Interference Study of Medical Body Area Network for Proactive Performance Improvement

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ABSTRACT

Medical Body Area Network (MBAN) is a new wireless communications technology designed to sense human's vital signals through tiny nodes in, on and around the human body wirelessly. MBAN will play an important role in enabling ubiquitous and non-invasive telemetry and healthcare systems in the future. In this paper, we analyze the interference in MBAN both from legacy wireless networks and neighbouring MBANs. We then study the possible solutions to fight against these interferences in MBAN including the channel sharing scheme to solve the inter-network interference. Experiments are carried out based on MQWIN400 radio platform to study the wireless channel in 400MHz band. We found the receiver's mobility makes the channel quite dynamic because of multipath effect.

Keywords: Medical Body Area Networks, Wireless, Interference

1. INTRODUCTION

The high aging population is becoming one of the big issues for developed countries like Australia. An increasing size of the aging population increases the cost of healthcare and is a significant challenge for the governments, healthcare providers and healthcare industry. Medical Body Area Network (MBAN) [4] consists of medical devices that communicate in and around the human body. MBAN can provide continuous and unobtrusive sensing and monitoring of health parameters in and on human bodies. For example, wireless medical devices implanted in the human body (Pill Camera) [4] offer an unobtrusive and safe method for continuous health monitoring and are expected to enable controlled drug delivery in the future. Unobtrusive and continuous parameter monitoring in natural physiological conditions opens the prospect of more efficient diagnostic methods.

MBANs can monitor vital body signs such as heart-rate, temperature, blood pressure, ECG, EEG and pH level of patients. By replacing cables with wireless links, MBANs can provide less invasive and more comfortable and efficient systems both in hospital and outside the hospital. MBANs are of particular interest to the healthcare sector to provide efficient healthcare services and ongoing clinical management. Examples of implantable devices that can be equipped with wireless transceivers include cochlear implants, retina implants, glaucoma sensors, intracranial pressure sensors, capsule endoscopes, glucose sensors, insulin pumps, heart pace makers, cardiac monitors, deep brain stimulators, visual neuro-stimulators, and many more.

In addition to medical application, the technology has important veterinary implications and its development is therefore crucial for almost all bioscientific endeavours. MBANs will play an important role in enabling ubiquitous communications, creating a huge potential market. In the area of healthcare, according to the World Health Organization's statistics, millions of people suffer from obesity or chronic diseases every day, while the aging population is becoming a significant problem.

In this paper, we analyze the interference issue in MBAN both from legacy wireless networks and neighboring MBANs. We then propose truthful online channel sharing based solution that distribute channel efficiently and truthfully by punishing MBANs for misreporting their channel requests including time, duration and bid for the channel. MQWIN400 (Macquarie University Wireless Implantable Node at 400MHz) platform is introduced and the 400MHz MICS band channel measurements are also provided considering the effect of the human tissue using a specialized solid human body phantom.

The remainder of the paper is organized as follows: Section II analyzes new opportunities of MBAN by describing new applications that MBAN can support. In section III, we analyze the interference in MBAN and its possible solutions. MQWIN400 platform and related research results are provided in Section IV, followed by the conclusion in Section V.

2. MBAN OPPORTUNITIES

The opportunities of MBANs come from the new applications that MBANs can enable. MBANs can provide ubiquitous monitoring for healthcare. Unlike conventional bedside patient monitoring, MBANs can provide a point of non-invasive care systems to pa-

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tients, the elderly, and infants in both hospital-based and home-based scenarios. Monitoring, autonomous diagnostic, alarm, and emergency services, as well as management of electronic patient record databases can all be integrated into one system to better serve people. MBAN can continuously capture quantitative data from a variety of sensors for longer periods. By addressing challenges such as the energy and throughput tradeoff, MBANs will enable telehealth applications because of their human-centricity and will facilitate highly personalized and individual care. As Figure 1 illustrates, MBANs integrated with a higher-level infrastructure will likely excel in healthcare scenarios, serving the interests of multiple stakeholders. In addition to delay-insensitive applications such as longitudinal assessment, MBANs that can offer real-time sensing, processing, and control will augment and preserve body functions and human life. MBANs researchers are already working to improve deep brain stimulation, heart regulation, drug delivery, and prosthetic actuation. MBANs technology will also help protect those exposed to potentially life-threatening environments, such as soldiers, first responders and deep-sea and space explorers.

