An Analysis of Body Area Networks in Health

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ABSTRACT

Over the last few decades, we have seen incredible advancements in medicine, which has perhaps only been matched by technological advances. Here lies a new and emerging technology known as Body Area Networks (BANs), at the intersection of health and embedded technologies. The development of sensors for monitoring critical body processes has resulted in the need to connect and interface with these small devices; both between each other and with healthcare providers. From sensors that can detect incoming seizures and alert the user via phone applications, to pacemakers which can connect wirelessly to a doctor's computer for data analysis, body area networks are changing the face of medicine. Sensor networks can have multiple different types of topologies; all with different advantages and disadvantages ranging from performance to power usage. In this paper, the networking of body monitoring sensors (both internal and external) will be explored by highlighting standards in place for BAN, evaluating communication protocols (range and power loss), and exploring how electromagnetic waves interact with the human body.

I. WHY ARE BODY AREA NETWORKS NEEDED?

In the United States alone, $730 billion is spent every year on what is estimated to be preventable illnesses, whether that be lifestyle choices or missed screenings [9]. Technology is rapidly advancing and sensors are ever shrinking, allowing scientists and engineers to create sensors embeddable within the human body and on the surface. This can play a critical role in early detection of illnesses, in addition to wellness tracking, keeping doctors and their patients informed of their condition in real time, not just at yearly physicals or with expensive lab work. These sensors and embeddable devices need a reliable, secure, and safe way to communicate with each other, and with some host device that can process and log that data transmitted by the sensors.

As defined by IEEE 802.15, a body area network is "*a communication standard optimized for low power devices and operation on, in or around the human body (but not limited to humans) to serve a variety of applications including medical, consumer electronics / personal entertainment and other*" [10]. IEEE BAN standards enable a new class of devices, specifically targeting use in, on, and near vital organs by defining specifications to safely and reliably communicate with sensors placed in key areas around the body to improve health outcomes through earlier detection and consistent monitoring. Other network types do not achieve an appropriate balance between power use, bandwidth, accuracy, and heat for use within the body.

II. MAIN OBJECTIVE OF BODY AREA NETWORKS

Body Area networks allow embedded devices within the body, on the body, and near the body to communicate with each other to improve health outcomes, track wellness and workout data, and many other non-health related use cases. Standards define what is safe for the body, security requirements, and interoperability requirements for these networks.

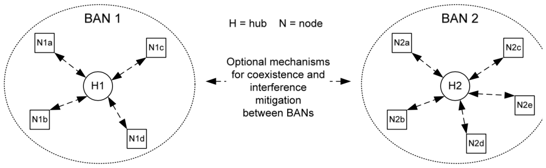
III. IEEE STANDARDS ENCOMPASSING BODY AREA NETWORKS

A. *IEEE Standard*

The 2012 IEEE standard 802.15.6 specifies the requirements for a body area network, ensuring safety and interoperability of devices. Network topologies, medium access control (MAC), security paradigms, bandwidths, and the human body communications physical layer specification are defined. Body area networks are composed of nodes, which contain a MAC layer, physical layer and a possible security layer, and hubs, which share all the functionality of a node while also coordinating the medium access and any power management of each node [10].

B. *Network Topologies*

A body area network is organized in a one or two hop star network topology, with many nodes connected to only one hub. Separate hubs are organized into separate body area networks. Mechanisms may be needed to account for interference and coexistence between multiple body area networks, but are not defined in 802.15.6-2012 [10].



C. *Medium Access Control*

The MAC frame is composed of the MAC Header (7 bytes), optional MAC Frame Body (0 to 255 bytes, the max frame body length), and Frame Check Sequences (FCS) (2 bytes), in that order [10].

The *MAC Header* is further divided into frame control, recipient ID, sender ID, and BAN ID. Frame control contains protocol version, acknowledgement information (policy, timing), security level, temporal key, BAN Security, sequence number, fragment number as well as more data. The recipient, sender, and BAN IDs used the abbreviated address of the associated device [10].

