Ultra-IoMT: An Ultrasonic Intra-Body Area Network for Implanted Medical Devices

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Problem Statement

Modern Internet of Medical Things (IoMT) implanted devices require a reliable and safe communication in order to coordinate between sensors and actuators within the human body. Prior research has demonstrated that using ultrasonic waves is a safer alternative to radio frequency (RF) when operating near human tissues for an extended period (Tang et al, 2005; Davilis et al, 2010; Hogg et al 2012). These concerns are recognized by government agencies and standards institutions such as the FCC, FDA, and IEEE. Recent research has demonstrated the feasibility of ultrasonic communications within the human body as a safer alternative (Galluccio et al, 2017; Santagati et al, 2017; M. Li et al 2018). Santagati and Melodia propose an ultrasonic platform and network protocol called UsWB that enables point-to-point communication between implanted devices and a gateway device worn on the human body as a patch (Santagati & Melodia, 2017). Their work, through experimentation, demonstrated the potential of communicating between proximal devices implanted within the human body with the ability to send data outside the body through an ultrasonic-to-RF gateway.

The proposed approach by Santagati & Melodia has several drawbacks. One major drawback deals with the limited distance of the ultrasonic links. Through experimentation, it has been demonstrated by (Galluccio et al, 2012) that distances between ultrasonic transducers must be within tens of centimeters and some experiments showing limits of distances of only 10cm. This limitation in signal propagation is well understood and stems from an increase in attenuation of the wave caused by inhomogeneous tissue absorption and interference (Getreuer et al, 2018). These limitations were further validated through additional experiments by (Santagati & Melodia, 2017) using human-like tissues such as porcine meats and by (Gallucio et al, 2017) using ballistic gel models with embedded inhomogeneous tissues to simulate ultrasonic signal propagation within the human body. Because the Santagati & Melodia's UsWB protocol does not provide a multi-hop network layer, devices that are implanted beyond the maximum distance supported by the ultrasonic links from the gateway device remain unreachable. This limitation thus necessitates the placement of multiple gateway devices on the body or limit the placement of devices within a 10-20cm from the gateway. These restrictions severely reduce the commercial viability and likeliness of adoption by the medical industry or regulatory bodies, such as the FDA.

Other attempts to address the link distance limitations did not demonstrate significant improvement, such as using blood vessels to guide ultrasonic waves (Galluccio et al, 2018) or experiments with alternative signal modulation methods, such as changes in frequency (M. Li & Y. Kim, 2018). Previous experiments with varying transducer design and placement similarly failed to extend the link distance (Demirrors, 2016; Charthad, 2014; Peisino, 2013).

Another well-understood issue involves damage to tissue and sensitive organs caused by heat emitted from implanted devices (Tang et al, 2005). This issue, after all, served as the primary motivation for considering ultrasonic waves as a safer alternative to RF (electromagnetic) waves, which generate heat from ionizing radiation. In this scenario, the electronic components of the device itself can raise the temperature of tissues to dangerous levels with excessive computation during sending, receiving, and processing signals. This issue is noted but not addressed by (Santagati & Melodia, 2017) or other intra-body ultrasonic networks such as (Galluccio et al, 2017; Kerametzadeh & Sodagar, 2018; Davilis et al, 2010).

The issue of heat generated due to peak operation is closely related to another critical issue of energy utilization. Implantable devices require expensive and risky surgical procedures to implant and maintain. In order to become commercially viable, these devices must be able to operate at low-power to maximize battery life. Some recent work with wireless recharging methods by (Charthad et al, 2014; Guida et al 2016) may become viable in the future but limited to charging devices near the surface of the skin. As such, methods that preserve battery life by operating efficiently and accounting for energy utilization are necessary. Santagati & Melodia's (2017) UsWB platform does not incorporate any energy-awareness beyond the efficiency of the selected electronics.