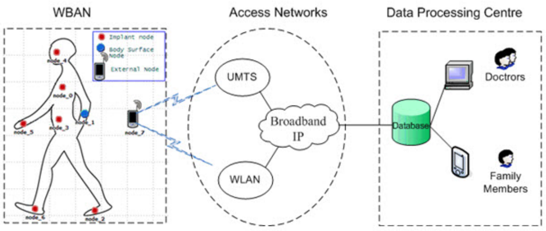

Fig.1: *MBAN and its Application Architecture.*

Totally implantable devices are less susceptible to infection. MBANs will enable the development of new medical applications that are crucial to sustaining affordable high quality health service delivery and health care in the increasingly aging population. The research into MBAN will lead to safe, less intrusive, reliable and cost effective solutions for a wide range of ambulatory and intensive care applications. It will enable novel medical and laboratory investigation systems, tailored post-operative drug delivery systems, artificial organs (e.g., pancreas) and precision micro-surgery.

More recent developments in the area of medical wireless technology include the formation of the Continua Alliance [6], an open industry coalition of over 200 companies with the goal of improving healthcare via the promotion of interoperability and connected health care technology and solutions and the formation of the European Telecommunications Standards Institute (ETSI) eHealth group [7] to coordinate ETSI activities in this area. The FCC created the Medical Device Radiocommunication Service (MedRadio Service) [7] incorporating the existing MICS band and including the adjacent "wing" bands at 401-402 MHz and 405-406 MHz. Altogether, the MedRadio Service will provide a total of five megahertz of contiguous spectrum on a secondary basis and non-interference basis for advanced wireless medical radiocommunication devices used for diagnostic and therapeutic purposes in humans. In addition, standardisation activities are under way in IEEE [9] for the physical and medium access control mechanisms for MBAN applications including implantable medical devices. The existence of a MBAN standard will provide opportunities to expand these product features, better healthcare and well-being for the users. It will therefore result in economic opportunity for technology component suppliers and equipment manufacturers.

3. WIRELESS CHANNEL AND CHALLENGES IN MBAN

3.1 MBAN wireless channel and challenges

An important requirement in MBAN is the energy efficiency of the system. A medium access control (MAC) layer is the most suitable level to address energy efficiency. This layer is used to coordinate node access to the shared wireless medium. MAC is the core of any communication protocol stack whose performance provides the basis for achieving Quality of Service (QoS) in any wireless networks. A versatile MAC should support distinct applications and different types of data such as continuous, periodic, burst and nonperiodic along with high level QoS. MAC plays a major determining factor in improving overall networks performance. The fundamental task in the MAC protocol is to avoid collisions and to prevent simultaneous transmissions while preserving maximum throughput, minimum latency, communication reliability and maximum energy efficiency.

There are lots of other problems to be solved to provide an overall solution of MBAN MAC, for example, power efficiency, power control and inter-network interference coordination. In order to design an extremely power efficient MBAN MAC, the uniqueness of the MBAN network topology and communication characteristics need to be utilized. Unlike other IEEE 802.15.4 [10] based sensor networks, MBAN is based entirely on a star topology and the MBAN coordinator usually has enough power and computing capacity. In addition, most of the communication is from MBAN nodes to the MBAN coordinator, i.e. uplink and downlink traffic is asymmetric. These allow to design a receiver (i.e., coordinator) initiated MBAN MAC protocol, so that MBAN nodes will be in a power saving state unless they are activated by the coordinator to wake up for data exchange. Interference coordination and network co-existence are key issues for the performance of MBAN. Previous Bayesian game based solutions [6],[7] are unrealistic in that they assume a symmetric case where full knowledge of channel state information of interfering channels and number of interfering networks are available. A practical MAC power control and coexistence protocol based on IEEE 802.15.6 standard is left to be defined to coordinate interfering MBANs to control transmission power and share frequency bands to minimize the effect of inter-network interference.

