Networking issues in medical implant communications

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Abstract

IEEE 802.15 working group established a new task group, body area network (TG-BAN), to develop short range wireless technology in and around human body recently. This paper investigates networking issues in implant communications at 2.4 GHz frequency band. The object is better understanding of medical implant networks and how and where to start TG-BAN work. We applied IEEE 802.15.4b and 802.15.4a-chirp spread spectrum (CSS) for implant communications. We derived a path loss model in the layered body and found two unique issues: clear channel assessment (CCA) of implant devices, interference from neighbor piconet in adjacent channel, and multihop long distance communication. All of them can be attributed to the rapid attenuation of electromagnetic wave through lossy tissue, which is about 30 dB more than the free space propagation. The carrier sense multiple access mechanism and transmit mask of 802.15.4b cannot be directly adopted. The modulation of 802.15.4a-CSS is robust to the interference from adjacent channel. A time division based MAC protocol should be considered by TG-BAN. Instead of routing among implant devices, a simple two-hop protocol which uses a body surface forwarder was presented and verified for long distance implant communications.

Keywords: *Body area networks, implant communications, carrier sense, medium access control;*

1. Introduction

Medical implants have a history of outstanding success in the monitor of patient's condition and in the diagnosis and treatment of many diseases, including heart disease, gastrointestinal tract, neurological disorders, cancer detection, handicap rehabilitation and general health monitor. The wireless link between external device and medical implant enables a doctor to reprogram therapy and obtain useful diagnosis information; the link among implant devices enables *in vivo* timely reactive treatment. The integrated communications from sensors inside the body to the outside telemedicine systems are attracting much attention in the ubiquitous medical computing [1-4]. Recently IEEE 802.15 established a new task group, body area networks (TG-BAN), to develop guideline for using short range wireless technologies in various healthcare services [2]. The main advantages of wireless system over wired alternative include enhanced physical mobility, reduced risk of infection and failure, less invasion and lower cost of care delivery.

To enter the next step of standardization, TG-BAN must decide whether to define a new PHY/MAC or an enhancement of IEEE 802 wireless personal area network (WPAN) standards. A new standard from scratch to satisfy all needs of healthcare may be not an economical option. TG-BAN therefore needs to evaluate current available or emerging IEEE 802 low data rate wireless technologies. Because none of IEEE 802 standard is not intended or designed for medical and implantable communications, it is unknown how efficient the WPAN technologies can support the life critical medical implant [5]. There are a number of fundamental questions: What are the requirements from WBAN applications? Can IEEE 802 wireless technologies fulfill medical and healthcare requirements? In which cares/environment do they not work? Where are the performance bottlenecks?

This paper introduces IEEE TG-BAN and investigates networking issues by applying IEEE 802.15.4b and 802.15.4a-CSS technologies to implant systems. The remainder of paper is organized as follows. Section II describes TG-BAN and medical implant applications. Section III gives a brief review of implant communications and analysis scenarios. In section IV, an implant propagation loss model in layered tissue is addressed. In section V we analyze the networking issues of implant communication in a piconet and among piconets. Section VI finally concludes the paper.

2. IEEE TG-BAN and medical implants

2.1 IEEE TG-BAN

Historically BAN was first discussed under the topic of PAN. Zimmermann is credited with inventing the concept of BAN based on his work at MIT and later at IBM [6]. He discussed a combination of portable computing devices and short range wireless link as providing a new paradigm for computing and communication. The link can be established through handshake and communication was made by direct touch by close vicinity (<2m). In the first version of WWRF Book of Vision, PAN was shown as the innermost sphere near to the user [7]. In 2004, BAN was defined as immediate environment around people which includes those ‘nearest’ object that might be part of body. In the context of WWRF and a number of European IST projects, Zigbee or WPAN based technologies were adopted for wireless communication in 2m ranging around body. However, as agreed by IEEE 802 committee, they are not designed to be used in critical situations where lives may be threatened by communication Quality-of-Service (QoS) issues [5]. TG-BAN is an endeavor of IEEE towards reliable wireless communications between healthcare and medical devices. It was not created in a vacuum. It is a natural extension of IEEE 802 standards from metropolitan area network (MAN), to LAN and to PAN. The TG-BAN will address a unique solution for body area networks that provide short-range communications in and around human body with consideration for human body safety. Its applications cover continuous waveform sampling of biomedical signals, monitoring of vital signal information, and remote control of medical devices. The device can be worn at body surface and implanted in the body.