Research Goal

The primary goal of this proposed study is to build upon the work by (Santagati & Melodia, 2017) by proposing a network routing layer that provides multi-hop communication on top of the UsWB platform's PHY and MAC layers. This proposed network layer will leverage ideas described by (Galluccio et al, 2017) for multi-hop routing while including insights from ad-hoc wireless sensor network research such as energy-optimization routing by (Jaipriya et al, 2018) and thermal-aware routing by (Tang et al, 2005). This proposal will present a new ultrasonic network platform called “Ultra-IoMT” that addresses the limitations and problems encountered by current ultrasonic intra-body networks. Specifically, the proposed methods will address the three problems previously described as follows:

1. Provide an ultrasonic multi-hop network layer that can relay packets throughout the ad-hoc intra-body network of devices. This allows for implanting devices at further distances throughout the body by relying on neighboring devices to relay information from source to destination. This approach will explore piggy-backing on existing packet communication to exchange information about network conditions and device status to avoid additional traffic caused by requesting information about the neighboring nodes.
2. Provide a dynamic routing algorithm that can optimize routes based on a cost function that includes temperature “hot spot” metrics gathered from back-routing of packets that include temperature data and thresholds from each node along the route. Another possible metric to help balance temperature levels may be gathered by tracking traffic to and from neighboring nodes.
3. Track battery life across neighboring devices and collect data using a similar method described above for temperature. This additional metric will be used as part of the routing algorithm to avoid routes that include devices with low battery life.

The effectiveness and performance of the proposed “Ultra-IoMT” platform will be evaluated using similar benchmarks by the previous studies. The networking reliability will be based on the Testbed and benchmarks outlined by (Galluccio et al, 2017) which include measuring the latency and reliability of packet transmission across network routes. The experiment will collect data from each node to monitor temperature and battery levels over various simulations. The “Ultra-IoMT” should demonstrate equalization of temperature and battery among the devices in the network. The approach should also achieve equivalent reliability metrics, such as error rates for packet delivery, when compared to experiments conducted by (Galluccio et al, 2017) and (Santagati & Melodia, 2017). The proposed methods are expected to result in longer packet delivery delays when compared to previous studies due to a routing policy that considers temperature and battery life metrics in addition to latency and congestion (i.e. QoS) as part of the cost function used to determine the best route.

Significance, Relevance, and Brief Review of Literature

The emergence of Internet of Things (IoT) has led to a proliferation of small devices used to sense and control the environment such as a home or office building. This wave of innovation has similarly prompted great interest from the medical and scientific community seeking to instrument medical devices within the human body in order to collect information about organ function and control delivery of medications or provide therapy through the stimulation of nerves. The ability to implant small devices that can communicate with each other to sense and respond to biometric readings and trigger electromechanical, such as pace makers, or pharmacotherapy, such as insulin injection, or perform cardiac resynchronization therapy leading to artificial organs that can coordinate with sensors and actuators across the body to perform complex organ functions. This area of research as led to a new field called Internet of Medical Things (IoMT) (Ivanov et al, 2018).

(Santagati and Melodia, 2018) proposed an IoMT platform allowing for ultrasonic implantable devices to communicate with each other in an ad hoc network within the human body. This IoMT platform describes two types of devices called IoMT Mote and IoMT Patch. The IoMT Mote is a 2cm x 1cm device that can be coupled to a medical sensor and implanted deep within the body tissue. The IoMT Patch serves as a gateway (or bridge) between various IoMT Mote devices scattered throughout the body and the outside environment such as a Wireless Access Point to the Internet. The communication between the IoMT Patch and the IoMT Mote uses an ultrasonic frequency channel. The selection of an ultrasonic frequency for intra-body device communication begins with (Davilis et al 2010) where they demonstrated through various experiments the advantage of an ultrasonic frequency channel over conventional RF bands such as WiFi or Bluetooth. Their goal was to identify an alternate to RF that did not cause damage to human tissue such as heat absorption or cavitation in the form of tiny gas bubbles created by pressure oscillation caused by emitting a wave. Davilis et al selected the ultrasonic frequency range (>20kHz) because of its success in underwater communication systems dating back to the 1940’s World War II. Ultrasonic waves achieve greater propagation within the human body, which is composed of 65% water, than RF which suffer from poor propagation due to the signal absorption by human tissue. Using an ultrasonic transducer made from piezoelectric material, a device can transmit a signal through human tissue using relatively low-power consumption. Galluccio et al successfully demonstrated the ability to leverage ultrasonic communication as an intra-body area network (BAN). Their work proposed a network layer design that included distributed routing using multi-hop communication with a thermal aware routing algorithm to minimize the temperature for nodes located near sensitive organs or tissues. The idea was to minimize the temperature along routes by allowing nodes to exchange signaling information such as thermal readings (Galluccio et al, 2012). The following image shows an experiment emulating a human body with an implanted IoMT device:

