Random Room Mobility Model and Extra-Wireless Body Area Network Communication in Hospital Buildings

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Abstract

Wireless Body Area Networks (WBANs) can help in enabling efficient patient monitoring solution for ubiquitous healthcare. Communication in WBANs is undertaken in two phases: *Intra-WBAN*, and *extra-WBAN*. The prevailing WBANs use cellular network or WiFi in the extra-WBAN phase involving communication between the on-body coordinator and Access Points (APs) connected to the medical server through the Internet. The medical applications of the WBANs have stringent requirements of low end-to-end delay and high packet delivery ratio. We evaluate the performance of extra-WBAN communication in the network of WBANs which is deployed within a building environment. We proposed a mobility model named *Random Room Mobility* (*RRM*), which is used to capture the dynamics of WBAN user mobility within the building. We studied the performance of extra-WBAN communication using the proposed mobility model and a Random Waypoint Mobility (RWP) [1] Model. The metrics used in evaluating the performance are packet drop ratio, average node-to-AP delay, and average residual energy per node. We show that with an increase in the number of WBANs, the traffic generation rate, and the payload size have high impact on the packet loss in the network. We studied the performance of extra-WBAN communication using the priority mode available in IEEE 802.11 for provisioning Quality-of-Service (QoS). We show that it is suitable for medical applications, when the size of network consisting of WBANs, including the QoS-enabled WBANs, is small.

Index Terms

Wireless Body Area Networks, Mobility Model, WiFi, and Healthcare

I. Introduction

A Wireless Body Area Network (WBAN) [2], [3] consists of different wearable sensors, which are used to monitor the vital signs of a human body and an on-body coordinator (for example, a PDA or a smart phone). Each sensor node in the WBAN contains sensing, processing, memory, and transceiver modules. All the modules of the sensor nodes, together with the on-body coordinator, are powered by individual onboard rechargeable batteries. Among all the modules, the transceiver module consumes more battery power for its operation. The rate of energy consumption of the transceiver depends on its transmission range. The rate of energy consumption increases as the tranmission range of the node increases. Thus, the nodes in a WBAN use a short-range (<2 meter) and low-power wireless transmitter to transmit the vital signs to the on-body coordinator acting as a gateway. It is assumed that the on-body coordinator is more powerful than the sensor nodes in terms of battery supply, processing power, memory capacity, and transmission range. The coordinator aggregates the packets, which are received from the sensors, and then relays the aggregated packets using the long-range transmitter to the nearest AP. Upon receiving the packets, it forwards them through the Internet to medical practitioners' computers. For instance, an architecture of the possible deployment of wireless network for health monitoring in a hospital building is shown in Fig. 1.

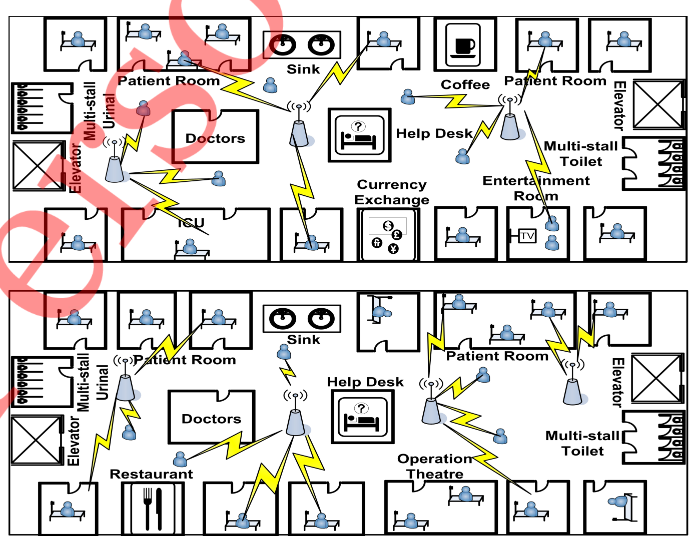


Fig. 1: A wireless network for health monitoring within a hospital

Medical applications of WBANs require high throughput (greater than 250 Kbps and even up to 10 Mbps), low end-to-end delay, and high reliability [4]. The Industrial Scientific and Medical (ISM) band is currently used as the carrier of the physiological signals transmitted by the sensors in the WBAN. The band has 16 channels and the bandwidth of each channel is 2 MHz. According to the IEEE 802.15.4 standard, the physical data rate supported is at most 250 kbps. An ECG monitoring system proposed in [5] contains three ECG sensors and a sampling module with wireless interface, which can tolerate the maximum sampling rate of 1kHz. In a WBAN, the coordinator may operate such ECG monitoring system along with other physiological sensors such as EEG and EMG sensors, thereby generating large amount of data for which it may require high physical data rate which would be higher than 250 kbps. The quality of the sensing physiological signal is very much important in healthcare. However, the scaling of the WBAN and increase of the accuracy of the sensing signal require the support for higher data rate to transfer data. For example, if a WBAN has 3 ECG sensors (each of them running at 300 Hz with accuracy of 12 bits), 12 EEG sensors (each of them running at 100 Hz with accuracy of 16 bits), and 6 EMG sensors (each of them running at 400 Hz with accuracy of 16 bits), then it will generate 68400 bps (68.4 kbps) data altogether. The wireless transmission of the generated data requires some more bits for synchronization, the source and destination headers, and checksum.

The unique features of a WBAN are the miniaturization of sensor node (to preserve the level of comfort of WBAN users wearing these sensor nodes), extreme energy efficiency, and high security and privacy. These features differentiate a WBAN from other wireless networks such as wireless sensor and ad hoc networks. Because of the unique features, the regular wireless network-based communication structure can not be used in the WBAN.