WBAN is defined differently from WPAN [2]. The first distinguished feature is that WBAN device can be physically on the surface or inside of a person’s body. The safety to human/animal body is therefore the first factor taken into considered. On the other hand, WPAN devices are only close to the user. Wearable IEEE WPAN devices are suggested to be separated at least 30cm distance from human body. Both wearable and implantable BAN devices are expected to be within 30cm distance from surface of body. Thus WBAN devices must be conscious of specific absorption ratio (SAR) to protect human tissue.

The second distinguished feature of WBAN is the possible energy scavenging operation. Battery may contain substance harmful to human body in case of leakage. Implanted devices may not carry enough energy for some operations in a long-term observation, e.g. movement and image compression. And medical WBAN sensors should be lightweight and small to achieve non-invasive and unobtrusive monitor. The size and weight of sensor is predominantly determined by the size and of battery which is directly proportional to its capacity.

Thirdly, WBAN channel is different from that of WPAN. At least one device is carried near human body which has a very complex shape and internal structure. The body surface channels mainly depend on space wave and surface wave propagation [8-11]. A larger attenuation around body surface was found [8, 9]. It was observed that antenna height has a major influence on the path loss in body surface channel [9]. A new floor reflection component and fluctuation in received energy due to body motions were observed [10]. Besides, the body is subject to small movements even in the static cases when sitting and standing. During normal activities and sports, movement becomes significant or extreme. The implant communication is not considered in WPAN. As tissue medium of humans is lossy and mainly consists of salt water, the propagation of electromagnetic wave attenuates in homogeneous tissue is much faster than that in free space [11, 12]. In addition the fading is frequency dependent and is strongly influenced by the layered body structure. And since WBAN devices are physically on the surface or inside of a body, they are in the near field of an antenna. The antenna pattern can be affected by new border conditions, e.g. tissue can absorb part of radiated radio energy. All these may imply a different modulation and antenna design from those of WPAN [9, 11, 12].

The last but not the least, medical applications of WBAN require guaranteed response to external stimuli, which is paramount in life critical services. However, the contention-based MAC protocols of existing low-rate WPAN make it difficult to provide the required QoS [5].

IEEE 1073 standard organization is currently developing a complete seven layer "medical information bus" for wireless data communication among point-of-care medical devices [13, 14]. The main objective is to define universal and interoperable interface that are transparent to end user, easy to use and self-configurable. Figure 1 compares the specifications defined by TG-BAN and IEEE 1073 in the ISO layer model. The IEEE 1073 is not so much keen on developing new wireless technologies, while TG-BAN focuses on PHY and MAC interface.

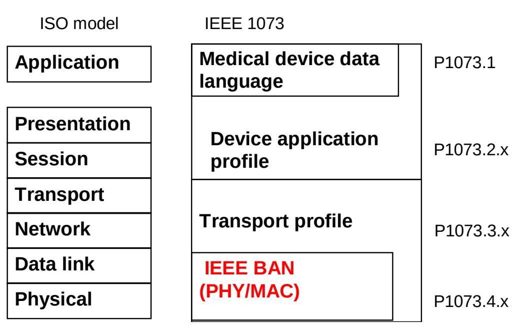

Fig. 1 Topology architecture of IEEE 1073

Medical BAN can be considered as a special type of wireless sensor networks (WSN). Table I compares them in detail to better understand the new requirements in PHY and MAC[1]. The common features include limited resources, low/modest duty cycle, energy efficiency, plug-

[1] Table I is shown in the last page of the paper.

and-play, diverse coexistence environments, and heterogeneous device ability. We also found significant differences in sensor device, dependability, networking, traffic pattern and channel. Medical BAN consider safety, quality and reliability as top priority, while general WSN are cost sensitive for market reason. To improve reliability, general WSN tend to distribute redundant sensors as backup for sensing, transmission and forwarding. In contrast, there is little redundancy in BAN for medical reasons. For example, vital signals, like EEG (Electroencephalography) and ECG (Electrocardiogram), are location dependent and can only be measured by deterministic location. Besides it is difficult to allocate redundant sensors in the limited area or space. Especially, it makes no sense to allocate sensors outside of the interest/effect area. The traffic pattern in medical BAN is usually featured by periodical real time data (EEG and ECG) and some priority burst data (alarm or alert) [16]. In contrast, general WSN typically consider versatile traffic. The medical information, especially the burst and low duty cycle alarm message, have very strict requirement in terms of QoS since they are life critical. This means more stringent QoS requirement than general WSN. The lack of redundancy, priority traffic, dominant periodical data and guaranteed QoS in versatile coexistence environment challenge the reliability of PHY and MAC in TG-BAN.