The optional *MAC frame body* constians a low-order security sequence number, frame payload and message integrity code (MIC), though the security sequence number and message integrity code are not present in unsecured frames, as indicated in the MAC header [10].

The *frame check sequence* is to be 16 bits, which are binary coefficients of a cyclic redundancy check (CRC) of degree 15, generated by the polynomial of degree 16, as in Equation (1):

$$G(x) = x^{16} + x^{12} + x^{5} + 1$$

The calculation field used for the CRC is the entire transmitted MAC frame, excluding the FCS field. The MSB of each octet is used in the calculation, with the MSB of the last byte representing the coefficient of x^0 and the LSB of the other octets representing the coefficient of x^{k-b-1}, where k is the number of bits (16) in the calculation field, and b is the position the byte was presented to the physical later, $b = 0$ for the first byte presented [10].

D. *Medium Access*

There are three modes for medium access: beacon mode with beacon periods, non-beacon mode with superframes, and non-beacon mode without superframes.

Beacon mode with beacon periods transmits a beacon to start a superframe, each with two exclusive access phases (EAP), 2 random access phases (RAP), two managed access phases (MAP), and a contention access phase CAP). In the managed access phase, the hub may arrange and schedule up, down, and bi-link intervals, provide unscheduled bilink allocation intervals, and type-O polled and posted allocation intervals. Within the EAP, RAP and CAP periods, CSMA/CA or slotted aloha based access may be used and specified by the hub. Non-beacon mode *with* superframes may only have the previously described managed access phase. If a node determines the hub is operating in non-beacon mode *without* superframes, the node is to treat any time interval as a portion of EAP or RAP and use CSMA/CA random access to access the medium [10]. Nodes may indicate to the hub that they will not be always active and save power by hibernating, even during wakeup beacon periods [10].

E. *Hub Coexistence and Interference Mitigation*

Hubs may shift the time periods they beacon at to not interfere with other BANs in the area or awaken nodes in the wrong network. Two hubs may share a single channel by interleaving their active superframes, i.e. alternating transmission within the channel by sending a series of requests to each other. There is not a defined standard on communication between hubs [10].

F. *Human Body Communications Physical Layer Specifications*

IEEE Standard specified narrowband and ultra-wide band physical layer specifications. A device that works on the specified narrowband must support transmission and reception in one of the frequency bands 402 MHz to 405 MHz, 420 MHz to 450 MHz, 863 MHz to 870 MHz, 902 MHz to 928 MHz, 950 MHz to 958 MHz, 2360 MHz to 2400 MHz, or 2400 MHz to 2483.5 MHz. Devices within the bands may use differential binary phase shift keying (DBPSK), gaussian minimum-shift keying (GMSK), differential quadrature phase shift keying (DQPSK), differential 8-phase shift keying D8PSK for modulation. The physical header, being 15 bits long, contains information about the MAC frame body, length of the MAC frame body, and information about the next packet. Transmit power should be transmitting at most -40 dBm and at least -10 dBm. The receive to transmit turnaround time must be between 75 and 85 µs, and transmit to receive turnaround time must not exceed 75 µs. For ultra wideband connections DBPSK or DQPSK may be used for multiplexing. Maximum transmission power is specified by local regulations [10].

IV. COMMUNICATION STANDARDS USED IN BODY AREA NETWORKS

A. *Introduction to Bluetooth & Bluetooth LE*

Bluetooth, while common in PANs [11], also has its use cases for BANs; both cover a similar physical range, which is why it's applicable to both. Bluetooth comes in two variants; the original standard (Bluetooth BR/EDR, more simply known as Bluetooth) and the standard that's optimized for smaller, lower power devices (known as Bluetooth Low Energy). Both of these technologies operate in the same radio frequency which is the 2.4 GHz ISM band. Both also utilize frequency hopping to reduce interference; the operating band is divided up into 79.1 MHz channels, with frequencies switched between at an *ideal rate* of 1600 hops/second [12]. Finally, both have a maximum symbol rate of 1 Megasymbol / second, which translates directly to 1 Megabit / second, and both have a similar physical topology known as a piconet in the specification, also known as a scatternet outside of the context of Bluetooth. These are the major similarities between the two; past this they start to differ in ways that allows Bluetooth Low

Energy to accomplish its goal of being a lower-power protocol [13].