Zarlink's ZL70101 and ZL70102 [1] are the world latest transceiver chips for medical implantable applications, which provide a second wake-up radio to activate the primary transceiver so as to save power by turning off primary transceiver but how MAC can utilize this to achieve ultra low power communication and meet the QoS requirements of medical applications is an open issue even for the IEEE 802.15.6 standard. [11]-[13] studied the channel state of frequency bands for on-body and in-body MBAN and concluded that there are channel diversity among different communication links both in the frequency and time domains and proper MAC mechanisms are necessary to protect one transmission from the interference of other nearby concurrent transmissions, like Earth Exploration Satellite Service (EESS), Meteorological-Satellite Systems (MetSat) and Emergency Position Indicator Radio Beacon (EPIRB) [5] in the same frequency or neighbour band. Thus a MBAN MAC design can explore user diversity among same source links and different source links to improve frequency efficiency and reliability.

Deep fading occurs when a signal received by a wireless node is highly degraded due to environmental factors such as temporal physical obstructions. Signals can also be degraded due to interference from other wireless networks sharing the same radio spectrum as in Figure 2, where an external system sends a strong signal in the MICS band. These phenomena may result in the inability of the wireless node to maintain uninterrupted communication with other nodes leading to degraded performance in terms of reliability and energy efficiency. Combating deep fading and interference is particularly significant in applications where reliable uninterrupted communication is required, such as in real-time monitoring of vital signs in an intensive care unit. Recent investigations of MBANs identified time-varying fading of radio signals in the human body as the major problem for reliable low power operation [6].

3.2 Interference from Nearby MBANs

Unlike cellular networks, MBANs are randomly distributed networks where two or more MBANs may overlap with each other and interfere with each other due to the limited available frequency bands. For example in a crowded bus more than 10 people may sit close to each other, so that each person's MBAN will interfere with the others. Severe interference will decrease the SINR dramatically and as a result cause

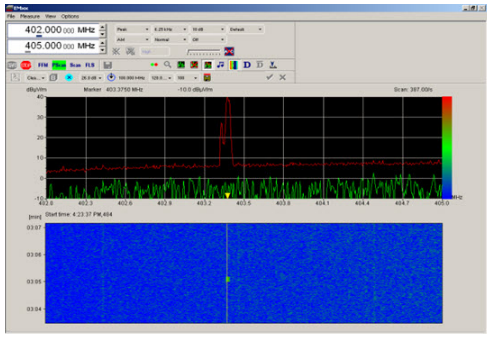

Fig.2: *MICS band is not clean in Australia.*

throughput degradation and packet loss. Packet loss also leads to energy waste and decrease in energy efficiency of MBAN nodes. Since stability is a critical issue in MBANs, interference may cause life critical packets loss and hence is a threat to patients' lives when MBANs are used in the healthcare sector.

To mitigate inter-network interference, many interference mitigation and coordination technologies have been developed to allow multiple networks exist. However, as shown by [16][17], when inter-network interference becomes too severe, channel sharing among nearby networks becomes more efficient than any other interference mitigation and coordination technology in practice. As depicted by Figure 3, i.e., we have

$$\log(\frac{h_{11}}{n_0})t_1+\log(\frac{h_{22}}{n_0})>(\log(\frac{h_{11}}{h_{21}+n_0})+\log(\frac{h_{22}}{h_{12}+n_0}))(t_1+t_2)$$

where h_{ij} is the channel gain between transmitter i and receiver j, and and h_{ij} is the intra-network gain if $i=j$ and inter-network interference gain for $i \neq j$.