2.2 Medical implants in TG-BAN

Implant communications have never been considered in IEEE 802 before. A small section of medical implants defined by TG-BAN is listed as follows:

- pacemaker to regulate the beating of heart and implantable cardioverter-defibrillator to treat episodes of ventricular fibrillation;
- prosthetic devices which include artificial retina and cochlear for blind and deaf person, and brain pacemaker for Parkinson’s disease etc.;
- capsular endoscope for diagnosis of gastrointestinal tract;
- *in vivo* vital sensors for health monitor;
- *in vivo* actuators, e.g. insulin pump for diabetes and bladder controller.

Usually communication is between implant devices and external controller (base station). The data rate varies strongly from simple data of a few kbps in pacemaker to several Mbps in capsular endoscope. The dominant data stream can be from implant device to external controller or *vice versa*, e.g. camera capsule and neuro-stimulator. In a closed-control application, e.g. a glucose sensor and insulin pump for diabetes, communications occur among implant devices.

The wireless interface of medical implant is challenged by its unique and fundamental difference from other WSN [3, 4, 8, 11]. Medical implants may have more stringent limitation in size and weight, and therefore limited processing, memory and power capacities. However, lifetime of implant devices which are usually in continuous operation must be maximized to avoid the risk, cost and patient trauma inherent in replacement surgical procedure. Power management of low power transceiver, processor and sensor/actuator, and sometimes energy harvest are necessary. And concern regarding radiation safety levels is also critical. Location is another challenge. A medical implant will be located by physician to where it provides the best patient care and comfort, with little consideration on the radio propagation and network. Furthermore, the material used should be biocompatibility with human body since human immune system is designed to combat foreign substances in the body. Figure 2 depicts several examples of medical implant BAN applications and implementation concerns [3].

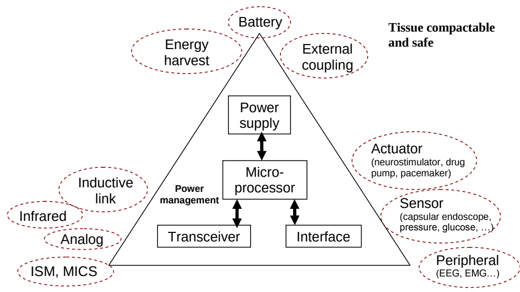

Fig. 2 Wireless TG-BAN implant applications and concerns of implementation

3. Wireless medical implant communications

3.1 Related works and system overview

Federal Communication Committee allocated a frequency band in 402-405MHz for medical implant communication service (MICS) on a shared, secondary basis in 1999. This frequency band best meets the technical requirements of implant communication for a number of reasons [17]. Before that, medical implants depended on magnetic coupling in the low frequency band, which require that the implanted device be in very close vicinity of outside controller. Other frequencies considered for implant communication include 916MHz, 1.5GHz, and Ultra-Wideband (UWB) [18-20]. Gupta *et al* asserted that classic open-air radio models are not applicable to implant network [12]. The proposed propagation model considered antenna, media and power loss due to tissue absorption. Tang *et al* presented a minimum energy coding based On-Off Keying with coherent receiver for retina prosthesis [21]. They even considered thermal effects in the routing protocol of mesh biosensor networks [20]. Research in [23] and [24] shows that a hybrid of chain and cluster based network architecture is more efficient than a tree-based approach.

Compared with the state of art MICS defined systems, an 802.15.4b and 802.15.4a based BAN in 2.4GHz ISM band would go beyond for peer-to-peer networking support, wide bandwidth, high data rate, mature chip design, and a small antenna design (therefore a small size of implant device) [25-27]. Timmons and Scanlon showed IEEE 802.15.4 can be used for medical sensor network when properly configured [26]. Gosalia designed antenna with extremely small form factor operating at microwave frequencies for artificial stimulation of retina cell used in visual prosthesis [27].