B. Bluetooth BR/EDR

As mentioned before, standard Bluetooth uses a piconet (or scatternet) topology. Devices are designated as being either a master or a slave. Piconets are limited to a maximum of seven devices, and each of those devices synchronizes their clock to the master device. This clock synchronization is what is used to perform frequency hopping, a mechanism responsible for much of Bluetooth's resiliency to interference. Four physical channels are defined for BR/EDR: basic, adapted, inquiry scan, and page scan. Channels are switched between periodically according to the master clock [13].

C. Bluetooth Low Energy

While it occupies the same frequency band, the way that Bluetooth Low Energy uses that band is slightly different. There are some similarities, mentioned above, but the larger differences between the two include the MAC, device categorization, security mechanisms, and of course, the power use. According to the specification, the MAC can be FDMA or TDMA. With FDMA, there are 40 physical channels split across the frequency band, each with 2 MHz of guard band frequency. Unlike BR/EDR, BLE’s physical channel is partitioned into just two sections for different event types: advertisement-type, and connection-type events. This yields two different device classes: advertisers, which transmit packets over the advertising channel, and scanners, which receive packets over the advertising channel [13].

D. Security

Security in Bluetooth is something that was considered by the designers. For BR/EDR, Elliptic Curve Diffie Huffman public key encryption is utilized to prevent passive eavesdropping of the Bluetooth connection. As far as man-in-the-middle (MITM) attacks go, PINs are utilized with the assistance of the user to verify identity of both devices. These PINs are user-facing and aren’t sent over-the-air. Given the configuration of these PINs, there’s a 1 in 1,000,000 chance of a successful MITM attack happening, doable by guessing *both* device PINs correctly as the attacking device. In the case of BLE, PINs aren’t utilized as many of the devices using this protocol as many of these types of devices aren’t generally user-facing or have a user-interface. As far as passive eavesdropping goes, two of the three association models are vulnerable to this- exception being the Out of Band association model. When it’s used, the encryption is done on the controller-side using AES-CCM cryptography [13].

E. Introduction to Zigbee

Zigbee is another protocol that is commonly used for low-power, battery operated, physically local networking. As of August of 2010, it was one of the most widely used radio standards in BANs. It’s an implementation of IEEE 802.15.4, which is a standard that defines both the physical and MAC layers. It encompasses requirements such as MAC channel association and dissociation, channel encryption, and the channel access protocol of slotted **or** unslotted CSMA/CA. The Zigbee standard defines that a device that’s part of a Zigbee network is either known as a generic *device* or it’s a *coordinator*. It further defines three possible types of data movement: device to coordinator, coordinator to device, or device to device. This flexibility is what allows Zigbee to conserve energy, as it allows devices to sleep where possible rather than continuously keeping receiver circuitry online (as it’s not always needed). Zigbee itself targets low-data-rate, low-power applications, occupying 3 ISM bands with data rates ranging from 20 Kbps to 250 Kbps. The common physical network topologies are supported — namely, star, cluster, tree and mesh [12].

F. Comparing Bluetooth & Zigbee

Between the two standards mentioned above; Bluetooth (Low Energy) is noted various times as being the superior option to Zigbee in the context of BANs. The authors of [12] hold the opinion that Zigbee holds better use in home and industrial automation, whereas Bluetooth is better suited for on-the-body-type devices and networks due to its lower cost and lower power consumption [12]. Also, as mentioned before, Zigbee's data rate is only capable of going up to 250 Kbps; this limitation is noted in [12] as being inadequate to support real-time, large-scale BANs. In fact, the downfalls of Zigbee are what led to a specialized task group of IEEE to be formed around creating viable standards for use in BANs (known as IEEE 802.15.6) [12]. With the advent of true wireless earbuds such as the Apple AirPods, it's also been shown that a device is capable of transmitting a large amount of data on/through the body, with signal path loss in this configuration ranging from 1 to 12 dB [14]. This shows a growing trend in the use of Bluetooth in body-area-sized networks.

