operations (within 10 meters). It optimizes battery life and has a maximum data rate of 250 Kbit/s. On the other hand, WLAN devices can transport up to 11 Mbit/s and offer an extensive coverage area (up to 100 meters). Considering the diversity of the application characteristics and user needs described earlier, it is expected that those two technologies, both occupying the 2.4 GHz band, will be used simultaneously in the same environment, which may result in mutual interference and significant performance degradation [8].

From a radio perspective, both technologies use direct sequence spread spectrum. Low-rate WPAN defines 16 channels in the 2.4 GHz band, each 7 MHz wide. The center channels are 5 MHz apart. On the other hand, the IEEE 802.11b specifications provides 11 channels occupying 22 MHz each. Center channels are also 5 MHz apart, starting at 2412 MHz. Thus, given this frequency map, it is possible to pick non-overlapping channels (for example 2410 MHz for low-rate WPAN and 2462 MHz for WLAN) to avoid any interactions between the two technologies. Unfortunately, optimizing a static network design is not always possible, either due to the large number of devices operating in a specific area, or due to constraints from prior deployments. Therefore, evaluating interference between low-rate WPAN and WLAN systems remains a legitimate goal, especially if the deployment trend for low-rate WPAN devices continues at the current pace and in already crowded WLAN coverage areas. Preliminary results on the effects of mutual interference between the two technologies have been reported in [8]. In this article, we use a different topology and enhanced application models in order to assess the performance and evaluate the solutions proposed.

B. Patient's Bedside Scenario

The network topology used in this scenario is depicted in Figure 1. On a patient's body, a vital sign sensor collects critical information about the patient, for example, heart beat and blood pressure and relays the information to a monitor located near the patient's bedside. In this case, low-rate WPAN is the wireless technology of choice since it matches the requirements of the application for a low data rate communication, limited coverage area, small size, and low power consumption. At the same time, a nurse carrying a PC tablet walks into the patient's room. She is corresponding with the patient's doctor via a high resolution video link. The communication between the PC tablet and a wireless access point (AP) located outside the patient's room is carried over a WLAN connection. The nurse is initially one meter away from the WLAN AP node and moves towards the patient's bedside at a speed of 1 m/s.

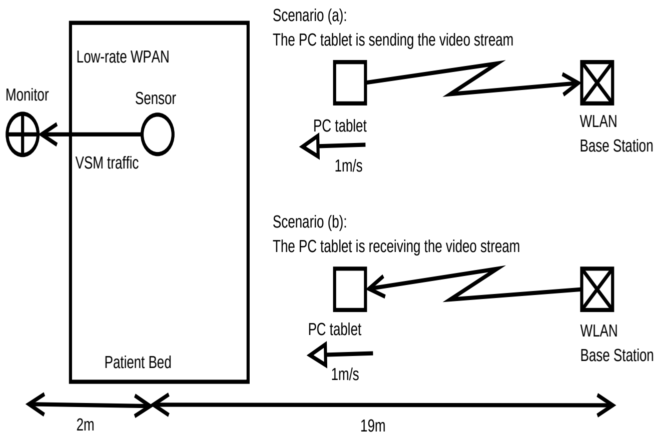

Fig. 1. Patient's Bedside Topology

Models for both WLAN and low-rate WPAN technologies were developed using the commercial network simulation package OPNET[1]. The simulation environment is based on detailed MAC, physical layer (PHY) and channel models. The parameters used in the simulations are summarized in Table I.

