Technical Considerations in Emerging Medical Body Area Network Spectrum Regulation

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Abstract—Medical Body Area Network (MBAN) technology provides a promising solution to improve patient care outcomes and lower healthcare costs. However, the current spectrum allocation cannot cater to increasing MBAN applications. Therefore, U.S., as well as other regions, have already been considering allocating a new spectrum for MBAN applications. In this paper we study a joint MBAN regulation proposal developed by Philips Healthcare, GE Healthcare, and AFTRCC that was recently presented to the FCC for the U.S. MBAN spectrum regulation. A brief summary of the joint proposal is firstly presented. Then the technical rationale behind the proposed parameters, such as frequency band selection, emission bandwidth limit, and transmission power limit, is discussed in detail. Link budget analysis and MBAN coexistence simulations are given to demonstrate that the proposed solution can address the requirements of MBAN application.

I. INTRODUCTION

U.S., as well as other regions in the world, are facing a severe aging problem, which puts serious health care delivery. By 2050, 50% of developed world population is expected to be chronically ill. Situation in developing countries is similar. For example, older adults will bear two-thirds of the total disease burden in China and nearly half in India by 2030 [1]. Also as the education level increases, people have higher expectation and more demands on health care. However, while the demands for health care are growing rapidly, the skilled health care staff is becoming scarce and likely will not meet such burgeoning demands in the near future. For example, about half of the registered nurse workforce will reach retirement age in the next 15 years and by 2020 there is expected to be a shortage of 1 million registered nurses in the U.S. [2]. Moreover, overload and tightening of health care budget has aggravated the impending health care crisis. These demographic, social, and economic trends highlight the need of innovative technologies to bring affordable and high-quality health care services to people that will improve their quality of life.

Ubiquitous patient monitoring is one of the promising solutions to address the health care challenges we are facing and medical body area network (MBAN) technology, which replaces the tangle of cables tethering hospital patients to their bedside monitoring units with wireless connections, is seen as a key component there enabling unprecedented portability for monitoring physiological signs in the hospital, at home and on the move. In the MBAN approach, multiple low cost sensors are attached on or around a patient, and these sensors take readings of patient physiological information such as patient temperature, pulse, blood glucose level, electrocardiographic (ECG) data, or so forth. The sensors are coordinated by a proximate hub device to form a MBAN and they communicate with the hub device via MBAN short-range wireless links. Information collected by the sensors is transmitted to the hub device through MBAN links, thus eliminating the need for cables. The hub device may process the collected patient data locally for diagnosis of medical conditions which in turn could trigger a treatment procedure, and/or communicate patient data to a central patient monitoring station via a wired or wireless longer-range backhaul link for centralized processing, display and storage. The backhaul network may, for example, include wired Ethernet and/or a wireless connection such as Wi-Fi or some proprietary wireless networks. MBAN technology enables untethered, unobtrusive and continuous monitoring/treatment and has the potential to revolutionize health care delivery. Among its benefits are extension of comprehensive and pervasive physiological monitoring into care areas that are currently unmonitored and even outside health care facilities (e.g. patient home), increased patient mobility and comfort, better infection control, more holistic monitoring with sufficient flexibility and scalability, improve health care workflow efficiency, safety and clinical outcome. Monitoring systems are advancing from basic alerting devices to predictive clinical decision support solution and MBAN can play an important role to simplify the collection of vital patient data and facilitate these solutions, so improving early detection of worsening patient conditions. This reduces health care costs.

Currently, MBAN is still at an early stage and there are some technical challenges need to be addressed before it can be widely deployed. One of the most important issues is the current spectrum allocation cannot effectively support wide deployment of MBAN applications and foster MBAN innovations due to either limited bandwidth or severe interference issues. To address this issue, the FCC has been considering allocating a new spectrum to MBAN services in the U.S. Europe and China are also initiating spectrum regulation activities for MBAN services. In the past years, Philips Healthcare, GE Healthcare, and the Aerospace and Flight Test Radio Coordinating Council (AFTRCC) have been working closely to develop a comprehensive solution for MBAN spectrum regulation and made a joint proposal to the
FCC in January 2011 [3], which provides a framework for the FCC to define MBAN rules and has gained positive feedback from the FCC.