V. ELECTROMAGNETIC WAVE AND ANTENNA INTERACTION WITH THE HUMAN BODY

A. Introduction

As Body Area Networks increase in their complexity and number of devices, the go-to form of communication is wireless transmission using antennas; these are called Wireless Body Area Networks (WBAN). This is preferred over wired communication as it's less modular, more difficult to scale, and requires managing a labyrinth of wires throughout a patients' clothes. Antennas work in two ways by converting voltage and/or current into an electromagnetic (EM) wave that propagates through some medium and also by receiving these waves and converting it into a voltage and/or current. This is why understanding how EM waves interact with the human body is a key concept in creating an effective BAN system. Being able to accurately model path loss and attenuation through tissues and muscles can help designers of BAN place their sensors in optimal locations to enable efficient communication.

However, air is not the only medium that is used in BANs. Recently, there has been some focus on narrowband human body communication or NB-HBC for short. NB-HBC couples EM signals (using 20-80 MHz carrier frequency) to the skin or outer layer of a human body via a coupler [2]. In this case the signal propagates through the outer skin as the medium instead of radiating it outward in all directions like an antenna. Using these methodologies, power usage using NB-HBC is roughly 100 times less compared to using WBANs and antennas [2]. Additionally, there is another form of communication that uses electro-quasistatic signal transmission using conductive layers below the skin. This allows one to bypass having a carrier-frequency at all, and it can also provide a sense of privacy as it is extremely difficult, if not impossible, to snoop the signal transmission via an external receiver. Scientists have thoroughly explored this method of communication [2]. This goes to show that understanding how EM signals interact through different mediums (layers of the skin, tissues, muscle, etc) is just as important as EM signals themselves (type of radio, transit / receive power, carrier frequencies, etc).

B. Standards Regarding EM Interaction with Human Body

The first distinction that should be made is that typical radio communication for BANs uses non-ionizing radiation waves like sound waves, visible light, and microwave [4]. This means that they are not dangerous to the human body in the general sense but there are other factors that need to be considered. Standard radio signals are enough to move atoms or cause them to vibrate; this includes human cells. When polar molecules (like water) are in the presence of electro-magnetic fields, they rotate as different parts of the molecule are attracted by the fluctuating electric field. As they rotate, they rub against adjacent molecules which produces friction, a form of heat. Standards are in place to ensure that certain tissues, like head tissues for example, do not exceed a temperature increase of 1 K to prevent injury or damage [4].

Scientists commonly use a parameter known as Specific Absorption Rate or SAR to measure how much EM energy is absorbed by human tissue. This is frequently used in modeling BAN systems as SAR has been empirically measured for most muscles, fat, and bones in the human body. SAR is defined as:

$$SAR = \frac{\sigma \times E^2}{\rho}$$

where σ is electrical conductivity, E is the RMS value of the electric field, and ρ is density - the overall units being watts per kilogram [3]. There are standards governing SAR as well since a high SAR could have negative impacts on the human body. The Federal Communication Commission sets the limit to 1.6W/kg averaged over one gram of tissue while the Council of European Union has the limit at 2 W/kg averaged over ten grams of tissue.