TABLE I
SIMULATION PARAMETERS

Parameters	low-rate WPAN Sensor	WLAN Device
Transmitted power (mW)	1	25
Application type	Vital Sign Monitor	Video
Packet Size (bit)	944	276.48K
Packet interarrival time (s)	0.0236	0.0667

[1]certain equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose

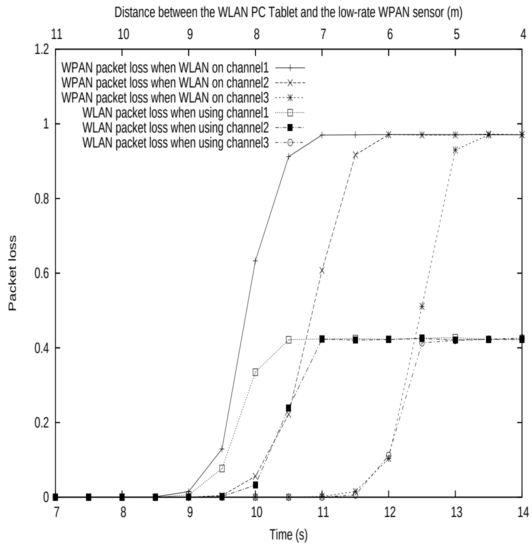

Fig. 2. Packet loss as a function of time when PC tablet is sending the video stream (a)

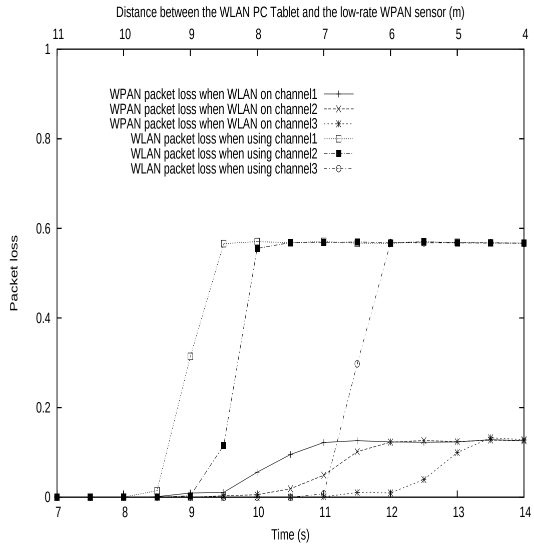

Fig. 3. Packet loss as a function of time when PC tablet is receiving the video stream (b)

C. Effects of Interference on the Medical Applications

The effects of interference on the both the low-rate WPAN and WLAN communications are shown in Figure 2 and Figure 3 where we plot the probability of packet loss observed at the MAC layer for the WLAN client (PC tablet) and low-rate WPAN monitor. In order to better understand the interactions between the two technologies, we make the video stream unidirectional and run two sets of experiments: in scenario (a) the PC tablet is sending the video stream, in scenario (b) the PC tablet is receiving the video stream.

Figure 2 gives the packet loss for scenario (a) when the PC tablet is sending the video stream, while Figure 3 gives the packet loss for scenario (b) when the PC tablet is receiving the stream. In both Figures, the packet loss is shown for WLAN and low-rate WPAN where low-rate WPAN is using the channel centered around 2410 MHz and the WLAN communication is using different center channels, namely, 2412 MHz (channel 1), 2417 MHz (channel 2), and 2422 MHz (channel 3). We verify that using other center channels for the WLAN outside the range of 2410-2422 MHz eliminates the interference with a low-rate WPAN centered at 2410 MHz.

As depicted in Figures 2 and 3, regardless of the experiment, the WLAN traffic (measured at the PC tablet) is significantly impacted, 42% and 56% of packet loss for scenarios (a) and (b), respectively. The effects on the WPAN are more dependent on the direction of the video stream. In scenario (a), the WPAN suffers close to 90% of packet loss. On the other hand, in scenario (b), the percentage of packet loss drops to 13%. Also observe a slight delay in the packet loss observed between scenarios (a) and (b). In scenario (b) the effects of interference on WPAN are delayed until the PC tablet gets closer to the low-rate monitor, however the packet loss on the WLAN device occurs sooner than in scenario (a). So when the PC tablet is receiving packets (scenario b), it is impacted sooner (at a distance further away) from the low-rate WPAN monitor. On the hand, when the PC tablet is sending data packets (scenario a) it is likely to be impacted later as the PC tablet gets closer to the WPAN monitor, Thus, the direction of the video stream has a significant impact on the percentage of packet loss obtained for the low-rate WPAN and WLAN systems. In scenario (b), the relatively small size of ACK packets, are less likely to interfere with the low-rate WPAN traffic as shown in Figure 3 where about 13% of packets are lost at the low-rate WPAN monitor. On the other hand, in scenario (a), (Figure 2), almost all the WPAN packets are lost as the nearby video stream sent by the PC tablet overwhelms the WPAN connection. Observe that as the distance between the WLAN center channel and the low-rate WPAN is increased, the percentage of packet loss is not as significant for the same physical distance between the WLAN and WPAN transmitters. Finally, in both scenarios (a) or (b), the packet loss obtained is not acceptable for the low-rate WPAN application considered.