Communication in WBANs is undertaken in two phases as follows: *intra-WBAN communication*, and *extra-WBAN communication*. In intra-WBAN communication, exchange of information between the sensors and the on-body coordinator takes place. The coordinator initiates the communication process by broadcasting a beacon message followed by a low duty-cycle MAC schedule for the sensors. The sensor nodes then transmit vital patient information in the form of packets in the scheduled time to the on-body coordinator over the shared medium. A survey on intra-WBAN (or intrabody) communication and design issues of it are found in [6]. A wireless autonomous spanning tree protocol [7] is proposed for intra-WBAN communication, in which the on-body nodes form a network and route the data using a slotted multihop approach. In extra-WBAN communication, there is exchange of information between the on-body coordinator and the AP. Currently, the main focus is on the communication issues in intra-WBAN phase. On the other hand, paying less attention to the communication issues in extra-WBAN phase, assuming that the coordinator could use an existing infrastructure of high power networks such as WiFi and cellular networks for delivering the physiological informations to the medical server. In this paper, we investigate the performance of extra-WBAN communication in the WBAN deployed within a building.

Lin et al. [8] is used to detect abnormal heart rhythms such as cardiac asystole and atrial fibrillation promptly. The system uses Bluetooth and WiFi in the communication phase, which is physically in between the ECG sensors and the coordinator (or hub), and between the hub and the AP, respectively. However, the energy consumption by the nodes due to Bluetooth technology is comparatively high. Also, when the number of such devices increases, the performance could be affected in terms because of the possibility of unfair bandwidth sharing among nodes and long waiting delay due to the round robin polling scheme and scatternet formation [9]. Misic and Misic [10] have analyzed the packet delay by using the IEEE 802.15.4 and IEEE 802.11b based radio interfaces for intra-WBAN and extra-WBAN communication in WBANs, respectively.

Each health monitoring device in a WBAN is designed to send the physiological information sensed to the on-body coordinator continuously either every second, minute or day. ECG monitoring systems need to send the sensed data samples every second. The samples of ECG signal of a patient suffering from cardiovascular diseases are required every second for diagnosis purpose, whereas the glucose monitoring device needs to send the samples every one hour. The size of queue in the nodes may be different from another because of the different sampling rate. The MAC layer in the protocol stack of the WBAN should work adaptively in the presence of heterogeneous type of nodes. To provide different service to the different type of data in wireless networks, IEEE 802.11 standard has introduced four types of Access Class. Similarly, IEEE 802.15.6 has also introduced eight types of priority. In this work, we also studied the performance of the network by considering the nodes with different types of priority.

WBANs are deployed mostly in medical environments. The patients monitored by the current WBAN technology should stay within the range of the receiver. If the receiver is placed inside the patient room, then the patients are not allowed to go out of the room. Francisco considered channel measurements taken at 2.4 GHz for various locations within a patient room in a hospital by keeping the receiver at a fixed place in the same room [11]. However, the measurements could be different when the transmitter moves out of the room. The channel model proposed based on the measurements cannot be used in the WBAN network consisting of moving users. The network should allow the mobility of users so as to enable the continuous monitoring of patients from any where within the building. Wireless signals get obstructed in a building environment by an internal wall that separates the rooms.

Mobility models are used to generate different mobility patterns [12] that have been followed by the mobile nodes in mobile wireless networks. These mobility models can be characterized through the node's mobility pattern or distribution within the confined area of simulation [13]. We discuss the node distribution in the first paragraph of Section II-A. We proposed a mobility model named RRM that modifies the RWP. It is observed that the nodes according to RWP staying in the central region of the simulated area for longer duration, after the long run of simulation. It is obvious that the APs in the central region of the building are overloaded with the requests for resources by the nodes. Also, the large gathering of WBAN nodes in the central region of the building may increase the signal interference for APs located in that region. Whereas, the nodes moving according to the RRM model do not exhibit such phenomena. As a result, the percentage of packet drop ratio of RWP is increased by 2% compared with RRM.

The contributions in the paper are summarized as follows:

- Mobility of the WBAN users is considered in studying the performance of the extra-WBAN communication. A mobility model named Random Room Mobility (RRM) Model is proposed, which modifies the Random WayPoint Mobility (RWP) model. The performance of the network using both the mobility models is studied.
- We have studied the network performance while considering physical data rate of 1 Mbps at the on-body coordinators with varying work loads and priorities. The QoS nodes in the network have priority to access the channel. In our study, we consider the network consisting of the QoS and non-QoS nodes.
- The simulation study includes the internal wall loss and the shadowing loss. These two types of loss can effect the performance of the wireless networks deployed within a building environment.

The organization of the paper is as follows. We discuss the mobility models used to evaluate the performance of the extra-WBAN communication in Section II. In Section III, we discuss the MAC issues in WBANs. We discuss about the signal interference arising due to the coexistence of neighbouring WBANs in Section IV. Section V discusses the path loss components that degrade the strength of a communication signal within a building. The performance metrics and the parameters considered in the simulation are discussed in Section VI and Section VI-A, respectively. The simulated results and discussion are provided in Section VI-B. We, finally, conclude the paper in Section VII.

II. WBAN User Mobility

Mobility is one of the imporant aspects of human life. In a hospital, patients carry the monitoring devices. The study in [14] revealed that mobility can improve patients' conditions being monitored by the doctors in a hospital. For example, a patient living in rest position for long duration of time may form pressure ulcer and muscle weakness. Therefore, patients are often advised by doctors to go around the floors of the hospital. In other cases as well, a patient may have to walk into a specialized room having non-portable medical equipment for testing and diagnosis. For example, haemotological patients (the disease related to the blood and bone marrow) are frequently taken to the X-ray machine to know the current status of deterioration level of the skeleton [15]. The health monitoring system deployed on a patient (i.e., WBAN) should not restrict their mobility.

