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Wireless Propagation and Coexistence of Medical Body Sensor Networks for Ambulatory Patient Monitoring

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Abstract—**In this paper we present the technical requirements and system issues for wireless Medical Body Sensor Networks (BSNs). Design guidelines are driven by the need to improve ambulatory patient monitoring and care while reducing logistic constraints for patients as well as healthcare professionals. We present our study on three key components of Medical BSN: On-body wireless link (to characterize the RF channel for body worn wireless devices), Coupling between bodies (to characterize the RF interaction between bodies) and Coexistence of Medical BSNs in the RF spectrum. Results and conclusions are presented through simulation and measurement studies. We also discuss our FCC petition for spectrum allocation.**

Keywords—Medical Body Sensor Network; Medical Body Area Network; wireless coexistence; listen before talk; ARQ

I. INTRODUCTION

Many issues loom in the U.S. Healthcare system. A shortage of 1 million registered nurses is expected by 2020 in the United States [1]. Hospital patient acuity will rise as nearly 80 million baby boomers age. For each active critical care bed in a standard hospital setting, 40 percent of patient care time is spent manually recording patient monitor information [2]. Hospitals must manage more than 300 external reporting requirements and internal reporting. Adults in the U.S. receive only about 55 percent of recommended care for a variety of common conditions [3].

Clinical decision support systems can help ensure that physicians have the most current information about the condition they are treating and that they are not overlooking important treatment options [3]. We consider the introduction of wearable Medical Body Sensor Networks as a key element of future decision support solutions to alleviate these pressures while simultaneously increasing patient safety and comfort during hospital internment.

A Medical Body Sensor Network (BSN) is a collection of non-invasive and body worn, wireless sensor devices. These devices would be capable of collecting real-time information regarding the medical condition of patients inside and outside a healthcare facility. The collected information could be processed locally at the patient or could be transmitted via a Wireless Medical Telemetry (WMTS) or other backhaul communications link to a centralized monitoring station. Healthcare professionals will have continuous access to patients' current physiological parameters via electronic health records and portable computing devices. Figure 1 illustrates the Medical BSN concept.

Medical BSNs hold great promise for reducing the constraints that wired patient monitors place on healthcare professionals and patients. Technology advances permit the development of low-power, miniaturized, BSN devices. However, the full potential of this technology requires careful attention be paid to the design of a reliable, on-body, wireless link as well as the coexistence of numerous, collocated Medical BSN systems along with other radio systems such as Wi-Fi, Bluetooth and Zigbee.

II. RELIABLE ON-BODY WIRELESS LINK

In this section we study the radio frequency (RF) channel for body worn devices. We look at the characterization of the radio propagation on-body and tradeoffs associated with different antenna types. We consider achievable performance through experimental studies and compare it to related literature from other research groups.

Recent effort devoted to characterization of the radio propagation channel for body worn devices has focused on propagation in the 2400 to 2483 MHz unlicensed band as well as 2 to 6 GHz ultra wideband spectral range.

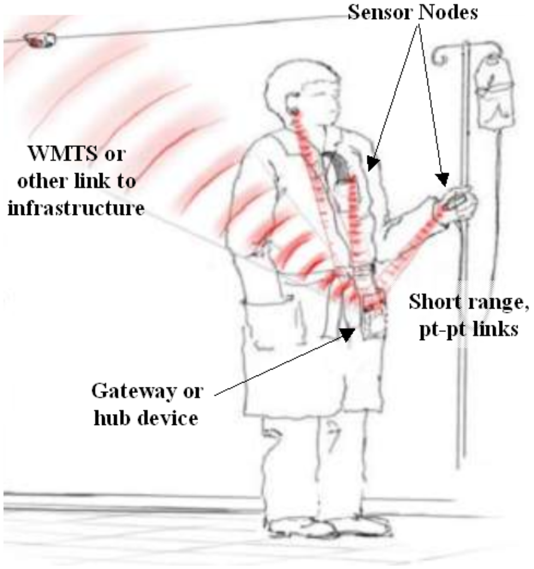

Figure 1. Illustration of Medical Body Sensor Network concept.

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At 2.4 GHz, the propagation of radio waves about the body has been modeled as creeping waves where RF power (field strength) decays exponentially with distance [4]. Path gain measurements have been performed by others within anechoic chambers and laboratory environments to quantify the influence of body posture, body movement, and antenna position. Measurements performed with monopole antennas oriented perpendicular to the body surface and placed on the chest and trunk showed average path gain values of –41 and –44 dB for anechoic chamber and laboratory environments, respectively [5]. Path gain measurements approximated a lognormal distribution and ranged 24 to 38 dB about the average values in the laboratory given body posture changes including walking, bending and turning.