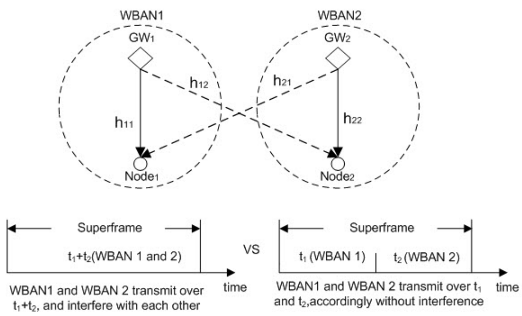

Fig.3: *MBAN An example of channel sharing.*

Channel sharing among MBANs introduces significant design challenges because of the mobility and safety requirements of MBANs. First, the channel sharing scheme must be on demand, so that MBANs can request for the channel access of each frame. Second, the channel access scheme has to make decisions on-the-fly, i.e., without the knowledge of future events on which networks will subsequently join or leave the channel sharing game. Third, channel sharing must be self enforcing so that each MBAN will benefit from sharing the channel with other MBANs instead of operating uncooperatively and causing interference to others. Fourth, it must be truthfulness enforcing so that no MBANs can gain unfair advantage by manipulating their channel requests.

Taking the above into consideration, we model the channel sharing problem as an online channel access auction, where users (i.e., MBANs) will request for channel access whenever channel bandwidth is needed to support the communications in the networks. Each request consists of a monetary bid, and channel access information which includes start time, end time and channel access length in the channel sharing problem. One of the users works as the auctioneer, which processes the requests on-the-fly, and forward the channel access grants to all the users. By decoding the channel access grants, each user can access the channel that is granted to him. In this way, users can request and share the channel with its neighbours to without collision or severe inter-network interference.

Although the online channel access auction design can easily meet the requirements of online real-time requirements, it opens up vulnerabilities to selfish users that try to gain unfair advantages over others by manipulating their requests, for example, a user can falsely report its channel request in terms of channel access duration, start time and end time, or bid to get more channel bandwidth at low cost. This channel access manipulation can even block other users from transmission at all if it is not solved properly. Therefore, an efficient online channel access auction design for MBANs' coexistence needs to address this problem so that misbehaved users will be punished; as a result, channel bandwidth can be fairly shared among users.

Assume that there are N users (i.e., MBANs) sharing a unique channel frame by frame, and each frame is identical for all the users. A central authority, for example, one of the MBANs, will decide the allocation of each frame to n users. Upon detecting a need for channel bandwidth from the application layer, users send requests to the central authority for channel access. Each request of user i is characterized by $v_i = (a_i, d_i, l_i, w_i)$. We refer to a_i and d_i as the arrival time and deadline respectively, and refer to l_i and w_i as channel access length and bid accordingly. Time is slotted (frame by frame) and all requests have channel access length between $[1, \Delta]$, i.e. $l_i \in [1, \Delta]$ indicating number of frames required. We have $a_i \leq d_i, 0 < l_i \leq (d_i - a_i)$ and $0 \leq w_i < \infty$. Each user can participate in the channel sharing procedure by simply sending its request v_i. Upon receiving the requests from users, the central authority allocates each user a subset of the frames so that users are assigned disjoint subsets, during which the end nodes and coordinator in that MBAN can exchange packets according to the IEEE 802.15.6 standard.

We model the above channel sharing problem as an online auction where each user (bidder) submit requests v_i to the auctioneer (central authority) whenever it needs channel bandwidth in terms of frames. The online auction procedure is randomly triggered by new request arrival or current winner departure. Online channel sharing scheme needs to make decisions on-the-fly, i.e. without the knowledge of the future requests coming. As a result, the overall performance of the online channel sharing can be largely degraded if users deliberately try to manipulate their requests. We use $v = (v_1, v_2, \ldots, v_n)$ to denote the requests from n users for current frame t. Online channel sharing scheme includes a channel allocation rule q and a payment rule p, where $q(v) = (q_1, q_2, \ldots, q_n)$ represents the channel allocation result, $p(v) = (p_1, p_2, \ldots, p_n)$ represents the amount user i needs to pay, and $q_i \in \{0, 1\}, 0 \leq p_i < \infty$. For simplicity, we consider one channel in this paper, so we have $\sum_i^n a_i = 1$. We will assume that users have quasi-linear utility function, so the utility of user i for allocation $q_i(v)$ and $p_i(v)$ is $q_i(v)w_i - p_i(v)$.