An improved mobility model can influence the performance of the wireless communication models. For example, the existing mobility models do not capture the dynamics of mobile user clumps during the gatherings in the cities of urban areas [16]. In a similar manner, a hot spot can be formed in the network by the WBAN users who are moving to different rooms within a building. Misra et al. [17] proposed a bio-inspired group mobility model for mobile ad hoc networks. In [18], a cross-layer handoff protocol is proposed for cognitive radio networks. The handover prediction and prior scheduling of the handover can improve the performance of mobile IPv6 networks [19]. Ref. [20] reviews the near optimum routing solutions for multiple mobile agents deployed in WSNs. Motivated by this requirement, in this work, we introduce a mobility model named *Random Room Mobility Model*. The WBAN user moves within the building by selecting a random room and random speed. Upon reaching the room, the user stays there for a short duration of time, which is termed as the pause time. The pause time can be defined as a user wants to stay inside the room for the duration to accomplish some kind of activity. The user selects the room within the building using a random variable with the probability mass function given below.

$$dest(n\_room) = \begin{cases} \frac{1}{r}, & 1 \leq n\_room \leq r \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

where, $n\_room \in \{$ 1, 2, ..., r$\}$, and r represents the room identification number and the total number of rooms, which are available inside the building, respectively.

Initially, the users are placed uniformly in the rooms within the building. After the start of simulation, the users select a room using Eqn. (1), and then select a position within the room by using the probability density functions (PDFs) for each of the dimensions in the room. The PDFs for length, breadth, and height of the room are given in Eqn.(2), Eqn.(3), and Eqn.(4), respectively. The destination position, which is within a selected room, is denoted by the tuple *tuple* (pos(l), pos(b), pos(h)).

$$pos(l) = \begin{cases} \frac{1}{l_{max}-l_{min}}, & l_{min} < l < l_{max} \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

where, the length of each room is bounded by the minimum (l_{min}) and maximum (l_{max}) values.

$$pos(b) = \begin{cases} \frac{1}{b_{max}-b_{min}}, & b_{min} < b < b_{max} \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

where, the breadth of each room is bounded by the minimum (b_{min}) and maximum (b_{max}) values.

$$pos(h) = \begin{cases} \frac{1}{h_{max}-h_{min}}, & h_{min} < h < h_{max} \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

where, the height of each room is bounded by the minimum (h_{min}) and maximum (h_{max}) values. The pseudo code of the proposed mobility model is given in Fig. 2.

A. Node distribution

Mobility models are very important in the simulation study of mobile networks. The spatial distribution of nodes within a confined area is different for different mobility models. We show the node distribution of the proposed mobility model (i.e., RRM) along with the Random Waypoint Mobility Model (RWP) in Fig. 3. In [21], authors review the long run stochastic stability of discrete RWP mobility model. The RWP mobility model has been widely used for the performance analysis of protocols in wireless communication networks. It is observed that a node moving using RWP stays for longer duration in the central region of the simulation area, after long duration of simulation run (10690 epochs in 100000 seconds). The node distribution for RWP is shown in Fig. 3. Few rooms, which are situated in the central and boundary region of the building have higher and lower node hit density, respectively. Consequently, it lacks in providing the dynamics of user mobility at the boundary rooms in the simulation area. The WBAN user may not move by selecting a position uniformly within the boundary of the building; otherwise, it may have multiple epochs within the same room. The WBAN user who is moving according to the RRM model covers each and every room uniformly in the building. In this paper, we investigate the performance of the WBANs in the building environment using different mobility models.

Random Room Mobility (RRM)

Inputs: cp = *tuple*($pos_l^{'}$, $pos_b^{'}$, $pos_h^{'}$) ▷ Initial position of the node

Procedure:

Go to a different room or specialized room: ▷ The nodes visit different specialized rooms that are selected uniformly within the building

rn ← dest(n_room) From Eqn. (1)

Repeatation of a room is not allowed until all rooms are visited by the node

Select a position within the room:

pos_l ← pos(l) From Eqn. (2)

pos_b ← pos(b) From Eqn. (3)

pos_h ← pos(h) From Eqn. (4)

set the tuple *tuple*(pos_l, pos_b, pos_h) as the new destination of the node, i.e.,

dp = *tuple*(pos_l, pos_b, pos_h) ▷ dp represents the destination position

speed, s = Get_Speed(S_{min}, S_{max}) ▷ Speed of the node is random. The random function returns a value which is uniformly selected from a given range

pause_time = pause time ▷ The amount of time the node pauses just after it reaches the destination

calculate the velocity (V) of the node in three dimensions, i.e., V = (V_l, V_b, V_b)

T_l = the last time when the position is updated

while (cp $\neq$ dp) **do**

  T_c = the current time

  T = T_c - T_l

  cp = (T $\times$ V_l, T $\times$ V_b, T $\times$ V_b) ▷ cp represents the current position of the node.

end while

pause the mobility of the node for pause_time.

End of room visit.

go to the *Procedure*.