The efforts by others have relied upon monopole antennas with a ground plane oriented perpendicular to the body surface. Such an antenna is not well-suited to small, disposable, body worn medical devices. As a result, we engaged Queen Mary University in London to simulate the performance of planar, printed circuit board antennas placed in close proximity to the skin [6]. Various printed antenna types were considered, including dipole, monopole, loop and inverted-L antennas. These simulations showed antenna efficiency on the order of 35 to 50% for inverted-L antennas located on the chest or wrist. Simulations also estimated path gain of -51 and -55 dB between printed monopole antennas on the left waist and right chest or right thigh, respectively.

We measured path gain between printed monopole and inverted-L antennas in the laboratory environment with a similar set of body posture and movements used by other researchers [4]. Measurements of path gain, S21, using printed, inverted-L antennas placed 10 mm from the skin are summarized in Table 1. These measurements were made with an Agilent E5071 network analyzer sweeping over 2.4 to 2.525 GHz range using a 1 MHz resolution bandwidth. Table 1 shows only the 1 MHz channel at 2.4 GHz. Figure 2 illustrates the measured path gain for subject 1 given various body postures and movements.

Comparison of our measurements with those from other research groups reveals similar variation in path gain given human subject movements. However, our measurements using printed, planar antennas show larger attenuation between the body worn antennas than reported by others using quarter wavelength monopole antennas oriented perpendicular to the skin surface.

Table 1. Measured path gain at 2.4 GHz using inverted-L antennas placed 10 mm from the skin. Transmit antenna on left waist.

Body Path Left Waist to	Path Gain		
	Average (dB)	*Standard Deviation (dB)*	*Range (dB)*
Right Chest			
Subject 1	-57.7	5.0	35.7
Subject 2	-60.5	6.8	60.2
Right Wrist			
Subject 1	-68.8	6.5	56.0
Subject 2	-63.9	5.6	58.8

These path loss measurements support the estimation of path loss as a normal random variable with an average value –63 dB and a standard deviation of 6 dB. For a normal random variable, 99.98% of the distribution falls above a threshold set at 3.5 standard deviations below the average value. For the on-body propagation channel 99.98% of the path gain will occur at values above –63 – (3.5*6) = –84.0 dB. Given a 0 dBm transmission, this on-body propagation channel model predicts received signal level exceeding –84 dBm greater than 99.98% of the time. Such a minimum received signal level is compatible with commercially available wireless transceivers. For example, the Nordic nRF24L01+ transceiver uses GFSK modulation and operates at 1 Mbps data rate with $1\text{x}10^{-3}$ bit error rate at –85 dBm signal level [7]. The Texas Instruments CC2510 transceiver uses MSK modulation to operate at 500 kbps data rate with an effective bit error rate of $6.25\text{x}10^{-6}$ given –82 dBm signal level [8].

Temporal and frequency diversity techniques might be applied to provide additional margin relative to the minimum signal level. Our measurements of on-body and body-coupled propagation with body worn, printed antennas reveal coherence bandwidths of over 6 to 10 MHz, respectively. These coherence bandwidths are derived with respect to a 0.9 threshold on the correlation function.

Reliable communication over the on-body wireless channel can be realized using simple, printed circuit antennas and low (1 mW) radiated power. Additional link margin to combat channel variation due to patient mobility and posture can be realized by incorporating frequency and temporal diversity mechanisms to the exchange of data messages within a Medical BSN.

III. COUPLING BETWEEN BODIES

Coexistence of Medical BSN systems has been identified as a key requirement of the IEEE 802.15 Task Group 6, Body Area Networks. This group has defined a performance requirement of 10 BSN systems within a 6 x 6 x 6 meter cubic volume [9] for medical or consumer applications.

The off-body propagation of radio signals from nearby Medical BSN systems represents a source of interference for an individual body sensor network. Considerably less work has been reported about the coupling of radio signals between body worn antennas on different, collocated people. Measurements made by University of Birmingham used quarter wave monopole antennas oriented perpendicular to the skin to measure the interference between two Medical BSNs at 2.45 GHz. Path gain between antennas at the left waist of one person and the near, right side of a second person was measured. Average path gain at 1.5 meter separation ranged between –47.1 dB and –51.1 dB, while standard deviation ranged between 4.5 and 7.5 dB [10].