In this paper, a summary of the Philips/GE/AFTRCC joint proposal is presented. Moreover, the technical considerations behind several key parameters are discussed. Link budget analysis and simulation results are provided to support the reasoning.

II. SUMMARY OF PHILIPS/GE/AFTRCC JOINT PROPOSAL

Philips Healthcare, GE Healthcare, and AFTRCC are major parties that have made significant contributions to the FCC MBAN proceeding. Based on extensive discussions, the tri-parties developed a concrete MBAN regulation solution, which was proposed to the FCC for consideration and is summarized as below.

- **Eligibility and Permissible Communications**
  Except for the purposes of development, testing and demonstration, operation of MBANS devices is
  - limited to transmission of data (no voice) used for monitoring, diagnosing or treating patients,
  - permitted by rule (without an individual license) by authorized health care professionals and by any other person, if such use is prescribed by a health care professional.

- **Frequencies and Authorized Locations**
  The proposed MBAN spectrum ranges from 2360 MHz to 2400 MHz and the proposed allocation is on a secondary basis, which means MBAN systems have to protect all the primary users and accept possible interference from those users. To protect the primary users, especially aeronautical mobile telemetry (AMT) sites, it is proposed to divide the MBAN spectrum into the two sub-bands, and the authorized locations of MBAN operations in these two sub-bands are defined as below.
  - **2360-2390 MHz** MBAN operations are limited to healthcare facilities only (in-door use only and mobile vehicles, such as ambulance, are excluded). MBAN registration, coordination, and electronic key/beacon mechanism are required to control MBAN access to frequencies within this band and enforce in-door use.
  - **2390-2400 MHz** MBAN operations are permitted anywhere (e.g. in-hospital monitoring, home monitoring and ambulance monitoring). MBAN coordination and electronic key/beacon mechanism are not required. Hospitals are required to do MBAN registration for the use of this band.

- **Emission Bandwidth**
  The 20-dB bandwidth $B$ should be no larger than 5 MHz.

- **Transmission Power (EIRP)**
  The transmission power $P$ (in dBm) should be
  - 2360-2390 MHz, $P \leq \min(0, 10\log(B))$
  - 2390-2400 MHz, $P \leq \min(13, 16 + 10\log(B))$, where $B$ is the 20-dB emission bandwidth in MHz.

- **Channelization**
  No specific channelization is required.

III. TECHNICAL CONSIDERATIONS IN THE PROPOSAL

In this section, the rationale behind the joint proposal is discussed in detail.

A. Technical Requirements of MBAN Applications

There are three major categories of MBAN applications: in-hospital patient monitoring, home monitoring and emergency ambulance applications. These categories have different technical requirements on MBAN communications.

1) **In-hospital Monitoring Applications**: In-hospital MBAN applications cover both simple single-parameter monitoring services used on general ward and much more complex multi-parameter monitoring services used in ICU. Table I shows the technical requirements of several typical in-hospital MBAN applications.

<table>
<thead>
<tr>
<th>Application</th>
<th>Raw Throughput</th>
<th>Latency</th>
<th>Raw BER</th>
<th>Battery Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECG</td>
<td>96 Kbps</td>
<td>&lt; 250 ms</td>
<td>&lt; 10^-6</td>
<td>&gt; 1 week</td>
</tr>
<tr>
<td>EMG</td>
<td>384 Kbps</td>
<td>&lt; 250 ms</td>
<td>&lt; 10^-6</td>
<td>&gt; 1 week</td>
</tr>
<tr>
<td>O2/CO2/BP/Respiration /Temp. /Glucose</td>
<td>&lt; 10 Kbps</td>
<td>&lt; 250 ms</td>
<td>&lt; 10^-6</td>
<td>&gt; 1 week</td>
</tr>
</tbody>
</table>

- **Raw Data Throughput**
  The target medical data throughput varies in a large range. Specifically, application-level data rates of $\sim$Mbps to $\sim$Mbps are expected, depending on the application, with most devices requiring PHY data rates between 250 Kbps to 1 Mbps. The emerging MBAN rulings should provide flexibility to meet such diverse data rate requirements.