Fig. 2: Random Room Mobility Model

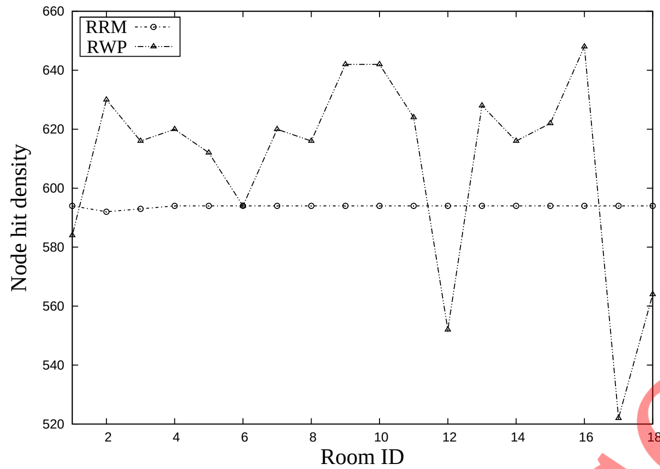


Fig. 3: Node distribution within the building

III. Medium Access Control in WBAN

The medium of communication used in wireless networks is radio frequence (RF). RF is a shared resource. Collision and interference are characteristic phenomena observed in wireless communications. Concurrent transmission of signals from multiple transmitters on the same RF channel can lead to signal interference, wherby the decoding circuitary in the receiver fails to decode the signal of the required transmitter. MAC protocols are used in the network to utilize the channel efficiently. For different types of applications, different wireless technologies use different MAC protocols. For example, WiFi adopts the CSMA/CA MAC protocol, which is based on the 802.11 standard [22]. In CSMA/CA, Distributed Coordination Function (DCF) is used to avoid the collisions and provide fair access to the channel. In [23], authors have rigorously analyzed a refined model for the IEEE 802.11 DCF. Each of the channel contending nodes senses the channel after Distributed Inter-Frame Space (DIFS), if the channel is idle and its backoff counter value is zero, the node is allowed to continue its transmission. Otherwise, the value of the backoff counter is decreased by one. If the transmission of the node fails, then it backs off the waiting time exponentially and retransmits the packets when the counter is zero. The process is continued until the number of retransmissions exceeds the retransmitting limit.

Energy constraint is a challenging issue in WBANs. In view of this, the contention-based protocols (for example, CSMA/CA) are not suitable for WBANs, as they consume an additional amount of energy due to the retransmission of the packets as a result of heavy collisions, and idle listening of channel. Marinkovic et al. [24] proposed a Time Division Medium Access (TDMA) protocol for WBANs, which outperforms CSMA/CA by several factors such as easy in implementation, reduced collisions, efficient bandwidth utilization, and increase in the sleep-time of nodes. However, it requires enforcing a very strict synchronization mechanism.

The MAC protocols proposed for WSNs work based on the mechanism called schedule-based wakeup [25], [26]. These protocols reduce the idle listening time of the nodes by using the wakeup mechanism, which, in turn, reduces the energy consumption. A MAC protocol proposed in [27] uses preamble sampling and scheduling in order to achieve low duty cycle in low power networks. A variant of the TDMA MAC protocol proposed in [28] uses a dedicated wakeup-radio to control the sleep and wakeup cycle of the main radio. This wakeup mechanism works along with the existing TDMA protocol. Consequently, the proposed protocol becomes more efficient in terms of energy saving and network delay. A comparative study of the well known MAC protocols, which are proposed for the low power networks, is available, in [29]. The wireless network using the TDMA MAC protocol requires a broadcasting message in every round of communication frame to synchronize the nodes. Li and Tan [30] proposed a WBANs based on body channel communication, which exploits the heart rythm information extracted from the sensory data to synchronize the sensor nodes.

The IEEE 802.15.4 [31] standard was released after the realization of Wireless Personal Area Networks (WPANs). A *superframe* is the fundamental communication unit of the MAC protocol included in the standard. The superframe consists of active and non-active periods. The active period has a beacon slot followed by Guaranteed Time Slots (GTSs) and Contention Access Period (CAP). GTSs are reserved for the transmission of medical emergency data. The CAP period uses the slotted CSMA or slotted Aloha to provide the fair access to the channel to the contending nodes. The nodes of a WPAN are put to sleep during the non-active period. The standard supports three types of topologies: star, mesh, and tree. Each of the topologies has a PAN coordinator. The coordinator coordinates the transmissions of the nodes in the superframe. As per the standard, the nodes in the WPAN can be configured as Reduced Functional Device (RFD) or Full Functional Device (FFD). FFDs have the capability to control the network functioning. A PAN coordinator is the FFD. RFDs have very limited control over the network. The network protocols based on this standard are not used widely in WBAN applications for many reasons such as high energy consumption and restricted mobility of the nodes.

Li and Kohno [32] proposed a dynamic TDMA-based protocol, which has the Contention-Free Period (CFP) followed by Contention Access Period in the superframe, unlike the superframe in the 802.15.4 standard, which contains the CAP followed by the CFP. Firstly, the coordinator allocates the CFP slots to the nodes. If there is a demand for more number of slots than the slots provided in the CFP, then it spans the CFP by those many of extra slots. It shrinks the CFP period, if the number of required slots is less than the number of slots provided in the CFP. Secondly, the coordinator starts the slot allocation process for the CAP just after the CFP. The inactive period in the superframe varies with respect to the varying number of slots in the CFP. By doing the dynamic allocation of slots in the CFP, the protocol achieves energy efficiency.

A new standard, IEEE 802.15.6 [33], was released recently for WBANs. The MAC protocol provided in this standard has no significant change as compared to the protocol provided in IEEE 802.15.4 standard. However, the standard has improved by providing better key exchange solutions in regard to the security aspects of the WBAN. The superframe in the MAC protocol supports two communication modes: *Beacon* and *non-beacon*. A beacon is sent by the coordinator in the beacon period of the superframe to provide control information such as boundary of the RAPs to the nodes. The contention free period (similar to the IEEE 802.15.4) in the superframe is further divided into multiple phases: *Exclusive Access Phases* (*EAPs*), and *Random Access Phases* (*RAPs*). EAPs are reserved for high priority devices. In RAPs, the nodes should use slotted Aloha to send their packets. The Contention Access Phases (CAPs) provided in this standard is the same as in 802.15.4. In all of the contention phases, Type I/II polling mechanism can be used to improve communication. The coordination of the MACs of different WBANs has not been resolved in the current standard. The beacon period in the superframe of the WBAN can overlap with neighbouring WBANs and leads to the collision of the beacon signals. The current standard provides an optional solution that uses beacon phase shifting code to avoid such collisions.