We measured the coupling between bodies over the 2400 to 2500 MHz band in an office building elevator lobby using an Agilent PNA N5230A network analyzer. Printed circuit, planar, inverted-L antennas were place on two subjects. Path gain, S21, measurements were made at 1 MHz sampling and with a variety of antenna locations. Participants were separated by distances of 1 to 5 meters, facing different

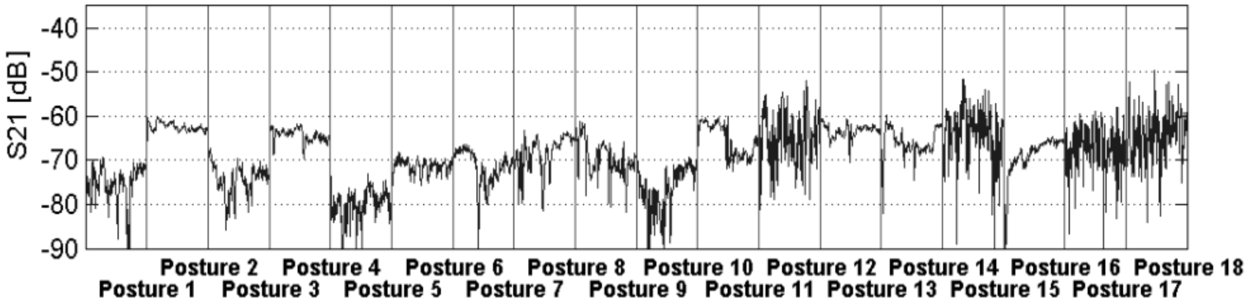

Figure 2. Path gain measurements for 1 MHz channel at 2.4 GHz using inverted-L antenna placed 10 mm from skin. Multiple body postures considered: standing upright, standing turned left, standing turned right, standing leaning forward, standing head forward, standing head right, standing arms out to side, standing arms over head, standing forearms forward, standing moving freely, sitting arms hanging down, sitting hands in lap, sitting moving freely, standing upright, walking back and forth, walking back and forth moving freely.

directions and with up to 10 other bodies located in the room. An average path loss of –67.9 dB and standard deviation of 5 dB was observed between the antennas. This average was calculated over the entire frequency range considered. The larger attenuations observed can again be attributed to the use of printed, planar antennas rather than quarter wave monopole structures perpendicular to the skin.

Further analysis of the body coupling data showed median path loss as statistically independent with respect to the test variables. The variance of path loss exhibited only slight dependency to body orientation and position of the body worn antenna on the transmitting body. These results are explained by the directional characteristics of body worn, planar antennas (body shadows half the azimuth plane) which enhances generation/reception of multipath signal components from the walls of the room. Indirect multipath signals, rather than direct path signals couple to other collocated bodies in the room. The presence of additional people in the room does not influence the body coupled path loss statistics observed between the pair of test antennas.

IV. COEXISTENCE OF MEDICAL BODY SENSOR NETWORKS

Coexistence is related to the Medical BSN performance in the presence of multiple BSNs and other RF devices sharing the wireless spectrum. Design choices are discussed through media access protocols and the potential of dedicated spectrum.

While there are many physical and media access control layer mechanisms to address the challenge of coexistence, Medical BSN applications also introduce requirements of 0.125 second latency and 10% packet error rate [9]. These requirements apply to a Medical BSN collocated with other BSN systems as well as other radio devices such as cordless phones, two-way radios, Wi-Fi, Bluetooth, Zigbee and others readily found within the hospital environment.

The availability of dedicated spectrum for Medical BSNs would significantly enable coexistence. Separating Medical BSN devices in frequency from unlicensed wireless devices found in hospitals allows the system designer to focus on meeting the performance requirements and coexistence among Medical BSNs. GE Healthcare has submitted a proposal to the Federal Communication Commission (FCC) to create a new radio service for wireless, Medical Body Area Networks, including BSNs, in the 2360 to 2400 MHz band [11, 12]. This proposal will help health care professionals provide more pervasive monitoring of patients while mitigating issues of interference and radio coexistence within the hospital environment. This proposal would also benefit from the ability to leverage highly integrated transceivers from the 2.4 GHz band, albeit with retuning for this adjacent frequency range.

Use of high data rates over the air yields short packets which reduce the probability of collision. Higher data rates also afford the opportunity to retransmit messages to achieve temporal and/or frequency diversity. Short packets also allow a node to sleep longer and preserve its battery supply.

