Improving Reliability for Ultrasonic Implantable IoMT Networks through a Robust Transport Layer

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Problem Statement and Goal

Modern Internet of Medical Things (IoMT) implanted devices require a reliable communication channel in order to coordinate between sensors and actuators within the human body. Existing protocols for IoMT devices provide for Physical and MAC layer definitions for point-to-point communication between nodes in an ad hoc network. Due to limitations of the physical layer, which uses ultrasonic frequency bands, nodes must be within 10cm in order to propagate through human tissue (Santagati et al, 2017). This requires a distributed routing scheme by participating nodes in order to communicate over longer distances by forwarding packets between nodes in an ad hoc network (Demirors et al, 2016). The absence of a robust transport layer within IoMT networks and protocols results in an unreliable end-to-end transmission across a multi-hop route within the network.

The goal of this research is to explore the applicability of a transport layer that provides error control and retransmission within an IoMT Ultrasonic network. The aim is to examine the existing protocols such as the UsWB Protocol proposed by Santagati et al or IEEE 802.15.6 and improve overall reliability of communication by providing guaranteed packet delivery across end-to-end routes within a Body Area Network (BAN). In completing this research, the successful outcome should demonstrate that the addition of a transport layer that provides error control with retransmission improves QoS metrics when compared to existing approaches.

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:

Fig. 4. Human-kidney phantom immersed in a background water-based gel.

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.

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 6 below depicts the UsWB packet segments (Santagati et al, 2017).

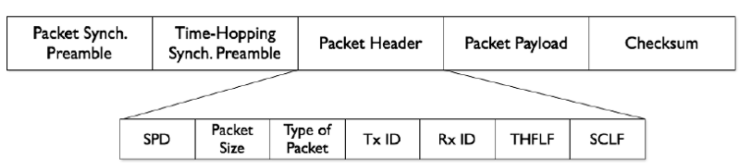

Fig. 6. UsWB MAC layer packet structure.

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.

Barriers and Issues

There are various challenges with ultrasonic intra-body networks. Chief 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).

Another issue important challenge involves the absence of a robust transport layer that can perform error control and flow control throughout the entire end-to-end route. 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 and 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. After the handshake is complete, the receiver will estimate the interference and calculate a frame code length and a spreading code length for transmission. Figure 2 depicts how this MAC time-hopping allows for multiple concurrent transmission between two pairs of nodes by selecting non-colliding frame and spreading code lengths (Santagati et al, 2017).

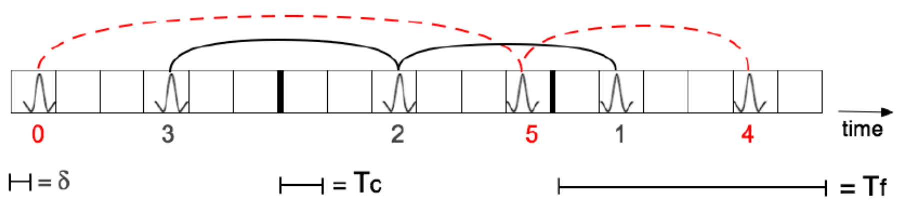

Fig. 2. Two concurrent transmissions with $N_h = 6$, $N_s = 3$, time-hopping sequences $\{3, 2, 1\}$ and $\{0, 5, 4\}$ and spreading codes $\{1, 1, -1\}$ and $\{1, -1, -1\}$.

Proposed Approach

This proposed research seeks to provide an improvement over the work by Santagati et al by extending their UsWB Protocol with a transport layer that leverages error detection and provides a mechanism for retransmitting packets when errors are detected using parity-based checksum methods and extending the UsWB Packet to include an additional retransmission code within the Packet Type segment of the header.

This study seeks to present the comparative results between a transport layer that includes error detection and retransmission with the existing UsWB protocol's unreliable end-to-end transmissions. The study will additionally examine the strengths and weakness of each method and propose future work.

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