The flexibility of the online auction method on the other hand makes the channel sharing design difficult and challenging. Selfish and malicious users can utilize this flexibility to manipulate their requests to control the auction outcome so as to have unfair advantage over others. In online channel sharing, users can cheat by not only rigging their channel access length and their bids for accessing the channel, but also by falsely reporting their start time and deadline for accessing the channel. A good online channel accessing design needs to resist these selfish and malicious behaviors. One well-known solution is to make the online auction truthful, i.e., no one can improve his utility by misreporting his request.

We assume that users are selfish; as a result user will not report channel request that has start-time earlier than its true start-time and end-time later than its true end-time. This is a practical assumption and makes sense for MBAN channel sharing problem, because each user will not benefit if it reports the channel usage earlier than it really need and delaying its channel usage will result in disadvantage. Since each user is selfish, it will only misreport its channel request that is no early start-time and no late end-time.

If we use $v_i^{'} = (a_i^{'}, d_i^{'}, l_i^{'}, w_i^{'})$ to denote the false request and $v_i = (a_i, d_i, l_i, w_i)$ as the true request, we have $a_i^{'} > a_i, d_i^{'} < d_i, w_i^{'} < w_i$, and $l_i^{'} > l_i$. We are interested in designing truthful online channel sharing scheme that is, for every $v = (v_1, v_2, \ldots, v_n)$ with $v_i = (a_i, d_i, l_i, w_i)$ and every $v_i^{'} = (a_i^{'}, d_i^{'}, l_i^{'}, w_i^{'})$, we have $q_i(v)w_i - p_i(v) \geq q_i(v_i^{'}, v_(-i))w_i^{'} - p_i(v_i^{'}, v_(-i))$,where $v_(-i) = (v_1, \ldots, v_(i-1), v_(i+1), \ldots, v_n)$, i.e., the utility of user i is maximized if and only if she submits her request for the channel access truthfully.

We consider the unit-length case where each time a user requests only one frame, i.e. $l_i = 1$. We can then simplify the channel access request by defining it as $v_i = (a_i, d_i, w_i)$. In the online channel sharing process, each user submits its request to the auctioneer for channel access whenever it finds that its MBAN needs channel bandwidth for the communication between its coordinator and the MBAN end devices. As a result, the channel allocation decision talks place at the beginning of each $critical frame$, when new users requests arrive for channel bandwidth, or when a previous winner finishes its usage of the channel.

Driven by the monotonic allocation methodology above, we apply the following channel allocation rule q (HIGHEST BID FIRST) to allocate frames to users: for each critical frame t, allocate frame t to the user i with the pending request that meets the following: $w_i = \max\{w_j : a_j \leq t \leq d_j\}$, i.e., the highest bid user for current frame will be served first.

In order to be truthful implementable, the pricing scheme has to be bid independent and monotonic. Otherwise, users can increase its utility by cheating. In online channel auction, a user's price when winning the auction depends on other pending users and their bids.

Since the set of pending users depends on the time, we need to design a pricing scheme that can remove the time dependency and still be monotonic. This means the price charged when a user cheats is no less than that when she reports truthfully. Taking the above into account, we define the payment rule p as:

$$p_i(v) = q_i(v)w_i - \int_0^{w_i} q_i((a_i, d_i, x), v_{-i})dx \qquad (1)$$

In words, a user will only have to pay the smallest value it could have reported in order to receive an allocation.

4. MQWIN400 BASED PRACTICES

In this section, we describe the MQWIN400, a MICS band hardware platform for the implantable MBAN research and the channel measurement activities and results.

4.1 MQWIN400 Hardware and Network Architecture

As shown in Figure 4, MQWIN400 is based on TI's SoC CC111[17], which is a low power sub-1 GHz designed for low power wireless applications. It combines the excellent performance of the state-of-the-art RF transceiver CC1101 with an industry-standard enhanced 8051 MCU, up to 32 kB of in-system programmable flash memory and up to 4 kB of RAM, and many other powerful features. The small 6x6 mm transceiver package makes it very suited for applications with size limitations. MQWIN400 provides general purpose I/O interfaces to support sensors like gyroscope, ECG, EMG, and other sensors. MQWIN uses the latest MICS band antenna ANT-403-SP Splatch[18]. The Splatch antenna uses a grounded-line technique to achieve outstanding performance from a tiny surface mount element. This unique antenna is designed for hand- or reflow mounting directly to a product's circuit board. Its low cost makes it ideal for volume applications. Unlike many compact antennas, the Splatch exhibits good performance in proximity to objects and persons. While suitable for a wide range of RF applications, the 403 version was designed to cover the 402-405 MHz MICS band.