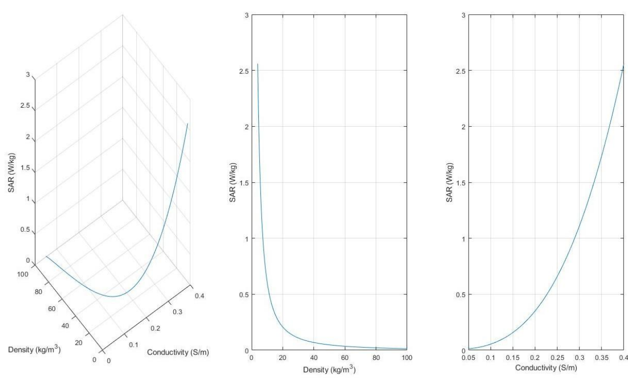


Figure 2: Demonstration of typical SAR values due to both a varying density (kg/m^3) and conductivity (S/m). Human tissue masses were taken from a database [7] and a range of 100 to 2000 grams was used. Density was calculated by creating cubes with dimensions varying from 0.1 to 0.8 meters and computing the human tissue mass over volume. Conductivity of human tissues were adopted from former research [8] and a range of 0.05 to 0.4 was used. The middle and right plots demonstrate the side view of the 3D plot of SAR when varying both the density and conductivity linearly.

SAR could be multiplied by mass in order to find the watts loss due to tissue absorption. This value (in dB) could then be subtracted from the transmit power to calculate the receive power.

C. *Antenna Considerations and Antenna Losses due to the Human Body*

Not only do EM waves have an impact on the human body, but the human body has an impact on the antenna itself. The human body is considered lossy, defined as capable of dissipating electrical or EM energy which requires the need to increase gains of transmitting antennas to compensate. Experts have defined a metric to quantify this effect known as human body-worn efficiency, which is defined as the total radiated power of the antenna when placed on the body divided by the total radiated power when the antenna is in free space. The overall power loss (or body loss) due to the presence of the human body is represented by this [4]. This phenomenon is actually explored in a study to evaluate over the air communication using Bluetooth (a commonly used communication standard for BANs) and how the human body influences the loss. The study used TRP or total radiated power to measure antenna loss, running several trials with the bluetooth device (in this case earbuds) with them inserted and with them in free space [5]. TRP is defined as:

$$TRP = \frac{1}{4\pi} \int_{\theta=0}^{\pi} \int_{\phi=0}^{2\pi} (EIRP_{\theta}(\theta, \phi) + EIRP_{\phi}(\theta, \phi)) \, sin(\theta) \, d\theta \, d\phi$$

where EIRP is the effective isotropic radiated power. The equation is commonly used to evaluate common commercial antennas and it essentially sums all of the radiated power over a sphere (this is where the double integral comes from), but ignoring the effect of directionality or polarization of the antenna [5].

The report shows that between 5 different bluetooth headphones, the overall mean for the 2.406 GHz band for body loss is 4.18 dB with the min being 1.2 dB and the max being 11.7 dB. For the 2.476 band, a mean of 5.14 dB, a min of 1.7 dB, and a max of 10.0 dB was reported [5]. This shows that presence of a body does inhibit the effective transmit power, and it also shows that this effect is greater at larger frequencies.

Other interactions such as body induced gain and changes in impedance are important considerations when working with BAN antennas. The human body consists of various tissues that carry dielectric properties, which thereby affect antenna gain. Additionally, input impedance will be influenced by the human body, especially in cases where the antenna is fixed on human skin via tape or other means. The overall effect on the impedance is dependent on the location of the antenna and moisture; the more moisture there is, the lower the impedance will be [5].

Another important factor to consider is loss that can occur when transmitting from BAN data back to LAN, i.e. transmitting from mobile nodes on a user's body to a stationary reference node. Losses can occur due to the "body shadowing" effect and other factors like multipath. Since the body blocks and absorbs RF signals, normal bodily movements can create shadowing effects as sensors and wearables become blocked by other parts of the body. The full system loss model for off-body narrowband (NB) and ultra-wide band (UWB) of WBANS has been determined [6]:

$$L_{SL(dB)} = \overline{L_S(d_0)_{(dB)}} + 10 \cdot n \cdot log_{10}\left(\frac{d_{(m)}}{d_{0\,(m)}}\right) + 10 \cdot log_{10}[\Lambda(\mu_{B(dB)}, \sigma_{B(dB)})] + 20 \cdot log_{10}[\Lambda(\mu_{F(dB)}, \sigma_{F(dB)})]$$