The PHY layer of IEEE 802.15.4b describes three frequency bands [28]. There are 16 non-overlapped channels where each has 5MHz bandwidth. Each channel can provide 250kps data rate. The basic MAC mechanism is CSMA. The medium idleness is evaluated during a CCA (Clear Channel Assessment) period of time. CCA can be a detection of energy above a threshold or modulation and spreading characteristic detection.

The CSS (chirp spread spectrum) PHY of 802.15.4a can provide enhanced immunity to multipath fading and extended range with very low transmit power [29]. A chirp is a linear frequency modulated pulse which sweeps the band at a very high speed. Its channel plan is identical to that of 802.11b systems. The default data rate is up to 1Mbps. Because of its frequency sweeping nature, 802.15.4a-CSS system adopts ALOHA for channel access.

3.2 Analysis scenarios and assumptions

We apply IEEE 802.15.4b and 802.15.4a-CSS technology for implant communications. Figure 3 depicts the analysis scenarios of this paper. Each people establish a piconet in star topology, where an externally worn controller acts as coordinator to collect data. The medical sensors, which can be implanted inside of body and worn at body surface, are devices of the piconet. We considered two cases: a single piconet and multiple piconets, for example, in a close space several patients live in a big medical ward or stay in a clinic.

Transmission power of all devices were assumed to be 0 dBm. The free-space path loss measured in dB is [28]

$$pl = 40.2 + 20\log_{10}(d), \qquad (1)$$

where the distance d is smaller than 8 meters. We assume that all medial implants are 30 mm under the surface skin. The total path loss from implant to an external controller is the sum of tissue loss and free space loss. The bit error rate (BER) of 802.15.4b in additive white Gaussian noise (AWGN) environment is [28]

$$BER = \frac{8}{15} \times \frac{1}{16} \times \sum_{k=2}^{16} -1^{k} \binom{16}{k} e^{20SNR(1/k-1)}, \qquad (2)$$

where SNR is the signal-to-noise ratio. For 802.15.4a-CSS running at 1Mbps, the BER becomes [29]

$$BER = \frac{6 \times Q(\sqrt{3 \times SNR_0} + Q(\sqrt{6 \times SNR_0}))}{2}, \qquad (3)$$

where $SNR_0 = SNR \times 14 \times 1.667$ and *Q()* is a Q function. To evaluate the networking issues, we did not consider any other noise source except packet collision during channel access.

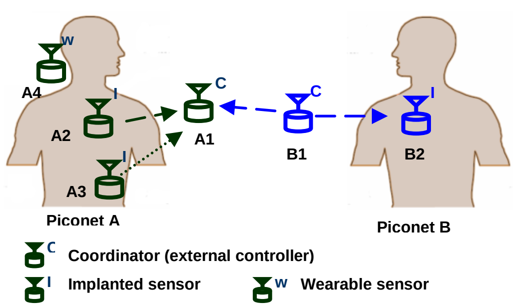

Fig. 3 Analysis scenario of implant communications

4. Radio propagation loss through layered tissue

Human tissue is a lossy medium for wireless communication. The energy of electromagnetic wave dissipates as heat and attenuates considerably when they reach receiver because most tissues (skin and muscle) consist of high water content. The losses are mainly due to absorption of power in tissue in terms of SAR [4, 12, 22-24]. We thus modeled the path loss by mainly considering the power absorbed by tissues.

Usually a medical implant is covered by layered structure. For example, a pacemaker is implanted in the heart muscle under skin and fat. We considered a layered half space with interfaces at $z = z_i, i = 1, \ldots N$. For simplicity, there is a vacuum for $z < z_0$ and a homogeneous medium for $z > z_N$. Each layer has a constant relative permittivity ε_{ri} and conductivity σ_i. The complex wave number for the time dependence $e^{-j\omega t}$ can be defined as

$$k_i = \beta_i + j\alpha_i = \omega\sqrt{\mu_0(\varepsilon_0\varepsilon_{ri} + j\frac{\sigma_i}{\omega})}\ , \tag{4}$$

where ω is angle frequency of exciting field, μ_0 is magnetic constant, and ε_0 is vacuum permittivity. Table II lists the dielectric properties of tissue considered in this paper [30]. The constant wave impedance of each layer becomes

$$Z_i = \frac{\omega\mu_0}{k_i} = \sqrt{\frac{\mu_0}{\varepsilon_0\varepsilon_{ri} + j\dfrac{\sigma_i}{\omega}}}\ . \tag{5}$$