- **Communication Range**
  In most in-hospital applications, the hub device of a MBAN would be either on patient body (e.g. portable monitor) or in close proximity (e.g. bedside monitor) to patient. Therefore, a typical in-hospital MBAN communication range would be no larger than 3 meters.

- **Link Performance**
  To maintain the required quality-of-service, the application-level bit error rate (BER) should be no larger than $10^{-6}$ for most patient monitoring applications. Considering that automatic retransmission (e.g. ARQ) could be used at the MAC layer to enhance link performance, the required physical layer (PHY) BER could be relaxed. Generally speaking, a PHY BER no larger than $10^{-4}$ would be sufficient for in-hospital MBAN applications.

- **Radio Propagation Model**
  Since MBAN applications require on-body communications, it is likely that patient body blocks the line-of-sight link between MBAN transmitter and receiver. The human body blockage could significantly attenuate MBAN signal and introduce a huge blockage loss. MBAN radio should
have sufficient link margin to counteract such possible blockage loss to guarantee MBAN link reliability.

- **Power consumption**
  Long battery life is a key factor to make future MBAN succeed. If the battery life of a MBAN system is too short, then recharging or replacing batteries would become a big burden and reduce patient monitoring workflow efficiency greatly. The desired battery life could range from one day to several weeks, depending on the MBAN application. To achieve such long battery life, the emerging MBAN solutions should provide flexibility to support low power radio designs, such as low duty cycle operation. It is expected that the aggregated duty cycle of an in-hospital is typically no larger than 25%. Such low duty cycle would enable MBAN devices to stay in sleep mode most of the time to prolong battery life and achieve good coexistence performance.

- **Self Coexistence**
  In in-hospital MBAN applications, it is likely that multiple patients stay nearby. Thus, the multi-MBAN coexistence must be considered to avoid inter-MBAN interference when determining the amount of MBAN spectrum. Different in-hospital usage scenarios have different MBAN densities and it is expected that the number of co-located MBANs usually would be no larger than 10 (such high density could happen in the areas like emergency room/ICU).

**2) Home Monitoring Applications:** Home monitoring will become a more important part of health care in the future as a key means to lower medical costs by focusing on prevention and early detection/treatment of diseases. The dominant home use case is monitoring for patient adverse events and a periodic collection of data from patients in a home environment. Home patients may not be critically ill, but may have an adverse event that can become critical, so monitoring information must be reliably communicated to the remote monitoring facility. Home health care applications have some different requirements compared to in-hospital applications.

- **Communication Range**
  A large communication range is desired in home monitoring applications. Patients need to have full mobility within their homes. To keep cost down, it is desirable to use a hub device to cover multiple rooms in patient home. A communication range of 10 meters is desired.

- **Raw Data Throughput**
  Typical data rates fall in the range of 1~50 Kbps. In the future, a higher data rate may be required.

- **Power consumption**
  Long battery life is even more critical to home monitoring applications and the desired battery life would be several weeks or longer. Low duty cycle is the key to achieve such long battery life. Home monitoring applications are usually event-driven, which means MBAN devices usually has a very low activity level and they become more active only when an adverse event happens to patient. Therefore, a typical aggregated duty cycle is usually no larger than 2%.

- **Self Coexistence**
  The number of co-located MBANs in a home environment is expected to be in the range of 1-4. Therefore, less spectrum would be needed to support MBAN coexistence in home healthcare applications.

**3) Emergency Ambulance applications:** The level of monitoring in many cases is the same as in-hospital applications for emergency care. A wide range of capability is needed based on patient acuity. High acuity applications, such as 12-lead ECG for heart attack case, demands a high data rate (e.g. Mbps) link. The communication range is short and usually no larger than 3 meters. Also the MBAN density is low, typically with 1-2 co-located MBANs, which requires less spectrum to achieve good coexistence. Since the requirements of this case is covered by the other two cases, it is not separately analyzed in the following discussion.