A. Priority to the WBAN users

The WBANs used in the medical applications have high demand for Quality-of-Service (QoS). The node with high demand should be given more priority, as compared to the nodes with non-QoS. The Enhanced Distributed Channel Access (EDCA) MAC protocol provided in the 802.11 standard supports only four type of access classes: *Background*, *best effort*, *video*, and *voice*. The background class gets the lowest priority and voice gets the highest priority. The medical applications include various types of physiological sensors such as PO_2 and EEG. They may have different priority. The priority mapping of the different physiological sensor nodes in the WBANs is provided in Table I. The non-QoS nodes in the network contend for the channel using the contention window size (CW_{min}, CW_{max}) = (31, 1023).

TABLE I: Priority mapping to the medical devices

Medical application	Priority	CW range
EEG	Extremely high	$\left[\frac{(CW_{min}+1)}{16}-1, \frac{(CW_{min}+1)}{4}-1\right]$
ECG	Very High	$\left[\frac{(CW_{min}+1)}{8}-1, \frac{(CW_{min}+1)}{4}-1\right]$
EMG	High	$\left[\frac{(CW_{min}+1)}{8}-1, \frac{(CW_{min}+1)}{2}-1\right]$
Blood Pressure	Medium	$\left[\frac{(CW_{min}+1)}{4}-1, \frac{(CW_{min}+1)}{2}-1\right]$
PO_2	Low	$\left[\frac{(CW_{min}+1)}{2}-1, (CW_{min})\right]$

IV. Density of Coexisting WBANs

The transmissions of nodes in the WBAN are controlled locally by the on-body coordinator, wherby they are free from signal interference. It is difficult to coordinate the transmissions when multiple such networks come in the proximity of one another, which may cause signal interference. The nodes in the WBAN can increase their power level adaptively to combat such situations. By doing so, the nodes may end up with the highest energy level. As a consequence, the battery in the nodes drain out so quickly. Mahapatro et al. [34] proposed interference-aware channel switching technique for WBANs to mitigate interference. The typical hardware solution proposed in [35] uses two hetergeneous radio interfaces in the cluster heads to mitigate interference in WSNs. One of the two radios is based on the IEEE 802.15.4 for short-range and the other based on IEEE 802.11 for long-range communication. The mechanism proposed in [36], [37] to mitigate interference enables two or more WBANs cooperating between themselves and having them agree on a common schedule, rather than sending data independently. Ref. [38] reviews the cooperative MAC protocols that have been proposed for mobile networks.

The signal-to-noise ratio (SINR) is one of the important measures used to estimate the quality of links in wireless networks. The receiver cannot decode the information properly when the SINR value is below the threshold. If there exists ‘n’ number of interfering sources, then SINR at receiver ‘a’ for the k^{th} source in the network can be calculated as follows.

$$\delta = \frac{P_k(a)}{N + \sum_{i \neq k}^{n} P_i(a)} \tag{5}$$

where the noise floor N = (κ $\times$ T $\times$ B) $\times$ Δ, and κ, T, B, and Δ represent the Boltzmann constant, system noise temperature, bandwidth, and noise figure, and their values are 1.3803e-23, 290 Kelvin, 2e+6 Hz, and 7 dBi, respectively. $P_i(a)$ represents the power received by the coordinator from the i^{th} source. One of the important measures used in estimating the quality of a signal is energy per bit to noise

(EbNo). It is calculated using the equation given in Eqn. (6).

$$EbNo = \delta \times (\frac{BW}{R}) = \frac{P_k(a)}{N + \sum_{i \neq k}^{n} P_i(a)} \times (\frac{BW}{R}) \tag{6}$$

where 'BW' and 'R' represent the bandwidth of the channel and the data rate of the transmitter, respectively.

Direct-Sequence Spread Spectrum (DSSS) is the modulation technique for the physical layer, specified in IEEE 802.11b standard. We use the Bit Error Rate model specified for 1 Mbps data rate to calculate the BER of the packet, which is the probability that a received bit in the packet is erroneous. It is calculated using the equation given in Eqn. (7).

$$BER = 0.5 \times e^{(-EbNo)} = 0.5 \times e^{-\left(\frac{P_k(a)}{N + \sum_{i \neq k}^{n} P_i(a)} \times (\frac{BW}{R})\right)} \tag{7}$$

Packet Success Rate (PSR) is the probability that all bits of a packet are successfully received. The PSR is calculated using the equation given below.

$$\begin{aligned} PSR &= ((1.0 - BER)^{\kappa}) \\ &= \left(\left(1.0 - 0.5 \times e^{-\left(\frac{P_k(a)}{N + \sum_{i \neq k}^{n} P_i(a)} \times (\frac{BW}{R})\right)}\right)^{\kappa}\right) \end{aligned} \tag{8}$$

The packet error rate is defined as the maximum probability minus the packet success rate, i.e., (1 - PSR).

V. Propagation Path Loss

The mobility along with the high degree of posture change of the WBAN users can partition the network frequently. Signal-to-Noise Ratio (SNR) for the communication channel in and around the human body fluctuates not only due to the posture change but also due to the shadowing and multipath of signals. Han and Park [39] studied the variation of channel parameters of the off-body communication channel at the receiver, while the human body carrying the transceiver rotates. WBAN users who are moving in and around the building may get connections with different APs which are working as relays for them. The path loss is the amount of signal power that attenuates while arriving from the transmitter. In a building environment, it depends on the type of the wall, which is made using different materials such as wood and concrete [40]. The power received by the receiver (or AP) from a particular sender (or on-body coordinator) can be calculated using the equation given below:

$$P_{rx} = P_{tx} + G_{tx} - L_{wall} - L_{shadowing} + G_{rx} \tag{9}$$

where, L_{wall} is the loss due to the number of internal walls that obstruct the Non Line of Sight (NLOS) communication between the transmitter and the receiver. $L_{shadowing}$ is obtained using the normal distribution with zero mean and variance (σ^2). G_{tx} and G_{rx} are the transmitter and receiver antenna gains, respectively.