For simplicity in analysis, we assume a plane of infinite extent avoids edge effect [2]. Take a normal incident linear polarized plane wave $E_0 e^{-j\omega t}\hat{y}$ impinge the layered structure, where E_0 is the amplitude of inciting field. The electric fields at depth z have the form

$$\begin{cases} E_{y0}(z,\omega) = E_0 e^{jk_0 z} + C_0 e^{jk_0 z} & z \le z_0 \\ E_{yi}(z,\omega) = C_i^{'} e^{jk_0 z} + C_i^{''} e^{jk_0 z} & z_{i-1} < z \le z_i \\ E_{yN}(z,\omega) = C_N^{'} e^{jk_0 (z - \sum_{n=0}^{N-1} z_n)} & z_{N-1} < z \end{cases} . \tag{6}$$

The unknown coefficients *C's* are determined from boundary conditions. Given the same permeability of all tissues, continuity of E_y cross all boundaries gives

$$[L_n]\begin{pmatrix} C_{n-1}^{'} \\ C_{n-1}^{''} \end{pmatrix} = [K_n]\begin{pmatrix} C_n^{'} \\ C_n^{''} \end{pmatrix}, \tag{7}$$

where $[L_n] = \begin{pmatrix} e^{-jk_{n-1}z_n} & e^{jk_{n-1}z_n} \\ e^{-jk_{n-1}z_n}/Z_{n-1} & -e^{-jk_{n-1}z_n}Z_{n-1} \end{pmatrix}$ and $[K_n] = \begin{pmatrix} e^{-jk_n z_n} & e^{jk_n z_n} \\ e^{-jk_n z_n}/Z_n & -e^{-jk_n z_n}Z_n \end{pmatrix}$. We have

$$\begin{pmatrix} E_0 \\ C_0 \end{pmatrix} = [M]\begin{pmatrix} C_N^{'} \\ 0 \end{pmatrix}, \tag{8}$$

[2] Our channel experiment for implant communications using phantom was arranged at the beginning of July for some reasons, which is just after the deadline of the special issue.

where $[M]=[L_1]^{-1}[K_1][L_2]^{-1}[K_2]\cdots[L_N]^{-1}[K_N]$. Then it is straightforward to compute all *C's* using Eq. 7.

Figure 4 compares the propagation loss in homogeneous tissue at the 2.45GHz frequency, which increases with the propagation distance. The less path losses in fat than those in skin and muscle can be attributed to less water content in fat. In general, the thickness of skin may range from 0.1 to 1 cm or more, and a layer of fat may be from 0.5 to 1.5 cm thick. Figure 5 plots the path loss in three-layered body (e.g. pacemaker) with a specified thickness of skin and fat. Without losing generality, we assumed the first air-skin interface is at $z=0$. The effect of layers can be observed. In the layered region, there are both forward and backward traveling wave because the field is partly reflected and transmitted at each boundary. The superposition of the two waves yields the resultant wave in the region, which has both standing- and traveling wave characteristics. The small oscillation of electric field energy in skin and fat is a consequence of standing wave in these regions. After cross the fat-muscle boundary, the electric field attenuates monotonously. Given the same depth (distance), path loss in layered body is more than that in homogeneous tissue. This can be attributed to the reflection loss (impendence mismatch) at the layer boundary. Particularly we compared the path loss through layered body to that of free space. Approximately 30dB to 40dB additional attenuation can be observed depending on the buried depth of implant device.

Although the path loss model is simple, it reveals the propagation difference in layered body and in free space. The layered body gives rise to variations in path loss due to refection. The exact field depends on the thickness of each layer, which varies between individuals and applications and with time, and border condition. The obtained additional attenuation compare with those in the free space is in accordance with the results in [12].

Table II Dielectric properties of tissues at 2.45GHz

	Skin	Fat	Muscle
Relative effective permittivity ε_r	42.4	6.0	48.1
Conductivity σ (S/m)	2.0	0.13	1.9