**B. Frequency Band Selection**
Currently, there are several spectrum bands available for medical applications, but they are not suitable for MBAN applications either due to limited bandwidth or uncontrollable interference.

- **WMTS Bands**
  The frequencies currently allocated for WMTS in the U.S. are divided into three separate blocks 608 – 614, 1395 – 1400, and 1427 – 1432 MHz bands, each of which only has 5 or 6 MHz bandwidth. These bands are widely used in hospitals for high-power long-range telemetry applications, such as applications hospital-wide ambulatory telemetry with centralized monitoring stations, and are subject to saturation by those uses. The limited continuous bandwidth and the heavy use of high-power telemetry radios make it very challenging, if not impossible, to deploy low-power MBAN systems within these bands without causing interference issues. Moreover, these bands are allocated only for the use within healthcare facilities and cannot be used for home healthcare applications. At last, the propriety radio technology used in the WMTS spectrum is expensive and not suitable for low-cost MBAN devices.

- **MedRadio Band**
  The 401-406 MHz MedRadio band is for ultra-low-power lower-bandwidth in-body/on-body applications, such as programmable implants and percutaneous blood glucose sensors. However, the limited bandwidth, stringent rules (e.g. listen-before-talk rules), and large antenna size makes it impractical for MBAN applications.

- **2.4 GHz ISM Band**
  The 2400 – 2483.5 MHz ISM band has some attractive advantages, such as worldwide harmonized allocation, large bandwidth, small antenna size, and numerous mature low-cost low-power radios available for the MBAN use. However, this band is already saturated by high-power devices (typically 100 mW) used in hospitals, and
will not support the growth of low-power (mW) MBAN devices due to potentially uncontrollable interference.

### Table II

<table>
<thead>
<tr>
<th>Technology</th>
<th>Devices</th>
<th>Typical TX Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wi-Fi (IEEE 802.11 b/g/n, channel bandwidth up to 40 MHz)</td>
<td>Hospital IT network Access Points, IP phones, smartphones, PDAs, Wi-fi telemetry devices, laptops</td>
<td>up to 100 mW</td>
</tr>
<tr>
<td>Bluetooth (IEEE 802.15.1), channel bandwidth 1 MHz, with frequency hopping</td>
<td>Bluetooth head phones, smartphones, PDAs, laptops, Bluetooth medical devices</td>
<td>up to 100 mW</td>
</tr>
<tr>
<td>ZigBee (IEEE 802.15.4, channel bandwidth 5 MHz)</td>
<td>ZigBee medical devices, ZigBee building automation sensors</td>
<td>several mW</td>
</tr>
<tr>
<td>Other proprietary radios</td>
<td>RFID devices, wireless medical devices</td>
<td>up to 100 mW</td>
</tr>
</tbody>
</table>

### 5 GHz ISM Band

Although it has a wide bandwidth and is worldwide available, the 5725-5850 MHz ISM band is not a good choice because it has too large propagation and body losses, which would result in unacceptable high power consumption. Furthermore, this band is also crowded with high-power wideband Wi-Fi (IEEE 802.11 a/n) devices, which can cause interference issues.

Therefore, the joint proposal proposes to allocate the 2360-2400 MHz spectrum for MBAN services on a secondary basis. The main reasons to choose this band include:

- The proposed band is immediately adjacent to the 2.4 GHz band for which many low-power devices exist today that could be easily reused for MBANS usage, such as IEEE 802.15.4 radios. This would lead to low-cost implementations due to economies of scale and ultimately lead to wider deployment of MBANS and hence improvement in patient care. At the same time, by using a dedicated band rather than the crowded 2.4GHz spectrum, quality of service for these life-critical monitoring applications can be ensured.
- this band has reasonable propagation and human body blockage loss characteristics and small antenna size, which make low-power miniaturized sensor device practical for implementation.

### C. Emission Bandwidth Limit

The 20-dB emission bandwidth limit is proposed to be 5 MHz, which would facilitate low-power, low-cost MBAN radio design and allow a great capacity to manage evolving medical applications.