where

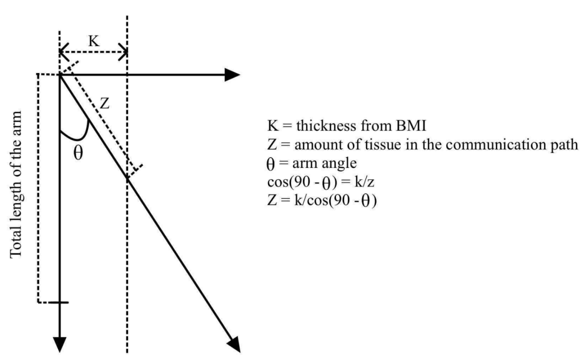
- $L_{SL(dB)}$ represents the system loss
- $\overline{L_S(d_0)_{(dB)}} + 10 \cdot n \cdot log_{10}\left(\frac{d_{(m)}}{d_{0\,(m)}}\right)$ represents the mean system loss (MSL) component which is defined as the decrease in received signal power due to signal dissipation in the medium as a function of distance. $\overline{L_S(d_0)_{(dB)}}$ is the MSL value at the reference distance $d_{0\,(m)}$. n is the system loss exponent and $d_{(m)}$ is the current distance, measured in meters (m).
- $\Lambda(\mu_{B(dB)}, \sigma_{B(dB)})$ represents a random variable with lognormal distribution for the body shadowing effect where $\mu_{B(dB)}$ is the mean value and $\sigma_{B(dB)}$ is the standard deviation.
- $\Lambda(\mu_{F(dB)}, \sigma_{F(dB)})$ represents a random variable with lognormal distribution for the multipath effect where $\mu_{F(dB)}$ is the mean value and $\sigma_{F(dB)}$ is the standard deviation.

The reason shadowing effects and multipath effects are random is because human motion is inherently random, and multipath is also characterized as random since the radio signals will bounce off many surfaces in all directions, making it greatly dependent on the environment. The random variables have been represented in lognormal distribution as this best matches the empirical data collected over 87,252 samples [6]. Additionally, the study found that the model is still accurate for off-body communication regardless of where the mobile nodes are located on the body [6].

Having a model that can accurately predict performance for antennas and radios is imperative as WBANs grow in popularity. Future research using this model could explore whether this model applies between mobile nodes (or sensors on the body). However, if the star topology is used where the central node is off-body, then this model could be utilized thoroughly in determining feasibility of the system.

VI. ESTIMATING POWER LOSS DUE TO WALKING MOTION

Wireless body area networks, especially those implanted within the body, have the unique challenge of permanence. Unlike a normal network, once a surgery is performed to implant a node into the body, it is very invasive and costly to change the location. Therefore, extreme care should be taken to ensure communication is seamless. This simulation shows the importance of two factors, height and weight, in determining the topography and placement of network nodes in a wireless body area network. In this scenario, we model a network configuration with a node implanted in the abdomen which communicates with a surface mounted device on the wrist, similar to a smartwatch.