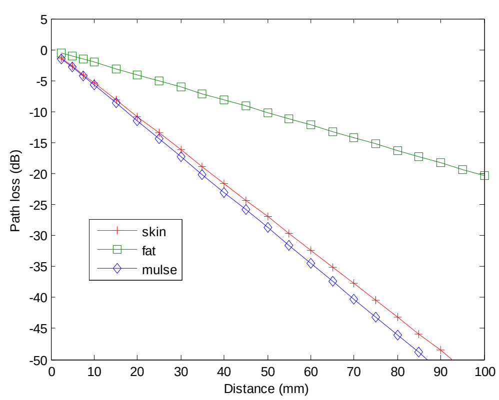

Fig. 4 Path loss in the homogeneous tissues

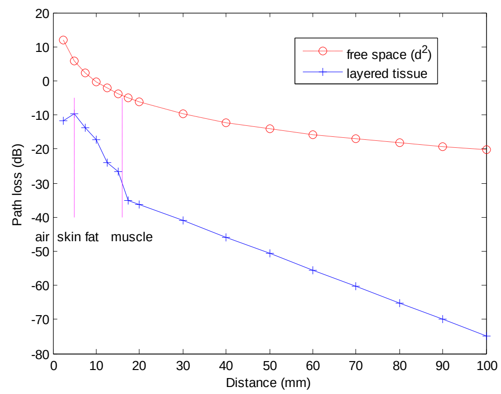

Fig. 5 Path loss in a three-layered structure (skin: 0.5m, fat: 1cm; muscle)

5. Networking issues

The additional implant attenuation obtained in previous section can be used to investigate the networking issues. For simplicity, we assumed the lossy tissue and antenna matching result to an additional attenuation of -35dB.

5.1 Clear channel assessment issue

We first considered CCA operation in the scenario shown in Fig. 3. The channel is occupied by an implant device A2. The free space sensors A4 and B1, and an implant sensor A3 detect the channel state through CCA operation. Because there is no specified CCA sensitivity in the standards, we assume two CCA thresholds: -85dBm and -95dBm [28]. A channel is considered to be free if radio signal strength is below the threshold. The circle-line in Fig. 6 draws the CCA ability of A4. The wearable sensor cannot 'see' the activity of implant when it is over 3 meters away from body surface given a -85dBm CCA threshold. The 3 meters distance can guarantee the correct CCA sensing of activity of an implant in the same piconet[3]. But in the multiple piconets case, the distance between an implant and a wearable sensor in another piconet, e.g. node B1 in piconet B, can be more than 3 meters sometimes. Another -95dBm threshold presents a much better CCA performance. The CCA range of wearable sensor is about 9 meters. The square-line in Fig. 6 shows the CCA ability of implant device A3 in the same piconet. We assume that the radio signal propagates from implant to body surface and enters body again[4]. The free space is only 0.5 meter even given a -95dBm CCA threshold. The distance is not enough even in a piconet. Usually the radio propagation and network are not considered by physician who put a medical implant into patients. For example, in the diabetes treatment, an implanted glucose sensor is buried under skin in the arm to measure blood sugar level, while the implanted insulin pump is put in the abdomen. It is hard to limit the distance between implants must be less than 0.5m in real applications.

Therefore, although wearable device's CCA at body surface works well, implant device's CCA is not reliable because of the bigger path losses through tissue. All implant devices which have failed CCA become "hidden nodes". All 'hidden' implants contend channel with transmitter in an ALOHA way, which is known for its low throughput and power inefficient.

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[3] We do not consider the shadowing of channel induced by body movement.

[4] As shown in previous section and Fig. 7 of [12], the path loss between two implants through tissue is more than 50dB when distance is larger than 10cm. A direct through body path between implants usually is not available.

This means CSMA does not work well in an implantable BAN. However, CCA of implanted devices is assumed to be reliable in [26]. The ALOHA channel access of 802.15.4a-CSS system can be considered as an extreme case of "hidden node" issue where all nodes are 'hidden' each other. Although research on "hidden nodes" is a hot topic in wireless ad hoc network, it is unknown the power consumption of the proposed methods. An alternative solution is to avoid the contention based protocol and adopt a time division multiple access (TDMA) approach instead [4].