Figure 1 (Santagati et al, 2015)

Demirrors et al further contributed to what is described as a paradigm shift from RF to Ultrasonic by proposing an Orthogonal Frequency Division Multiplexing (OFDM) scheme that can achieve higher data rates of 28.12 Mbps. One well-known drawback with frequency multiplexing occurs when using narrowbands, such as ultrasonic frequencies, limiting the number of concurrent communications especially when using guard bands to prevent interference (Gallucio et al 2012).

Santagati et al formalized a state-of-the-art transmission protocol for Ultrasonic Wide Band (UsWB) that provided MAC through adaptive time-hopping and security through AES encryption using a 128bit key exchange between nodes in the BAN. Their proof-of-concept yielded a bit error rate (BER) of 10^{-6} and current consumption of 9.1mA for IoMT Patch and 3.4mA for IoMT Mote device. Their results also demonstrated a max range of 10cm distance between nodes. Although this range is considered excellent when compared to previous achieved distances of only 1-3cm for implanted devices such as (Guida et al, 2016 and Gallucio et al, 2012), this range requires a multi-hop routing scheme for communicating longer distances between devices such as a device implanted in the brain needing to communicate with a device located in the abdomen.

The UsWB Protocol defines the packet for communication between IoMT nodes. The packet includes headers for describing the transmission type, time-hopping frame length, spreading code length, checksum, packet type, and packet size. Figure 2 below depicts the UsWB packet segments (Santagati et al, 2017).

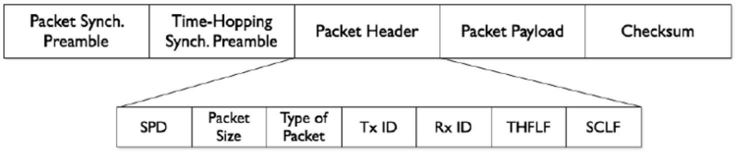

Figure 2 (Santagati et al, 2017)

The packet type is a 3-bit field that describes the packet as either Ready-to-Transmit, Clear-to-Transmit, Ack, Nack, and Data. This 3-bit packet type field allows space for two additional packet types that can be used to provide error control and retransmission requests across nodes within a route.

There are various challenges with ultrasonic intra-body networks. Among these challenges is battery life. Implantable devices require expensive and risky surgical procedures to implant and maintain. In order to become commercially viable, these devices must be able to operate at low-power while preserving reliability requirements. Santagati et al performed experiments on their IoMT Mote and Patch device and calculated an expected battery lifetime of 12 to 14 years. Work by (Guida et al 2016 and 2018) proposed a solution to this problem by demonstrating an ultrasonic battery recharging method that can fully charge a .22F capacitor in 210s. Unfortunately, inductive power transfer is inefficient and therefore requires the device to be relatively near the human skin surface (Charthad et al, 2014). Additional research is required to identify other methods of recharging the device battery. In the absence of a rechargeable approach, a very efficient and low-power operating modes is required to extend battery life as much as possible. Various techniques have been proposed such as deactivating the transducer when the device is not in use or throttling down data rates when high transfer speed is not required (Santagati, 2017).

Other work by (Jaipriya et al, 2018) proposes an energy optimization routing algorithm for ad-hoc wireless sensor nodes. Their work attempts to use smarter routing decisions to reduce the amount of traffic that is sent through nodes in the network to preserve battery life.