First, a 5 MHz bandwidth limit would provide flexibility and technology neutrality, allowing industry to develop appropriate MBAN solutions, especially to leverage most of the available 2.4 GHz ISM band solutions to produce relatively low-cost MBAN devices. Some popular 2.4 GHz ISM band low-power short-range radio solutions, which are commercially available and have been widely deployed, and their parameters, are listed in Table III. A 5 MHz limit would accommodate almost all of the currently available 2.4 GHz low power wireless solutions and result in low-cost and mature MBAN solutions.

Secondly, a 5 MHz bandwidth limit creates flexibility to cater to the diverse needs of MBAN applications, especially high data rate and low power consumption needs. As shown in Table I, MBAN applications have a large variety of requirements on data rate and some applications may need high raw data throughput. For example, a classic multi-lead ECG node may require as high as 96 kbps medical raw data throughput to forward its ECG signal to a hub device in a real-time cardiac monitoring system while at the same time, the desired battery lifetime is more than a week. Assuming 25% duty cycle and 40% protocol overhead (including physical layer, MAC layer and application layer protocols), the required raw data rate should be at least 640 Kbps. For the EMG case, the required raw data rate would be at least 2.56 Mbps. In the future, the required raw data rates could be even higher to achieve better

<table>
<thead>
<tr>
<th>Technology</th>
<th>20-dB Emission Bandwidth</th>
<th>PHY Data Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bluetooth</td>
<td>1 MHz</td>
<td>1 Mbps (2 and 3 Mbps for enhance data rate modes)</td>
</tr>
<tr>
<td>IEEE 802.15.4</td>
<td>2.5 MHz</td>
<td>250 Kbps mode</td>
</tr>
<tr>
<td>Nordic Semiconductors Proprietary solutions (e.g. nRF24L01+)</td>
<td>&lt; 1 MHz for 250 Kbps mode; 1 MHz for 1 Mbps mode; 2 MHz for 2 Mbps mode</td>
<td>250 Kbps; 1 Mbps; 2 Mbps</td>
</tr>
</tbody>
</table>
monitoring performance. To provide such a high data rate with a long battery lifetime (> 1 week) and a very low error rate, a broad emission bandwidth is preferred. A 5 MHz emission bandwidth limit allows MBAN radio to adopt very simple modulation schemes (e.g. GFSK, FSK, BPSK, and Offset-QPSK) that have low spectrum efficient (e.g. <= 1 bit/s/Hz) to achieve such high data rate. Those modulation schemes are very mature for low-power implementation and currently widely used in Bluetooth, ZigBee and most of the 2.4 GHz proprietary low-power solutions. Also it provides potential to further improve raw data rates to meet the requirements of future MBAN applications.

Thirdly, a 5 MHz limit would allow for broad emission bandwidth to significantly prolong MBAN device battery life via low duty cycle operations. A higher emission bandwidth (e.g. ~ MHz) enables MBAN devices to operate at higher data rate modes (e.g. ~ Mbps) and therefore achieve low duty-cycle operation. Low duty-cycle operation facilitates low average power consumption and long battery life. For example, the Nordic nRF24L01+ chipset has a power consumption of 34 mW (0 dBm transmit power) either with 1 Mbps (1 MHz bandwidth) or with 2 Mbps (2 MHz bandwidth) in the transmission mode, a power consumption of 39.3 mW with 1 Mbps and 40.5 mW with 2 Mbps in the receive mode, and a power consumption of 78 uW in the standby mode (standby-1 mode). There is almost no difference between the 1 Mbps option and the 2 Mbps option in terms of average power consumption in their TX/RX modes. However, the 2 Mbps option can reduce the duty cycle almost by half and therefore double the battery lifetime compared to the 1 Mbps option.