Fig.4: *MQWIN400 platform.*

A typical MQWIN400 network as shown in Figure 5 consists of multiple implantable nodes in a patient and a coordinator node, which typically works as a relay that has both an MBAN radio such as IEEE 802.15.6 and an 802.15.4 transceiver, to exchange communications between MBAN and the external world. Sensors collect physiological data from a patient's body, after that these data are transformed to digital signals and transmitted out to a gateway device. It collects all the data from the WBAN nodes and forwards it to WAS. WAS will process the data received according to their types and IDs and then display and save them. Network management packets carry network information and will be used for network setup and provide node information on WAS. Each node can have multiple sensors. Each sensor may be treated as one data channel. WAS gets all the data for all the sensors from WBAN through a USB interface. The information in each packet can correspond to sensing data such as CO2, Oxygen and HP levels as well as network working information such as Node ID, Channel ID and network state.

4.2 MICS band Channel Measurement and Results

In this subsection, we describe MICS band channel measurements and initial results based on using a solid human body phantom. Different types of human tissue have different dielectric properties result-

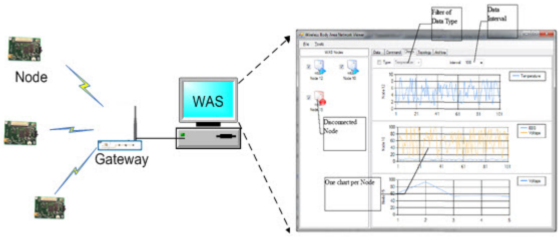

Fig. 5: *MQWIN400 platform.*

ing in different radio signal propagation effects. Radio propagation is also affected by body posture, body movement and the amount of tissue in the radio path. Channel models also need to incorporate the antenna technologies. Due to the relatively low frequency of operation in the vicinity of 400 MHz and a short operating distance, near-field effects are expected to be significant.

In our experiments, we place the MBAN node inside a human phantom which was designed to have the same dielectric properties as the human muscle. A receiver is placed outside of the phantom and connected to a PC to save the RSSI information into a file for processing. The implant wireless channel characteristics will be captured through a comprehensive measurements campaign in typical usage environments as shown in Figure 6. A MQWIN400 node will send 250 packets per second to the receiver. AT Each time a packet is received, the RSSI will be measured and stored on the PC for processing.

We considered two scenarios so far. In the first scenario, the distance between the transmitter and receiver are fixed. There are two people working around the human phantom. We want to see the multipath effects from the people nearby and the path loss caused by the human phantom. The transmitted power is 1mW and the distance between the implant node and the external receiver is 1 meter. As shown in Figure 7 and 8, the average received RSSI is -69dBm. Activities of the people working around the phantom introduce dBm dynamics to the pass loss.

Fig. 6: *Channel Measurement Setting.*

In the second dynamic scenario in Figure 9 and 10, we try to observe the received signal strength when the receiver node is placed on a person's hand and the person is moving. The average distance between the transmitter and receiver is around 80 cm. We run the experiment for 600 seconds. Figure 8 depicts that the received signal level is quite dynamic varying from -80dBm to -30dBm and has an average of -65dBm. The signal can go from good to bad in a very short time and may cause significant packet loss. We can see from Figure 8 that around 15% of the packets have the received RSSI below -70dBm; as a result, the MAC layer needs to be carefully designed to meet these situations by adaptive power control and retransmission schemes.