III. WLAN Handover as a Solution for Interference Mitigation

As shown in section II-C, the effects of WLAN interference on the low-rate WPAN causes significant performance degradation for the applications using the low-rate WPAN, which is extremely undesirable in medical environments. This leads us to investigate potential interference mitigation solutions for this problem.

Given that low-rate WPAN systems are mainly intended for point-to-point and low-bandwidth communication, it is not realistic to expect that a pair of low-rate WPAN scan the wireless channel and dynamically decide to change frequencies. Although not precluded by the specifications [7], dynamic channel scanning is likely to consume more power and bandwidth, and add more complexity on a low-rate WPAN medical sensor. Therefore, the solution envisionned here focuses on a WLAN handover technique in order to mitigate interference. Since the low-rate WPAN will also impact the WLAN communication as the WLAN PC tablet gets close to the low-rate WPAN monitor, we propose to use the measured packet loss at the WLAN PC tablet in order to trigger a handover for the WLAN connection to use a different AP operating outside the range of frequencies utilized for the low-rate WPAN communication. In the remainder of this section we give a brief overview of the WLAN handover solution envisioned and the trigger mechanisms used, before we discuss in more details the performance improvements achieved for the specific scenario described in the previous section.

A. Handover Mechanism

In a nutshell, our proposed handover mechanism for WLAN works as follows. The WLAN station (or PC tablet) continuously monitors the link performance and issues a trigger for a handover when the interference level is sensed to be too high. The trigger decision is based on measurements conducted to quantify the performance of the link. Section III-B discusses the trigger we propose to use in greater details. As for the handover, we distinguish two cases depending on the presence of multiple interfaces on the WLAN device performing the handover.

If the WLAN device is equipped with multiple network interfaces for different technologies such as UMTS, IEEE 802.11a, etc, the device triggers a handover to another technology that is not operating in the 2.4 GHz Band. In this case, we expect the low-rate WPAN performance to be significantly improved in the absence of WLAN interference, and the handover latency for the WLAN to be negligible since traffic is continuously received on the WLAN interface while the redirection is taking place on the target network interface.

On the other hand, if no other network interface is available, the WLAN device triggers an intra-WLAN handover to switch to an AP operating on a different center channel (if one is present). If the station succeedes in finding a new AP operating on a non-overlapping channel, the WPAN - WLAN interference is eliminated and the low-rate WPAN is no longer impacted by the WLAN traffic.

The main advantage we see in performing a handover is that the interference between WLAN and WPAN is reduced, if not completed eliminated. In addition, this method does not require the development of new collaborative protocols between WLAN and WPAN. By choosing a handover solution, coexistence is achieved without the cost of modifying existing protocol specifications.

B. Handover Trigger Parameters

In this section, we discuss what measurement parameters are used to initiate the trigger event and how they are computed.

Typically, handovers across different APs within an IEEE 802.11 network are triggered by a poor received signal strength indicator (RSSI) measured on the WLAN station. The use of the RSSI is adequate in this case since intra-WLAN handovers are primarily concerned with a station's distance with respect to the AP it is communicating with. As the WLAN station moves further away from the AP, the signal received is attenuated by various propagation losses. Thus, when the RSSI at the station falls below a pre-determined threshold, the station starts looking for another AP in its range before triggering a handover for its connection.