Fourthly, broad maximum emission bandwidth can provide medical-grade link reliability. A wide bandwidth could be used to achieve high spreading gain via spectrum spreading technologies or coding gain via simple channel coding while still maintaining a high enough rate to support MBAN applications. For example, simulation results of four data rate modes under AWGN channel are shown in Fig. 1 The 250 Kbps mode uses the direct sequence spectrum spreading (DSSS) scheme with Offset QPSK (O-QPSK) modulation, as defined in IEEE 802.15.4. The 500 Kbps mode adopts DSSS with O-QPSK modulation, as defined IEEE 802.15.4b. The 1 Mbps mode uses O-QPSK modulation with a \(\frac{1}{2}\) rate repetition code. The 2 Mbps mode just uses O-QPSK modulation. All the modes have the same 20-dB emission bandwidth of around 2.6 MHz. From the simulation results, one can see the 250 Kbps, 500 Kbps, and 1 Mbps modes can achieve about 8.3 dB, 5.2 dB, and 3 dB signal-to-noise-ratio (SNR) gain at the bit error rate of \(10^{-4}\) respectively, compared to the 2 Mbps data rate mode. This elegant performance-rate tradeoff can be used by a MBAN device to adaptively adjust its transmission to achieve medical-grade performance with low power consumption. Moreover, the spreading gain/coding gain and low duty cycle achieved with broad emission bandwidth will be helpful to mitigate possible interference.

At last, a 5 MHz limit is feasible from practical implementa-

tion aspects. If a MBAN system has a bandwidth that is wider than the coherent bandwidth of typical MBAN channels, it would require a complicated equalizer to deal with possible multipath fading (or frequency selective fading) and thus increase cost. Therefore, it is preferable to adopt a emission bandwidth limit that is smaller than the coherent bandwidth of typical MBAN channels. Due to the proximity of the 2.4 GHz ISM band to the 2.36 - 2.4 GHz band, channel measurement results for the 2.4 GHz body area networks (BAN) in the literature can be used to study channel characteristics of MBAN channels. In [4], is shown there that in most cases, the coherence bandwidth of typical 2.4 GHz BAN channels is no less than 5 MHz. That means that with a channel bandwidth of 5 MHz or less, the frequency selective fading effect is negligible and no equalizer is required. Therefore, 5 MHz is a good choice for the maximum emission bandwidth in the sense of simplifying MBAN radio implementation and reducing costs. Moreover, a bandwidth that is too large usually requires a high sampling rate and data processing speed, which could increase power consumption. Thus, a too large bandwidth is not desired for MBAN applications since a long battery life is a priority. A 5 MHz is usually acceptable for those low power applications.

D. Amount of MBAN spectrum

The amount of spectrum allocation should be capable of supporting MBAN operations with simple radios in high-density deployment cases. As shown in Section III, it is envisioned that in some worst in-hospital cases, such as waiting areas of Emergency Rooms (ERs), elevator lobbies, preparatory areas for imaging services etc., up to 10 MBAN networks could co-locate with each other. Contention-based protocols may be used to coordinate the distributed MBAN operations in order to avoid interference among the MBAN devices. Frequency-hopping and listen-before-talk (e.g. channel sensing multiple accesses (CSMA)) schemes are two popular contention-based protocols that are suitable for MBAN
Therefore, to support ten co-located ECG MBAN networks, the packet loss rate of a hub device or SpO2 device would exceed $10^{-3}$. Thus, $5$ non-overlapping channels are required to support $10$ co-located MBANs. Considering that MBAN radios may use simple modulation schemes, such as FSK and OQPSK, that usually have around or even less than $1$ bit/s/Hz spectrum efficiency and guard bands may be needed at band edges to meet out-of-band-emission (OOBE) limits, approximately $15$-$20$ MHz spectrum would be required to support MBAN coexistence. Furthermore, to protect primary users, MBAN should avoid using the spectrum utilized by co-located primary users. In a worst case scenario, $20$ MHz of the proposed spectrum may be occupied by a primary AMT user (e.g. iNet AMT system) and not available for MBAN operations. Therefore, a total of $40$ MHz spectrum is needed to adequately support harmonized coexistence between MBANs and primary users and among MBANs in the in-healthcare-facility use case.

For home applications, a $10$ MHz allocation would be sufficient to support $1 \sim 4$ MBAN networks, even when there is a primary user (e.g. $6$ MHz amateur radio signal) to be protected.

In summary, the joint proposal, which proposes to allocate a contiguous $40$ MHz spectrum for in-healthcare-facility applications with $10$ MHz for out-of-healthcare-facility use, can support MBAN operations in dense deployment scenarios with frequency separation requirements to protect primary users.