TABLE II: The values of QoS parameters resulted for different settings of the network

Load type	LP nodes (%)	MP nodes (%)	HP nodes (%)	VHP nodes (%)	EHP nodes (%)	Density of network nodes	Average QoS delay (s)	Average delay (s)	Packet delivery (%)
Low	-	-	-	-	25.0	High	0.0145	0.0634	80.9
Low	-	-	-	25.0	-	High	0.0146	0.0635	80.9
Low	-	-	25.0	-	-	High	8.659	1.7558	61.7
Medium	-	-	-	-	25.0	High	0.0350	6.3681	66.4
Medium	-	-	-	25.0	-	High	0.0351	6.4418	65.6
Medium	-	-	25.0	-	-	High	9.8231	4.7213	7.0
High	-	-	-	-	25.0	High	0.0542	5.5136	61.6
High	-	-	-	25.0	-	High	0.0541	5.4547	62.2
High	-	-	25.0	-	-	High	9.6133	9.5303	5.5
Low	20.0	20.0	20.0	20.0	20.0	High	9.5000 (LP) 0.0246 (MP) 0.0140 (HP) 0.0134 (VHP) 0.0487 (EHP)	1.02937	40.3 87.2 84.0 86.7 82.4
Medium	20.0	20.0	20.0	20.0	20.0	High	9.7565 (LP) 0.07057 (MP) 0.0352 (HP) 0.0350 (VHP) 0.2622 (EHP)	0.267047	4.3 57.5 63.9 63.9 58.1
High	20.0	20.0	20.0	20.0	20.0	High	9.8065 (LP) 0.1673 (MP) 0.0572 (HP) 0.0569 (VHP) 9.5652 (EHP)	1.74777	1.7 42.5 49.9 48.9 28.2
High	-	25.0	-	-	-	High	0.4115	6.1675	59.0
High	-	33.0	-	-	-	Medium	0.2094	5.4949	65.5
High	-	50.0	-	-	-	Low	0.1285	4.2227	75.6

Medium	25.0	-	-	-	-	High	0.0620	6.4206	64.7
Medium	33.0	-	-	-	-	Medium	0.0528	4.6689	72.2
Medium	50.0	-	-	-	-	Low	0.0395	0.1035	86.6
Low	25.0	-	-	-	-	High	0.0247	0.0632	81.4
Low	33.0	-	-	-	-	Medium	0.0172	0.0412	91.8
Low	50.0	-	-	-	-	Low	0.0088	0.0122	98.3
Low	12.5	12.5	-	-	-	High	0.0249 (EHP) 0.0454 (HP)	0.0655	80.4 (EHP) 81.7 (HP)
Low	12.5	12.5	-	-	-	Medium	0.0168 (EHP) 0.0296 (HP)	0.0426	91.3 (EHP) 90.7 (HP)
Low	12.5	12.5	-	-	-	Low	0.0081 (EHP) 0.0112 (HP)	0.0124	98.5 (EHP) 98.3 (HP)
Low	10.0	-	-	-	-	High	0.0240	0.0697	82.0
Low	-	10.0	-	-	-	High	0.0439	0.0713	80.8

VI. Performance Metrics

The following metrics are used to analyze the performance of the network of WBANs.

- *Percentage of Packets Dropped:* It is defined as the ratio of the number of packets dropped to the number of packets sent by the coordinators in the network, i.e.,

$$\text{Packet drop}(\%) = \frac{N_s - N_d}{N_s} \times 100$$

where, N_s and N_d denote the number of packets sent by the WBANs and number of packets delivered successfully, respectively.

- *Average Node-to-AP Delay:* It is defined as the average duration of delay incurred by the network for the packets to be delivered to the nearest APs successfully. The delay is the sum of the channel accessing delay and the propagation delay.
- *Average Residual Energy:* It is the ratio of the summation of residual energy of the coordinators and the number of WBANs present in the network. It is calculated at the end of the simulation time.

A. Simulation settings

We have simulated the network consisting of WBAN users (representing patients) moving within a building, using the network simulator NS3 [41]. The simulation area is 40m $\times$ 40m $\times$ 10m. It is further divided into number of floors and each floor has a number of rooms of same dimension. Description about the parameters and the values used in the simulation are provided in Table III.

TABLE III: Simulation Settings

Parameters	Value
Floors in a building	2
Number of rooms in each floor	9
Height and Length of each floor	5.0 and 10 meter, respectively.
Concrete internal wall loss	5dB
Minimum receive power	-30dB
CCA	-35dB
Wireless MAC	802.11
RTS/CTS	Off
Mobility model	Random room mobility
Pause time	5.0s
Speed	1.0 - 1.5 m/s
Tx Power	5.0dB
Tx current (Ampere)	0.0174A
Rx current (Ampere)	0.0197A
Tx gain	1dB
Rx gain	0dB
Device datarate	1 Mbps
Initial energy(Joules)	2.0J

B. Results

In a hospital, the number of patients carrying WBANs may increase or decrease over time. Also, patients can walk in and around the hospital building for some kind of activity. It is very difficult to know the number of WBANs coming in proximity of one another *a priori*. The capacity or the throughput of the wireless channel decreases when the number of WBANs increases in a given region, as the medium is shared among the WBANs. We investigate the performance of the MAC protocol (in our case, it is the low data-rate WiFi) by varying the number of WBANs within the simulation area. In order to study the performance using simulation, initially, the WBANs are uniformly deployed inside the hospital building. We have used two different mobility models for the performance study. RWP and RRM models are discussed in Section II. After the start of simulation, WBANs move with different speeds to different rooms within the building according to the mobility model. Each room in the building has a single static AP to relay the real-time data packets of residing WBANs to the medical server. We have studied that the percentage of packet drops increases when the number of WBANs increases in the confined simulation area. The packet drop ratio (PDR) is low when the number of WBANs is less than 30. In this case, the interference power accumulated at the APs is very low. This could be the reason for low PDR. The percentage of packet drops is around 70%, when the number of WBANs and packet size are 80 and 2000 bytes, respectively. In this case, interference has significant effect on the PDR. We have also observed that around 2% of packets drop more for the RWP model as compared to the RRM model as shown in Fig. 4. The observations made in this paper are based on the single wireless channel used in the extra-WBAN communication.