Another prevalent issue with current ultrasonic networks involves the limited propagation distance between two ultrasonic transducers. Current work has estimated the maximum distance to be between 10-20cm depending on the tissue absorption characteristics (Davilis et al, 2010; Galluccio et al, 2012). Various experiments have been conducted to increase the distance of the ultrasonic links within the body. Evaluations of different frequencies (M. Li & Y. Kim, 2018) and formfactors such as the diameter of the transducer (Demirors et al, 2016) have not yielded any significant increase in link distances.

Galluccio et al (2018) explored a solution to extending the distances of ultrasonic links using blood vessels to guide ultrasonic waves within the human body. Their experiments concluded that blood vessels, such as veins or arteries, with a curvature of more than 7 to 10 degrees results in a rapid drop in acoustic intensity, severely reducing the propagation distance. Because these vessels commonly curve throughout the body, this approach did not address the problem of distance limits between ultrasonic devices. Their work, in fact, observed that “free blood”, or blood that is not encapsulated within a blood vessel, demonstrated better propagation distances when compared to blood vessel guided medium (Galluccio et al, 2018).

Galluccio et al (2017) proposes a multi-hop communication protocol for intra-body area networks (IBAN) to address the problem of unreachable devices experienced by ultrasonic networks such as Santagati and Melodia’s (2017 & 2015) UsWB network. This work demonstrated potential for circumventing the distance limitations of ultrasonic links by applying ideas from ad-hoc wireless sensor networks (WSN) including work by (Tang et al, 2005) on routing algorithms for implanted sensor networks. This approach is promising and further considered as part of this proposed work.

Another important aspect involves the protocol used for sending and receiving data while avoiding collision and interference with other concurrent communications. The creation of IEEE 802.15.6 defines the Physical and MAC layer for a Body Area Network establishing a general framework for point-to-point communication between nodes, allowing for multiple concurrent nodes to share a channel. Santagati et al provide a specific protocol implementation to the MAC sublayer as part of their proposed IoMT Platform called UsWB Protocol. This layer defines a protocol for establishing a connection by performing a two-way handshake, followed by sending a Request-to-Transmit packet and a corresponding Clear-to-Transmit packet. During this handshake, a spreading code is exchanged. The spreading code is based on the spread-spectrum concept, which uses a pseudo-random generator to produce a sequence of spreading codes. The seed used to generate the sequence of numbers along with the frame length is exchanged during the handshake so that the receiving node can generate the same sequence of codes. The spreading codes are then used to determine what intervals the signal is transmitted and sampled on within each frame (Santagati et al, 2015). This method allows for shared access to the medium by multiple nodes. Figure 3 depicts how this MAC time-hopping allows for multiple concurrent transmission between two pairs of nodes (Santagati et al, 2017). One pair of nodes are communicating on the 0, 5, and 4 interval within the frame while the other pair are communicating on the 3, 2, and 1st interval within the frame. These intervals are based on the spreading codes that were generated using the seed (or code) that was exchanged.

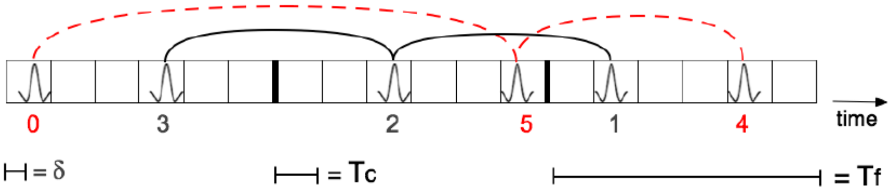

Figure 3 - (Santagati et al, 2015)

Another challenge faced by intra-body networks, involves temperature increases that cause damage to tissues and organs. Like the motivation for selecting ultrasonic as an alternative to RF, that emit ionizing radiation from electromagnetic waves, heat can also be caused by the electronic components. Thermal-aware routing in wired implanted sensors was proposed by (Tang et al, 2005) and demonstrated the ability to equalize temperature across the network sensors within the body through a dynamic routing method. This method is further explored as part of this proposed study