If all Medical BSNs within a spatial region were perfectly synchronized in time and frequency, it would be possible to share a single, frequency channel among multiple patients. Assuming a 2% duty cycle for an individual BSN node and time division multiple access used within each BSN, a total of 50 BSN devices could be supported on a perfectly synchronized channel. However, such synchronization requires active management between BSN hubs on proximate patients or a distributed, control infrastructure. A distributed infrastructure introduces cost and complexity to a Medical BSN deployment, as a downlink must be provisioned with reliable coverage for every hub throughout the facility. Such a synchronization infrastructure represents a significant obstacle to commercialization of BSNs within a medical environment.

Realization of synchronization via exchange of messages between hub devices on different patients is no less an obstacle given the need for robust message exchange and the additional receiver and processing requirements imposed on the BSN hub. Hubs will consume additional battery and bandwidth resources with such an active messaging scheme. Such a distributed synchronization approach would require each Medical BSN hub to increase its traffic with respect to the number of collocated hubs.

Given the mobility of ambulatory patients, discovery of proximate BSNs would require additional and frequent exchange of messages. This additional traffic conveys no patient data, increases the probability of collision between BSNs and, therefore, is highly inefficient. Furthermore, there is no commercially proven protocol for synchronization of independent, mobile networks. The development of distributed BSN synchronization requires further research and is likely to consume much of the spectrum that it seeks to reuse.

Unsynchronized Medical BSNs can operate using contention-based protocols, such as listen before talk (LBT) and/or frequency hopping, to facilitate coexistence amongst each other as well as primary radio systems. The body-coupled signal, as detailed above, imposes attenuation on the same order as the on-body channel, making LBT highly effective. Frequency hopping is another proven technique that supports mobile patients moving about with respect to one another. Automatic repeat request (ARQ) can be highly effective in reducing the number of redundant retransmissions required, further reducing the probability of packet collision.

V. SIMULATION OF PROTOCOL MECHANISMS

We evaluated the mechanisms discussed in the previous section (frequency hopping, frequency diversity, LBT, ARQ) through detailed simulations which are presented in this section.

Our simulation scenario consisted of Medical BSN equipped patients moving within an area of 10 by 10 feet. Each BSN implements a time division multiple access (TDMA) network among its hub and sensors. This scenario was evaluated multiple times with random patient positions and motion.

During each TDMA frame (i.e. beacon period), a single packet is transmitted by the hub and each sensor node on a designated frequency channel. The frequency of each Medical BSN changes periodically in an uncoordinated and asynchronous manner (across BSNs) to reduce collisions.

The protocol mechanisms were implemented using Network Simulator NS2. For each protocol case considered, a total of 50 trials was conducted. Each trial included 10 hubs each with 10 sensors. Each trial represented a unique, random draw of time and frequency parameters and lasted for $1\text{x}10^5$ frames. Trials were evaluated using a printed monopole antenna propagation model, 32 byte messages and 1 Mbps data rate. The aggregate duty cycle for each of the ten BSNs was approximately 10 to 15%. The frequency hop pattern changed every 16 frames and LBT threshold of –87 dBm was considered.

The first experiment simulated the case with simple TDMA for each BSN. For each hub beacon message under the simple TDMA link layer, a sensor node sends a single packet. With dual frequency, every packet is sent twice within each frame, using a different frequency and hop pattern for the second, redundant transmission. With ARQ, a sensor's redundant transmission is sent only if its hub failed to receive the first attempt in that frame. With LBT each transmission is subject to a fixed, time deferral if the device observes other BSN activity during the beginning of its time slot. The deferred transmission still occurs within the TDMA slot assigned to the device. Regardless of ARQ and LBT the redundant message is sent on a second frequency for diversity gain.

Figure 3 shows the average frame error rate from these simulations as a function of the number of available channels (i.e. bandwidth). This frame error is the probability of a