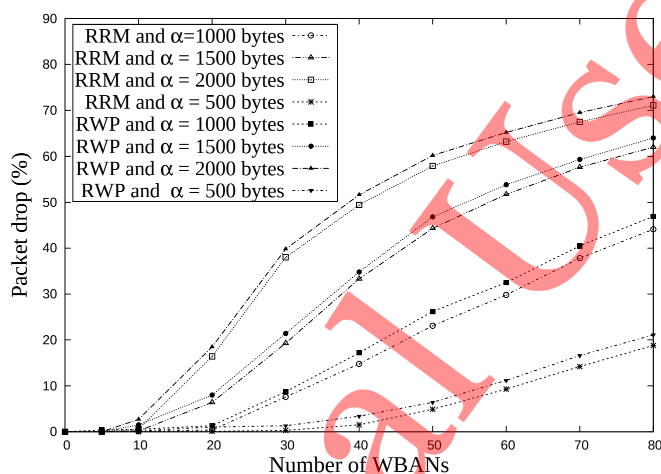
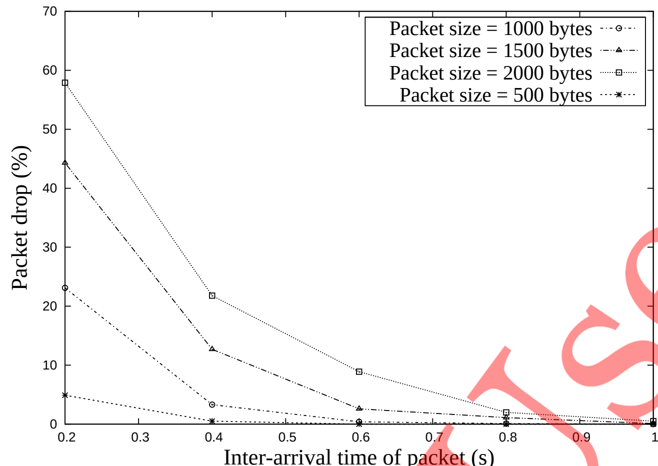


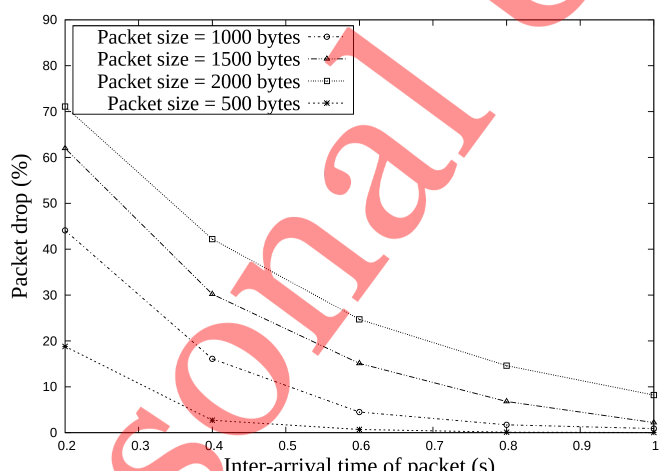
Fig. 4: Number of WBANs versus percentage of packets dropped

Sensor nodes will have different traffic generation rate, which depends on the kind of phenomenon being monitored by the nodes. For example, a temperature sensor should send only the temperature data to the control center every second, and a ECG sensor should send the samples of the ECG signals every second, so as to reconstruct the continuous signal at the receiver. We define the traffic generation rate as the rate at which the packets are generated by the application. The traffic generation rate is more when the inter-arrival time of packets is more. We study the performance of extra-WBAN communication in the network by varying the size and the inter-arrival time of packets. The percentage of packet drops is less than 5 % for the inter-arrival time of 0.8s while the number of WBANs N=50. The packet drops is around 1% for all different sizes of packets considered in the simulation and inter-arrival time of 1.0 second, as shown in Fig. 5(a). The percentage of packet drops is more than 10% for the inter-arrival time of 1.0 second and packet size is 2000 bytes. It is quite high for the packet size, which is greater than 1500 bytes, and the inter-arrival time of packets is 0.2s. In this case, the number of WBANs in the network is 80. The percentage of packet drops is around 20% for small packet size (i.e., 500 bytes) with

0.2 second of inter-arrival time, and it is quite high for large packet size (i.e., 2000 bytes), as shown in Fig. 5(b).



(a) Number of WBANs, N=50



(b) Number of WBANs, N = 80

Fig. 5: Inter-arrival time of packet versus percentage of packets dropped

The coordinator (or hub) in the WBAN is also a energy-constrained device powered by a battery. However, it is more powerful than the physiological sensor nodes. In this paper, we study the amount of energy consumed by the coordinator due to the continuous operations such as transmission and channel sensing in the network. At the end of simulation (i.e., after simulation duration of 1000 seconds), the average residual energy of the coordinators is calculated. Around 25% of battery power is left with the coordinators, when the number of WBANs, N=80, in the network, and the size of a packet is 1000 bytes, as shown in Fig. 6.