5. CONCLUSIONS

In this paper we have focused on the understanding of interference in MBAN in terms of opportunities, challenges, as well as describing our research activities and experiments. We firstly analyzed the potential applications followed by the challenges of MBAN from the point of energy efficiency, interference mitigation and high data rate and network co-existence issues. The experimental implant-node MQWIN400 hardware was then described together with MBAN network. These were then used to set up experiments for implantable MICS band channel measurement. We explored two scenarios to see the path loss caused by the human phantom and the effect of human movement. We found the receiver's mobility makes the channel quite dynamic, so the MAC layer needs to be designed to include channel aware schemes to handle these situations. Our future work will be to further analyze the wireless channel by considering more typical application scenarios and then study network interference from nearby MBANs. We will then design a MAC protocol to deal with issues.

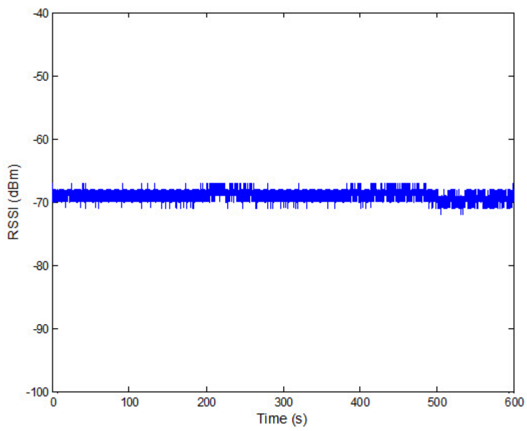

Fig. 7: *RSSI Measured in Static Scenario.*

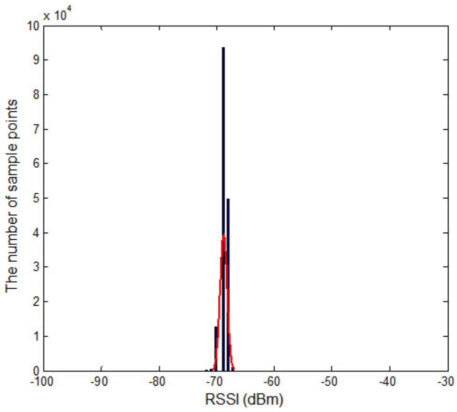

Fig.8: *RSSI Distribution in Static Scenario.*

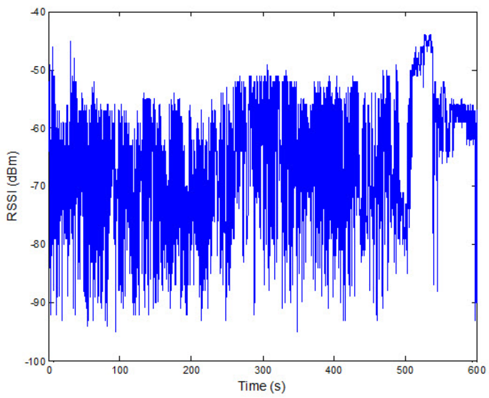

Fig.9: *RSSI Measured in Dynamic Scenario.*

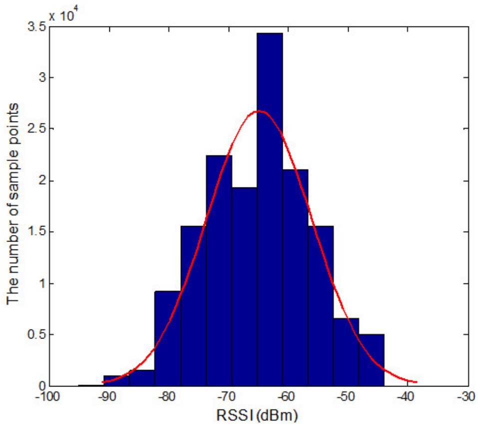

Fig.10: *RSSI Distribution in Dynamic Scenario.*

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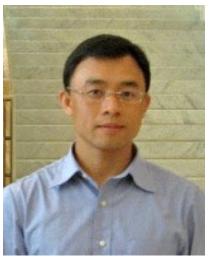

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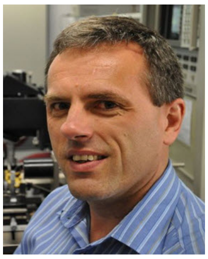

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