In an interference-constrained environment, such as health-care, we propose a new category of performance measures in order to trigger a handover between two WLAN APs, since the RSSI measure alone does not reflect the level of interference between WLAN and other technologies operating in the same band. We propose to use the number of packets retransmitted at the MAC layer as a measure of the number of packets that have been discarded due to packet collisions. In the simulation scenario described later, we use an average number of retransmissions over a one second interval. If the number of retransmissions is greater than two per packet, the WLAN station triggers a handover. Note that this measure captures the percentage of packet loss at the receiver. In addition, this measure can indirectly provide information about packet collisions at the receiver at the other end. For example, if a station correctly receives data packets but observes that its AP is trying to send the same data packets several times, it means that the station's acknowledgments are lost at the AP. In that case as well, the station should trigger a handover.

At this point, we observe that other parameters can be used in the handover decision in order to capture the specific application requirements in terms of bandwidth, delay, and packet loss. If real-time applications require low jitter and high bandwidth, TCP traffic is more sensitive to packet loss due to the window congestion algorithm and flow adaptation. Given the range of applications that are likely to be supported by the WLAN technology, we envision that different threshold requirements will be devised and made available at the MAC layer where most of the link performance is measured. For example, in order to better support a real time video streaming application, the delay between each packet received can be monitored and a handover can be triggered if the delay variance (also known as jitter) goes beyond a predefined threshold.

IV. Effects of WLAN Handover on Performance

In this section, we discuss the advantages and performance trade-offs related to performing a handover across different WLAN APs in order to mitigate interference between WLAN and WPAN networks. In particular, we see that during the handover, the WLAN station is unable to receive data packets, but once the handover is done, both the WPAN and the WLAN show a lower packet loss.

A. IEEE 802.11 Handover mechanism

The handover in an IEEE 802.11 network consists of three stages, which are the scanning stage, the authentication stage and the association stage. The scanning stage is strongly dependent on the number of channels a station has to probe. During this stage, the station scans every channel for a duration of *MinChannelTime*. If at least one AP has replied, the station remains on the same channel for *MaxChannelTime* interval, in order to identify all APs operating on the same channel. Assuming at least one AP was found on the channel scanned, the station chooses one of the APs and executes the authentication and association stages. If no APs were found on the channel, the station goes to the next channel and starts the discovery stage over. Table II gives the handover latencies as a function of the number of channels scanned when performing a MAC layer handover according to the algorithm described. The values used for *MinChannelTime* and *MaxChannelTime* are $5ms$ and $10ms$, respectively.

Once the station is attached to a new AP, it has to determine if this new AP is connected to the same subnet. If the new AP is connected to the same subnet as the old AP, the handover only consists of a MAC layer handover and thus the station will receive data packets again through the new point of attachment. Otherwise, if the new AP is connected to a different subnet than the old AP, the station has also to perform an IP layer handover. This handover latency will produce an additional delay before the station receives or sends data packets. Table II compares the latencies obtained using a MAC layer handover, to the ones representing the cumulated MAC layer and IP layer handover latency when obtained when Mobile IP version 6 (MIPv6) is used for the handover [9].

TABLE II
MAC LAYER AND IP LAYER HANDOVER LATENCIES IN WLAN NETWORK

Delta channel	MAC layer Handover latency (ms)	IP layer Handover latency (ms)
0	12.097	77.160
1	17.071	84.795
2	22.170	89.908
3	27.465	92.812
4	32.692	100.067
5	37.953	103.398
6	43.055	110.142
7	48.328	115.545
8	53.530	122.366
9	58.733	125.932
10	63.800	129.084
11	69.309	132.369
12	74.342	140.824
13	79.336	149.195

Table II shows that the handover latency varies significantly according to the network configuration and addressing scheme used (from $12ms$ to $149ms$). From a network design point of view, it is preferable to connect all APs on the same subnet, as long as the number of APs and stations remain small. At least, APs used to provide robustness and fault tolerance could be deployed on the same subnet. Table II also suggests that special attention should be paid to the AP channel allocation, and the algorithm a station uses to switch between channels. For instance, channels 1, 6, and 11 are the only three non-overlapping channels among the 11 channels available in IEEE 802.11b. Thus, it may be worthwhile to prioritize the channel scanning during the discovery stage, so that channels 1, 6, and 11 are scanned first [10].