### E. Transmission Power Limit

The MBAN transmission limit should be chosen to enable MBAN applications to achieve medical-grade link performance while minimizing possible interference to other in-band users. Link budget analysis is presented to demonstrate that the proposed maximum radiated power limits are sufficient to meet the performance requirements of typical in-hospital and home MBAN applications.

Three typical low-power short-range radios, including IEEE 802.15.4 DSSS + O-QPSK with

![Fig. 2. Coexistence performance with 1 Mbps PHY data rate](image1)

![Fig. 3. Coexistence performance with 2 Mbps PHY data rate](image2)

In [5], a frequency hopping based scheme was studied and the conclusion was that approximately $18$ MHz is required to support the co-existence of ten heavily loaded and mobile BSNs with acceptable packet loss probability. Here, we consider the performance of a CSMA based protocol (IEEE 802.15.4 CSMA/CA scheme for non-beacon mode) under a wireless ECG MBAN scenario. The ECG MBAN network studied here has a star topology and consists of a Multi-lead ECG sensor, a SpO2 sensor, and a hub device. The assumed traffic patterns are:

- ECG data: $96$ Kbps raw data, $1$ packet per $8$ms, $111$ bytes/packet
- SpO2 data: $1.76$ Kbps raw data, $1$ packet per $0.5$ms, $125$ bytes/packet
- Command data (from the hub to sensors): one packet per $30$s, $133$ bytes/packet

Some parameters used in the analysis are:

- IEEE 802.15.4 packet structure, 15-byte PHY/MAC overhead
- Maximum back-off number $N_{\text{bo}} = 5$
- Contention window size: fixed to $127$
- Error free transmission (reasonable assumption considering low bit error rate requirement)
- Two raw PHY data rates studied: $1$ Mbps and $2$ Mbps
- No ACK to simplify the analysis

The analysis is based on the method presented in [10]. Here we assume that a packet loss rate, which is caused only by collisions among multiple MBAN devices, of no larger than $10^{-3}$ is acceptable for MBAN applications. This is a reasonable performance criteria considering the importance of medical data in high acuity applications.

Fig. 2 demonstrates that if the physical layer data rate is $1$ Mbps, then one channel can support only one MBAN network. If two MBAN networks stay at a same channel, the packet loss rate of a hub device or SpO2 device would exceed $10^{-3}$. Therefore, to support ten co-located ECG MBAN networks, $10$ non-overlapping channels are required. For the $2$ Mbps PHY rate case, Fig. 3 shows one channel can support at most two MBAN networks with packet loss rate less than $10^{-5}$. Thus, $5$ non-overlapping channels are required to support $10$ co-located MBANs.

![Raw data rate: 1 Mbps](image3)

![Raw data rate: 2 Mbps](image4)

Link budget analysis is presented to demonstrate that the proposed maximum radiated power limits are sufficient to meet the performance requirements of typical in-hospital and home MBAN applications.

![Fig. 2](image5)

![Fig. 3](image6)
a 20-dB bandwidth of 2.6 MHz and 250 Kbps data rate, O-QPSK with a 20-dB bandwidth of 2.6 MHz and 2 Mbps data rate, and FSK modulation with modulation index of 0.5, 1 MHz bandwidth and 1 Mbps data rate, are considered as MBAN examples in the link budget analysis.