Proposed Approach

This study plans to build upon the UsWB platform proposed by (Santagati & Melodia, 2017) by extending the platform to include a network routing layer that will provide support for multi-hop communication between the intra-body devices. An important aspect of this work involves a dynamic routing algorithm that will utilize a cost function for determining the next node to relay a packet. This cost function will include several metrics including temperature and energy level (i.e. battery life) of neighboring nodes. The proposed methods are decomposed into the following aspects:

1. PHY and MAC Layers

   The PHY and MAC layers will leverage the same design used by (Santagati & Melodia, 2017). The PHY employs two forms of modulization to help avoid collision and interference. The first form is called Adaptive-Time Hopping that is synchronized using spread-spectrum codes generated using pseudo-random number. The random number is exchanged and used to synchronize on the corresponding time interval (also called chip) to sample (read) from the channel (Santagati et al, 2015). Santagati et al, also employ Binary Phase Shift Keying (BPSK) modulization to reduce interference between nodes when using shared frequencies. BPSK is a well-known scheme used to indicate a 0 or 1 depending on the phase of the carrier wave. For example, a wave that begins growing positively at the start of an interval may indicate a 1 and a wave that progresses negatively indicated a 0 (M. Li & Y. Kim, 2018). The Digital-to-Analog pipeline begins by performing symbol mapping of the data and then applies the BPSK using the spreading code generated to convert to a collection of wave shapes that start with a rising phase or a falling phase in accordance with each bit of data. These shapes (modulated data) are then spread across time using the Adaptative-time hoping where the signal is propagated and received at intervals determined by the spreading code sequence generated. The Analog-to-Digital applies the reverse process by sampling the channel (reading) at specific time-hops based on the spreading codes generated and decodes the binary data from the BPSK modulated signal.

Along with the UsWB PHY and MAC layers, the corresponding UsWB Packet will be used. The intent is to leverage these layers as-is with little modification preserving the recommended transmission rates of 700kBps and operating above 20kHz frequency (above human hearing) (Santagati et al, 2017).

2. Network layer and Multi-hop communication

   The proposed networking layer will allow for a multi-hop communication between nodes. A new packet will be defined to capture source and destination of a packet including reserved space for capturing network metrics and route information. This packet is propagated down the network stack and sent as payload as part of the UsWB packet. Each hop will propagate the packet up to the network layer which will then determine if the packet must be forwarded or if the packet has reached its destination. Using a proposed Dynamic Routing and Back-routing method, additional data is collected bidirectionally each time a packet is transmitted a corresponding confirmation is returned using the same route (elaborated further below). This layer will leverage the underlying point-to-point MAC and PHY layers proposed by (Santagati et al, 2015) and leverage a multi-hop approach demonstrated by (Galluccio et al, 2017).

   Additionally, the network layer will keep track of neighboring nodes by tracking the nodes that participate in a route including source and destination nodes. This information is used by the routing algorithm as a set of candidate nodes that are considered for forwarding a packet.

3. Dynamic Routing Algorithm

   The routing of packets from source to destination will be dynamically decided by each node that receives a packet that must be forwarded. Selecting the next node to forward a packet will be based on a cost function that accounts for Temperature, Battery Life, and QoS (such as latency, reliability, and congestion) for each candidate node (i.e. device). Each time a packet forwarding occurs, the node creates a new packet that encapsulates the received packet and includes it’s node identifier and local metrics (temperature, battery life etc). This allows the destination node to collect metrics on the nodes along the route. A back-routing method discussed later is used to provide metrics in the reverse direction.

The following is an approximation of a pseudo-algorithm for selecting a node:

```
IF DestinationNode is not a neighboring node (not reachable):
For each Candidate C from list of neighboring nodes:
T ← last known cached temperature reading
B ← last known remaining battery reading
L ← last known delay of transmission
E ← count of packets dropped since last successful transmission
IF T or B exceed threshold limits: continue to next candidate
        cCost ← Cost(T,B,L,E)
IF cCost < bestCost:
bestCandidate ← C
bestCost ← cCost
Forward Packet to node C
```

The method for obtaining the last known readings for each metric from a neighboring node is elaborated in the “Back-Routing Method” section below. This dynamic routing scheme allows for the route to change given the conditions of the network (i.e. temperature levels etc). This approach can be generalized as a load balancing problem where workloads are distributed evenly across a collection of resources (Tang et al, 2005). The cost for selecting a node is therefore a function that takes the various readings and applies a weighted coefficient to determine an overall cost given the routing policy for the network (Khanh, 2019; Galluccio et al, 2017).