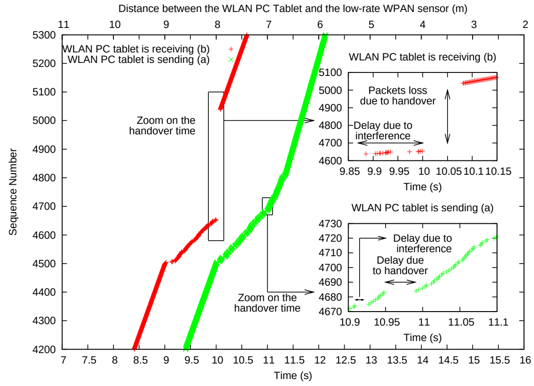

Fig. 4. Video Stream Packet Sequence at the Application Layer

B. Application and MAC levels implications

Now that we have quantified the handover delay latencies, we investigate the impact of the WLAN handover on the WLAN performance. Figures 4, 5, and 6 represent different aspects of the WLAN handover impact on performance. For these results, we use a network configuration that produces an average handover latency, namely, where the two WLAN APs considered are on the same subnet, and the station has to switch channels 13 times, either because it missed the AP replies, or because it has to scan all channels before finding an AP. The MAC handover latency is around 80 ms acccording to Table II.

Figure 4 represents the IP data packet reception sequence at either the AP for scenario (a), or the PC tablet for scenario (b). We can see that the data packet reception sequence in both scenarios is impacted by the WPAN-WLAN interference. Although no packets are lost at the IP layer because the MAC layer is doing retransmissions, we can see some additional delays in the sequence of packets received. When the handover is triggered, we observe a different impact on the data reception sequence depending on the scenario considered. When the PC tablet is sending video (scenario (a)), the handover latency implies a gap in the data reception on the receiver's side. This delay is due to the fact that the station is queuing data packets during the handover.

On the other hand, when the WLAN PC tablet is receiving the video application (scenario (b)), packets are lost during the handover. From the time the WLAN PC tablet starts the handover until the completion of the handover, data packets are still reaching the old AP and are then lost. In this particular example, 350 packets are lost. This corresponds to the number of packets generated during the handover plus some of the packets generated during the interference period, which were not received by the WLAN PC tablet because of the additional delay due to retransmissions.

Figure 5 shows the ratio between the number of retransmissions and the number of data packets generated (expected to be sent). For each data packet, we observe that 1.5 (on average) retransmissions are needed when the node is within the interference area. At time 10 s, the PC tablet triggers