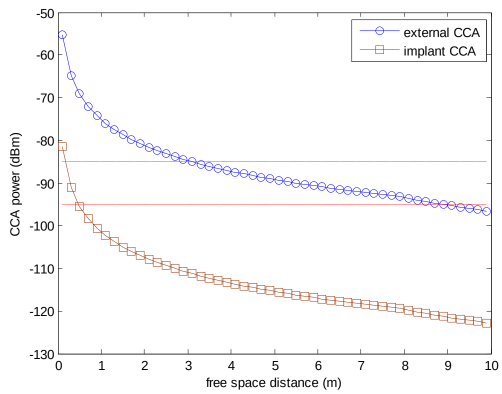

Fig. 6 CCA of medical implant devices

5.2 Inter-piconet interference issue

We then considered implant communication in the multiple piconets environment. As shown in Fig. 3, when node A2 is transmitting to node A1, node B1 may communicate with node B2 at the same time. Packets from A2 and B1 may collide at node A1 when CCA fails. We specified a 1 meter distance between A1 and A2. Figure 7 plots the BERs received at A1 when packet collision occurs. The horizontal axis is the separation distance between A1 and B1. In the case two piconets works in the same channel, it is almost impossible for a smooth communication [5]. The BER is more than 1% even when B1 is 20 meters away from A1. The square-line in Fig. 7 describes a case where two piconets operate in adjacent channels. The transmit mask is 20dB attenuation outside the working channel as required in the standard. To achieve 0.01% BER, the separation distance should be larger than 5 meters. In real implementation, typical transmit mask is more than 20dB. Given 25dB relative power attenuation, the separation distance still should be larger than 3 meters. This separation between BAN piconets seems hard to be guaranteed in some environments, e.g. clinic and ward. During network formation phase, the coordinator scans all channels to find an unoccupied one to work in. There is no requirement that two piconets cannot work in adjacent channels. As shown in Fig. 7(a), the free space signals in adjacent channel can severely interfere to the implant communication because the tissue attenuation may be bigger than the spectrum mask. Therefore TG-BAN requires a more stringent out-band attenuation than that defined by 802.15.4b. Figure 7(b) describes the packet collision of 802.15.4a-CSS. Different from the case of 802.15.4b, the free space signals in adjacent channel with 25dB attenuation cannot severely interfere to the implant signals.

[5] A smooth communication means the link BER is less than 0.1‰.

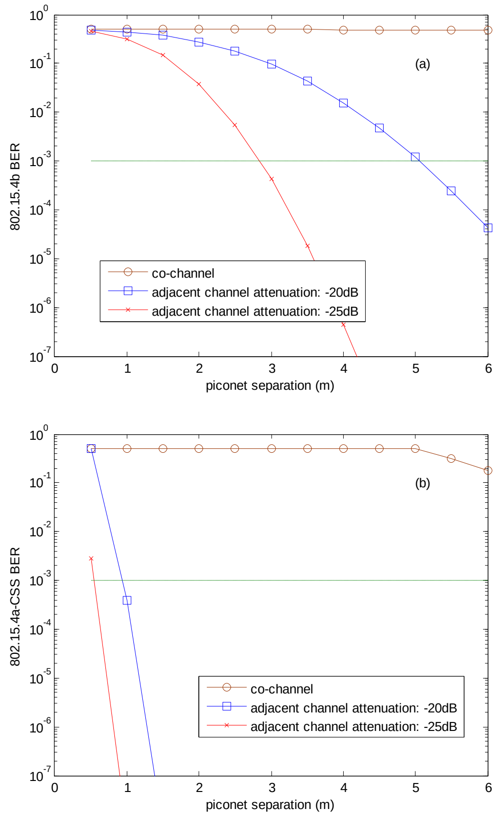

Fig. 7 BER received at A1 in the coexistence of BAN piconets: 802.15.4b (a), and 802.15.4a-CSS (b)

5.3 Long distance implant communications

Long distance communication among implant devices was considered in [4, 22-24]. The motivation is to balance thermal effect resulting from communication radiation and power dissipation by routing data through multihop. The basic idea is to organize implant sensors into cluster and route data using SAR minimization metrics. These can be considered as an extension of energy efficient routing in general WSN.

In the scenario considered by TG-BAN, there is always an externally worn coordinator which is outside of body. On considering the significant difference of radio attenuation in tissue and in free space, it is intuitive to select body surface coordinator as a message forwarder. The data packet from implant sensor first goes to the out-of-body forwarder and is then forwarded back into body to the destination. This is termed the two-hop protocol. To compare it with multihop methods in [4, 22-24], we measured the propagation loss over body surface in the anechoic chamber using a vector network analyzer. The experiment objects are human body and phantom body in static standing posture. The chip antenna was attached on to the upper half of body at number of positions, where the receiver antenna was put in the middle of abdomen, and the transmitter antennas was on the writs, arm, rib, chest, shoulder and head. All positions are in the line-of-sight. Figure 8 plots the obtained path loss over body surface in dB which can be given by

$$PL = 46.4 \cdot \log_{10}(d) - 56.9\,. \tag{9}$$

The path loss in free space per Eq. 1 was also shown for comparison. The average on-body path loss followed the free-space curve with about 20dB lower. Comparing Fig. 5 with Fig. 8, the in-body path loss through tissue is generally 20dB lower than the on-body path loss over body surface. In other words, the on-body link has about 20dB budget to cover the same distance compared with the in-body link. The on-body path loss of human body is 2dB bigger than that over the phantom body. This can be attributed to the difference in dielectric properties between human body and phantom body. Another reason may be the movement of human body, e.g. heart beat and respiration.