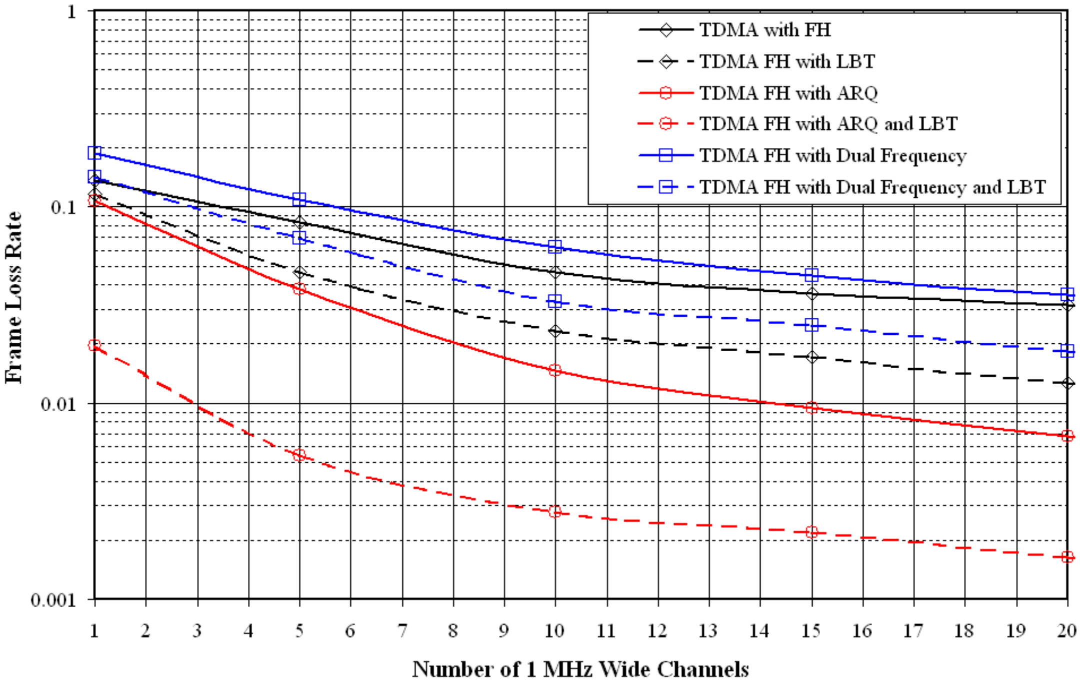

Figure 3. Probability of TDMA frame loss from an individual sensor. Various coexistence protocol mechanisms considered in a scenario with 10 Medical BSNs each with hub and 10 sensor nodes, moving about a 10-by-10 foot area. No external interference sources (e.g. Bluetooth, Zigbee, Wi-Fi) included in the simulation scenario.

sensor failing to transmit its data message to its hub within a single TDMA frame, considering any redundant transmissions. Looking at the results of Figure 3, it is interesting to note that the dual frequency mode has a higher frame error rate than the simple TDMA case. This is because with two packets being sent by the hub and sensor, there are increased collisions as the network appears as one with double the number of nodes. In the absence of other competing, non-BSN radio systems, the simple increase in the number of packets outweighs the increased reliability due to the secondary transmission at a different frequency. However, when listen before talk is employed for dual frequency mode, the error rate is better than the simple case illustrating the performance benefit of dual packet transmissions.

ARQ has the best performance out of the three different protocol cases considered as this link layer leads to more efficient utilization of the channel by having retransmissions only when required. Fewer packets in the air leads to fewer collision opportunities. Combining ARQ with LBT further improves the performance. This improvement is not surprising since ARQ with LBT captures the benefits all the protocol mechanisms, retransmitting only when necessary on a second frequency, with both the transmissions avoiding collisions using LBT.

Increasing the number of 1 MHz channels in the available hopping pool decreases the probability of frame loss. It should be noted that the results of Figure 3 apply to 32 byte messages. Satisfaction of the IEEE 802.15 Task Group 6 Body Area Network requirements for 10% packet error rate with 256 byte packets as well as scalability for many more than 10 sensor nodes will require the availability of additional frequency channels [9]. Furthermore, these channels are assumed to be free of other radio services (i.e. dedicated spectrum) or otherwise available after avoiding frequencies in use by other services within a shared band.

The Medical BSN packet size and frame time along with the simplified LBT mechanism allow sufficient frequency and temporal resources to employ all these protocol concepts together. The trade-off is the increased power consumption for both sensor nodes and hub given the LBT monitoring interval and the numerous transitions between transmit and receive operating modes.

VI. CONCLUSION

The coexistence challenges of Medical Body Sensor Networks applied to ambulatory patient monitoring in the hospital can be addressed with a combination of physical and media access layer mechanisms. Dedicated spectrum would greatly facility this problem. Use of techniques to minimize packet collision include frequency hopping, listen before talk and high data rates for short packets. Our measurements and simulations show that these mechanism can be highly effective in the design of a Medical BSN system.

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