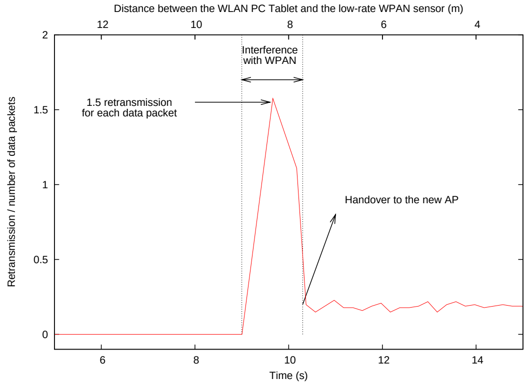

Fig. 5. WLAN MAC Packets Retransmissions

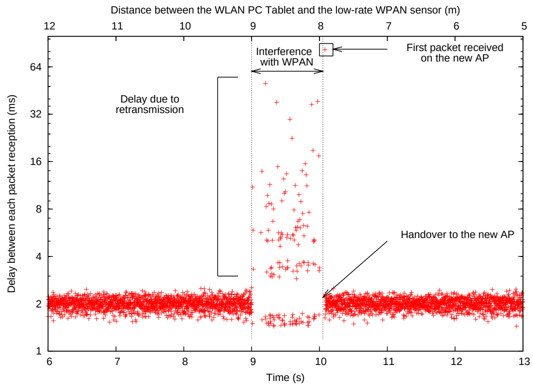

Fig. 6. WLAN Packet Delay Jitter

the handover because of the high number of retransmissions during the last second. Once the handover on the other AP is done, no more retransmissions are necessary.

Figure 6 represents the inter-arrival time between two application packets. Note that the inter-arrival time for the application chosen is 2 ms. We can see from the results on Figure 6 that most of the packet inter-arrival times vary between 1.8 ms and 2.2 ms when packets do not need retransmissions. On the other hand, when packet needs to be retransmitted, the packet inter-arrival time is around 3 ms. When the PC tablet enters the interference area (around 9 s), the packet inter-arrival time becomes more significant (up to 80 ms) and highly variable (between 1.6 ms and 80 ms). Note that this packet inter-arrival time is unacceptable for the video application considered. Once the handover is completed (at 10 seconds) the inter-arrival time returns to normal, around 2 ms.

In summary, these results show that a handover on another AP is very valuable, not only for the WPAN communication, but also for the WLAN systems. Based on different parameters such as the number of packet retransmissions used here, or even the packet inter-arrival time, a WLAN station can trigger a handover that improves both the WLAN and WPAN links performance. At this point, it is important to mention that since the link measurements are performed on the WLAN, the handover happens when the WLAN measurements indicate a problem on the link. In the case where the WLAN station is receiving data frames (scenario a), the WLAN link is the first (and the most) impacted by the interference and the handover can be initiated quickly so as to minimize and even eliminate any interference on the WPAN link. On the other hand, when the WLAN station is only receiving ACK frames (scenario b), it takes more time to determine that another technology is operating nearby. As a consequence, the WPAN, which is the first effected, will be impacted as long as the WLAN station does not trigger the handover (in our simulation, the WPAN will be perturbed during 1 second).

Another effect of the handover solution is that the handover latency might be important in WLAN networks. If the WLAN traffic is redirected to another technology, the handover process will not affect the traffic. During the time the redirection is taking place, the flow is continuously received on the WLAN interface of the station. Once the redirection is done, the traffic reaches the station via the target interface. If the station is moving to another WLAN AP, the reception of packets will be interrupted during the handover process. In the simulation results shown in Figure 4, there are a total of 42 packets lost during the handover.

V. Concluding Remarks

In this article, we explore the use of multiple wireless networks in support of medical device communications. We concentrate on a patient's bedside scenario, which includes a combination of low rate and low latency applications utilizing low-rate WPAN in addition to more traditional bandwidth hungry applications using WLAN. We investigate the behavior of these two wireless technologies operating in close proximity on overlapping channels and quantify the effects of mutual interference on their performance. The packet loss observed in both low-rate WPAN and WLAN systems makes the communication useless.

We propose a handover solution for the WLAN in order to dynamically assess the presence of the low-rate WPAN and look for a different access point on a different center channel. The main contribution of this article lies in the definition of new link performance measures, namely the number of packets retransmitted, in order to assess the presence of interference on the band and trigger an intra-WLAN handover. We evaluate the performance of the solution proposed by analyzing the data packet sequence at the WLAN receiver and the packet inter-arrival delay jitter. We show that this solution is benefitial for both low-rate WPAN and WLAN systems.

We are currently working on extending this solution in order to provide additional mechanisms that would aid in better detecting interference, even on remote devices and victim systems, in order to expedite the handover initiation and execution processes.

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