Alternatively, (Jagannath et al, 2019) demonstrate the viability of leveraging Machine Learning algorithms with low time complexities for inducing a model that can select the best route. This approach may be considered and compared to an alternative to a heuristic based function for cost.

Depending on the routing policy used, some metrics may have thresholds that exclude it as a candidate (such as when battery or temperature is at critical levels). The selection of a node to forward a packet to is simply a search for the optimal minima between neighboring nodes. Various possible scenarios can result in no node available to forward (either due to exclusion rules or unreachable). For these scenarios, a buffer or cache will be used to temporarily store the packet for a predetermined amount of time (max delay) and transmitted later when a node is available or initiate back-routing for an undeliverable packet.

4. Back-Routing Method

   The goal of back-routing is to collect updated metric information of the network without performing out-of-band requests for metric information across the nodes in the network (Quy et al, 2019). These metrics will be captured within the payload of a confirmation packet. It is important that the same path be taken in reverse order and not compute a new route. This is accomplished by each node visited inserting its node identifier within the new packet that is forwarded (see Dynamic Routing above). The back-routing of packets will occur when a packet reaches its destination or when a node fails to identify a next candidate node to forward the packet to. In both cases, a back-routed ACK packet will be sent in the reverse order through the nodes that forwarded the packet. Each node will receive the packet and propagate the packet up the networking stack to allow for inclusion of network metrics. This results in a new packet that contains the local node's network metrics (temperature, battery life, QoS etc) and this packet is forwarded on to the next node.
5. Other Design Considerations

   Given the nature of these medical devices, it may be necessary at times to force a packet to a destination that may be currently unavailable due to temperature or battery life levels. In order to account for these critical scenarios, a packet priority can be used to denote packets that are not urgent and can be buffered while waiting for a route and urgent packets that should bypass routing policy constraints in order to expeditated the transmission. This approach is similar to the concept known as expedited forwarding (Tanenbaum, 2003).
6. Evaluate the QoS, including latency, error rates, and congestion performance of the network

   The evaluation of QoS and network efficiency will utilize the same benchmarks used by (Galluccio et al, 2017) and will replicate their environment (they refer to as "TestBed") which includes 4 mock medical devices encapsulated within ballistic gel each with an ultrasonic transmitter. The same PHY layer configuration will be used to match frequency and transmission rates. An additional comparison of transfer and error rates can be evaluated against (Santagati & Melodia, 2017) as a baseline of point-to-point communication between pairs of nodes.

Another evaluation involves the effects of human bone as a medium for wave propagation. All known studies of ultrasonic communication seem to use soft-tissue for their experiments. It is well-understood that solids are known to propagate acoustic waves more efficiently and therefore may in fact yield longer propagation distances.

7. Evaluate the Temperature and Energy levels of the devices

The experiment will collect temperature and battery levels for each node participating in a simulated network to evaluate the performance and effectiveness of the routing algorithm. The results should show a balance (or equalization) of temperature and battery level when simulating network activity over time. Additional tests will be performed by artificially raising the temperature and lowering battery levels across random nodes in the network and performing simulation. The elevated temperature should drop over time due to exclusion from routes and no device should run out of battery. If successful, this experiment can be replicated in a larger "TestBed" with many ultrasonic transducers exchanging data within a ballistic gel to simulate the human body similar to the experiment conducted by (Galluccio et al, 2017). The results of the simulated tests should match the mock Test Bed results.

This proposed study, if successful, would be the first known ultrasonic intra-body network to employ dynamic routing methods for reducing temperatures and preserving battery life. The study also seeks to demonstrate that devices can be implanted at greater distances across the body circumventing the physical limitations of ultrasonic wave propagation by using multi-hop network communication.

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