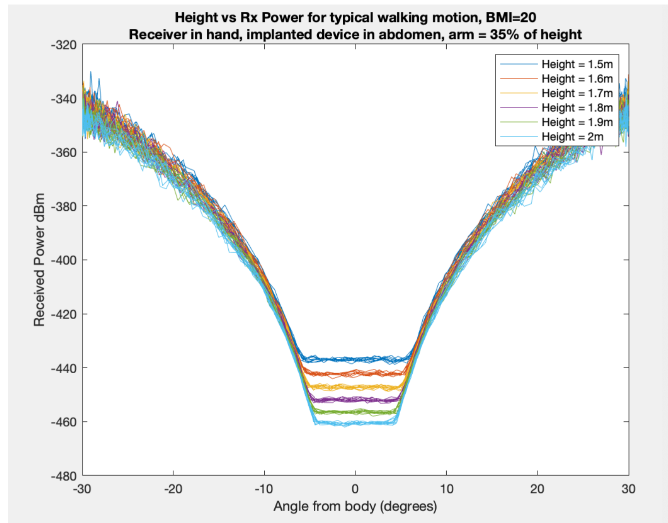
Model of tissue in communication path

The above model shows the estimation we used for visceral fat between the node and the hub. By calculating ratios of BMI to visceral fat thickness calculated by cardiovascular researchers [15], it is possible to obtain an average tissue thickness, K. That average tissue thickness can be combined with the angle the arm is at from the body to get the amount of tissue in the communication path in the equation show above, and the free space path is simply the arm length - tissue path length. Researchers have also previously calculated the path-loss exponent for WBAN signals traveling through human tissue, *n* to be 6.29 [16]. Using this data, we can estimate the total path loss given the amount of free space in the path, combined with the amount of tissue in the path by the equation below:

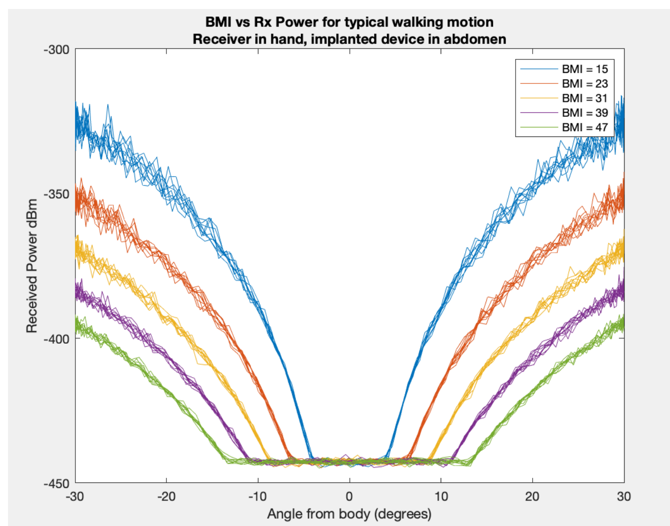
$$Path\ loss\ (dB) = 20\ log\ (f) + 10\, n\, log\ (d) + Constant$$

$$Rx(dB) = Tx(dB) - PL(tissue) - PL(free)$$

Simulations for changing heights and are shown below:



Simulations for changing BMI are shown below:



Gaussian random noise was added to each datapoint to simulate minor changes in posture. The simulation results show that while height has more of an effect when each simulated person's arm is at rest, weight has more of an effect on most angles the arm holding the device may be at, from 0 to 30 degrees. Doctors and engineers should be particularly careful to design adequate networks to account for people of all shapes and sizes. The simulation results show that a single node transmitting to a device within the arm would be incapable of transmitting enough energy to be received, unless with an extremely sensitive device, in the range of -450dBm. Future work should be done better considering multiple hop networks, multiple nodes, and full-scale models of bodies accounting for different tissue than just visceral fat and modeling accordingly.

VII. CONCLUSIONS

Throughout this paper, Body Area Networks were analyzed in depth. Standards surrounding BANs were explored by reviewing IEEE specifications on network topologies, MAC, medium access and beacon nodes, hubs and the effect of multiple hubs, and the physical layer. Next, common communication protocols used in BANs were covered including Bluetooth BR/EDR, Bluetooth LE, and Zigbee. It was concluded by multiple authors that Bluetooth LE is a dominant competitor in the field of BANs due to its wireless, low-power, low-cost and higher bit rate when compared to other standards like Zigbee. Additionally, a thorough analysis into how EM waves and antennas interact with the human was completed. Since wired BANs are impractical, WBANs are commonly used so factors like dielectric effects, skin moisture, and SAR need to be considered. Equations defining total radiated power of antennas and models that define the loss from a BAN's hub to off-body device shows were also covered. Lastly, a simulation was performed to explore received antenna power values and system loss during a walking motion in a WBAN system.

Simulation results show that absolute care must be taken in configuring adequate transmission power and network topologies to ensure that it matches individual body compositions. More work should be done to include multiple tissue types and more intimate models of body composition and path loss should be created to guarantee accuracy in transmission.

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