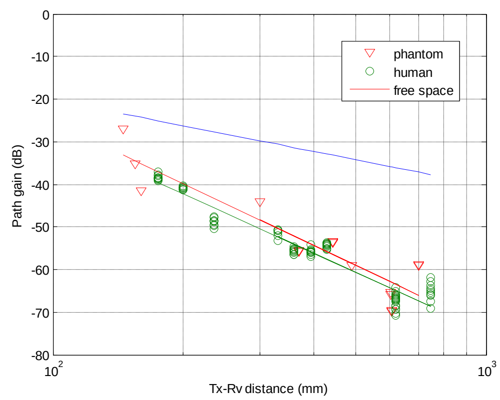

Fig. 8 Path loss of 2.45GHz radio over body surface

Several benefits of the two-hop protocol can be immediately found. A body surface device has less limitation than implant devices. Even battery recharge is practical possible. This gives more freedom in channel access, routing and management design. The body surface coordinator is natural manager of total network. Communication between any pair of implanted devices can be researched within two hops. No complex routing algorithm and distributed network management are needed. And the thermal effect is simple and constant.

6. Conclusion

Scalability of MAC is another consideration. The number of GTS and slot in beacon mode of 802.15.4 may be not enough when we envision a large number of wearable and implanted sensors will be placed in the body in the future. There may be more than 100 electrodes for EEG measurement.

The unreliable CCA of implant indicates that CSMA cannot be adopted in the implant BAN. The modulation and transmit mask of 802.15.4b is not robust enough to the inter-piconet interference in adjacent channel. That is the 802.15.4b is not a good reference for TG-BAN. The modulation of 802.15.4a-CSS is robust to the interference from adjacent channel. However, the ALOHA protocol deteriorates system performance when network is heavily loaded. Therefore the MAC protocol of TG-BAN should be TDMA style. The future work will focus on this direction.

In conclusion, we explored IEEE low-rate WPAN technologies for emerging medical implant communications in this paper. This is an initial effort of the ongoing standardization of TG-

BAN. We derived a path loss model in the layered tissue body and found approximate 30 to 40 dB additional attenuation comparing with the propagation in free space. The rapid attenuation of electromagnetic wave through tissue leads to unreliable CCA of implant device and interference from neighbor piconet in adjacent channel. The CCA range of implant devices is only 0.5 meter, which is smaller than the distance between implant devices in some of TG-BAN applications. The inter-piconet interference in adjacent channel is a new issue. The modulation and transmit mask of 802.15.4b is not robust enough. Because the path loss over body surface is less than that through tissue, we presented and verified a simple two-hop protocol, which use a body surface forwarder, for long distance communication between implants.

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Table I Comparison between medical BAN and general WSN

	Medical BAN	General WSN
Common features	Limited resources: battery, computation, memory, energy efficiency Diversity coexistence environment low/modest data rate, low/modest duty cycle Dynamic network scale, plug-and-play, heterogeneous devices ability, dense distribution	
Sensor/ actuator	Single-function device Fast relative movement in small range device lifetime, days, <10 years (implant sensor) Safe (low SAR) and quality first	Multi-function device Rare or slow movement in large range network lifetime and device lifetime, months, <10 years Cost sensitive
Dependability	Reliability (first), guaranteed QoS Strongly security (except emergency)	Expected QoS, redundancy-based reliability Required security
Networking	Small scale star network No redundancy in device Deterministic node distribution	Large scale hierarchical network redundant distribution Random node distribution
Traffic	Periodical real time (dominant), burst (priority) Uni-directional traffic M:1 communication	Burst (dominant), periodical Uni-directional or bi-directional traffic M:1 or point-point communication
channel	Specific medical channel, ISM band Body surface or through body	ISM band Obstacle is unknown