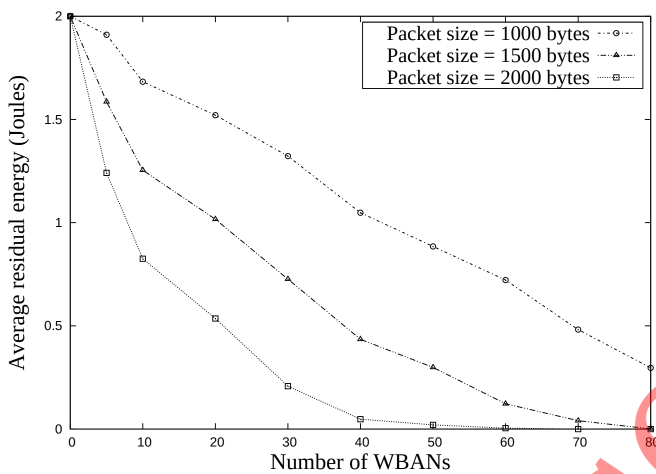


Fig. 6: Number of WBANs versus average residual energy

Health monitoring applications of WBANs require that the physiological information should be successfully delivered to the receiver (or medical server) on time. Getting the packets to the receiver on time ensures that the WBAN user (patient) gets a timely response from the doctor. There is a chance of increasing the neighbours for the nodes, when the network is scaled by adding more number of new nodes. Thus, the average number of neigbouring nodes of a node that contends for the channel in the network increases. As a result, the average channel accessing delay in the network also increases. This aspect was studied by varying the number of WBANs, the inter-arrival time t, and the size of the packets α. The average node-to-AP delay in the network consisting of 80 WBANs is more than 0.5 second for t = 0.2s and α = 1000 bytes, as shown in Fig. 7. This delay is undesirable in the network consisting of medical devices. The size and inter-arrival time of packets considered in the simulation match with real traffic generation characteristics of the medical devices. For instance, the EEG signal is sampled by the sensors at 512 Hz with an accuracy of 16 bits, whereby the system generates 8192 bits (1000 byte) per second. The average node-to-AP delay increases to an undesirable value when the number of WBANs exceeds 60, when t=0.2s, and the packet size is 1000 byte. Delay-constrained applications of the WBAN may have the nodes sream video data, and medical applications, which have ECG sensors coupled with EEG and heart sound recorder, generate high traffic. With the current network configuration, these types of applications suffer severely in terms of delay.

In ubiquitous healthcare, the network may contain QoS and non-QoS enabled WBANs. The sensor nodes in a non-QoS enabled WBAN are used neither in medical applications, nor in delay-constrained applications. For example, the WBAN may have an associated smart phone used for messaging applications and it may also have few devices for gaming applications. The QoS enabled WBANs are used in the medical applications. These WBANs hold priorities which are extremely high and low for accessing the channel. There are seven priority classes provided in the IEEE 802.15.6 standard. In a large network, the WBANs with different priority may come in the proximity of one another, whereby the users with higher priority may lock the backoff counter for longer time. As a result, the WBANs with lower priority may experience increased delay in accessing the channel than expected. We simulated the network consisting of different percentages of WBANs of different priority types. The remaining WBANs in the network are of non-QoS type. We have considered five types of priority, as follows: *Extremely high priority* (*EHP*), *very high priority* (*VHP*), *high priority* (*HP*), and *medium priority* (*MP*). We classify the network size as High (80 WBANs), Medium (60 WBANs), and Low (40 WBANs). Similarly, we classify the network load as High (packet size is 1500 bytes), Medium (packet size is 1000 bytes), and Low (packet size is 500 bytes). We show that the QoS parameters such as delay and packet delivery change with respect to the percentage of QoS and non-QoS WBANs. The QoS parameters, the average QoS delay which is the average of the delay experienced by the QoS-enabled WBANs, average delay, which is the average of the delay experienced by the network consisting of QoS and non-QoS WBANs, and packet delivery ratio of the QoS-enabled WBANs, are tabulated in Table II.

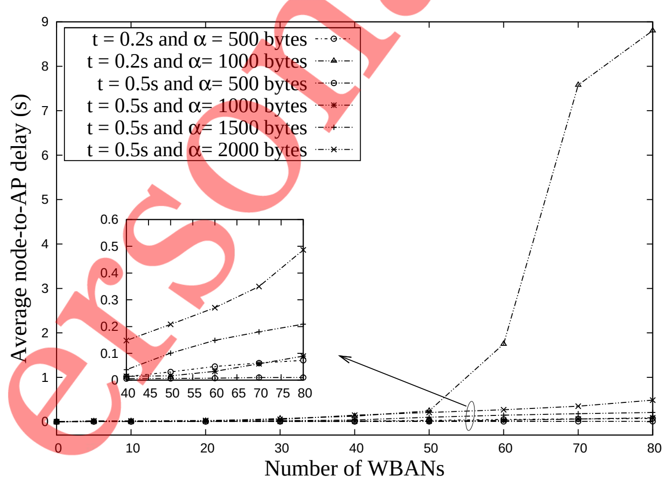


Fig. 7: Number of WBANs versus the average delay

VII. Conclusion

The prevailing extra-WBAN communication phase in WBAN can use the existing infrastructure-based wireless networks such as WiFi and cellular to deliver the aggregated data packets of the on-body coordinator. Different performance metrics were chosen to evaluate the performance of extra-WBAN communication, such as the packet drop ratio, node-to-AP delay, and average residual energy. Medical applications can have few number of WBANs (less than 40) generating packets (size of each packet is 500 bytes) every 0.2 second. The average delay of QoS WBANs, the average delay of non-QoS WBANs, and the percentage of packets delivered of QoS WBANs, are 0.0088s, 0.0122s, and 98.2%, respectively. The extra-WBAN communication using WiFi is able to deliver the physiological information to the medical server, while meeting the stringent requirements for low delay and packet drop ratio.

In the future, we will study how well the healthcare network will perform when the coordinator applies different modulation techniques adaptively with respect to the network condition. Further, we will try to propose an efficient location management technique for the healthcare networks deployed in a building, which would help network protocols to perform better.

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