1) Link budget Analysis for In-hospital Monitoring Applications: One typical in-hospital MBAN usage is for communications between an on-body MBAN sensor device to an proximate off-body MBAN hub device (e.g. bedside patient monitor) within a same room. In this case, the required communication range of the MBAN radio link is set to 3 meters, which should be sufficient to cover a typical patient room. Table IV summarizes the link budget analysis results with the following assumptions: AWGN channel model with free-space path loss, 3 meter communication range, 0 dBm TX and RX antenna gains, central frequency of 2400 MHz (worst case), 10 dB receiver noise figure and 6 dB implementation loss. In all the three cases, more than 35 dB link margins are achieved. These high link margins can be used to counteract the fading effects introduced by the presence of the human body and imperfect antenna orientation/matching. In reality, proximity to the human body introduces shadowing of signals from the opposite side of body-worn MBAN antenna and also influences the tuning and radiated efficiency of the MBAN antenna. For example, the channel fading statistics of the 2360 – 2483.5 MHz frequency range were calculated in [6] using the CM4 (on-body to external device) channel models developed by IEEE 802.15.6. It was shown that the 99%-tile fade depth at 3 meters is 19 dB. The link budgets after considering this 99% fade depth are are 25.1 dB for the IEEE 802.15.4 solution, 16.9 dB for the O-QPSK, and 18 dB FSK cases. The high link margin would enable MBAN radios to tolerate moderate interference. Moreover, high link margins imply that the proposed 0 dBm transmission power limit is sufficient to support possibly higher data rate services in future MBAN applications which may require higher SNR.

Another typical in-hospital MBAN usage is for on-body communications (e.g. communications between an on-body sensor device and an on-body portable monitor) and a typical communication range of the MBAN radio link is 1 meter in this case. To model realistic on-body channels, the two CM3 (on-body) channel models, which were developed in the IEEE 802.15.6 based on extensive measurements conducted by different organizations [7], are adopted. The first model was proposed by NICT (Japan) and the pathloss can be calculated as

\[ PL(d)[dB] = a \log_{10}(d) + b + N, \]

where \( a = 6.6 \text{ dB} \), \( b = 36.1 \text{ dB} \), \( N \) is a normally distributed variable with zero mean and standard deviation of 3.8 dB and \( d \) is the TX-RX distance in mm. The second model was proposed by IMEC (Netherlands) and the pathloss formula is

\[ PL(d)[dB] = -10 \log_{10}(P_0 e^{-m d} + P_1) + N, \]

where \( P_0 = -25.8 \text{ dB} \), \( m_0 = 2.0 \text{ dB/cm} \), \( P_1 = -71.3 \text{ dB} \), \( N \) is a normally distributed variable with zero mean and standard deviation of 3.6 dB and \( d \) is the TX-RX distance in cm. With a TX-RX distance of 1 meter, the pathloss (in dB) generated with the NICT model is a normally distributed random variable with mean of 55.9 dB and standard deviation of 7.3 dB (i.e., with 99% probability an on-body channel with a TX-RX distance of 1 meter has a pathloss value lower than 64.6 dB) while the pathloss generated with the IMEC model is a normally distributed random variable with mean of 71.3 dB and standard deviation of 3.6 dB (that i.e., with 99% probability an on-body channel with a TX-RX distance of 1 meter has a pathloss value lower than 79.6 dB). In the analysis, 79.6 dB is used as pathloss. It is worth noting that 79.6 dB is a conservative choice that covers most of the channel measurement results in the literature, for example see [8]. Table V shows that a 0 dBm transmission power can provide a 14.1 dB link margin in the DSSS O-QPSK case, 5.9 dB margin for O-QPSK, and 7 dB margin for FSK cases for the on-body portable monitor use case.

![Table IV](image)

**TABLE IV**

**Link Budget Analysis for Bedside Monitor Case**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DSSS O-QPSK</th>
<th>O-QPSK</th>
<th>FSK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Information data rate (( R_b ) [Mbps])</td>
<td>0.25</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Average TX power (( P_T ) [dBm])</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>TX antenna gain (( G_T ) [dB])</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Center frequency (( f_c ) [MHz])</td>
<td>2400</td>
<td>2400</td>
<td>2400</td>
</tr>
<tr>
<td>Path loss at 3 meter, ( L_1 = 20 \log_{10}(4\pi f_c d/(3 \times 10^8)) ) [dB]</td>
<td>49.6</td>
<td>49.6</td>
<td>49.6</td>
</tr>
<tr>
<td>RX antenna gain (( G_R ) [dB])</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>RX power (( P_R = P_T + G_R + G_T - L_1 ))</td>
<td>-49.6</td>
<td>-49.6</td>
<td>-49.6</td>
</tr>
<tr>
<td>Average noise power (( N = -174 + 10 \log_{10}(BW) )) [dBm]</td>
<td>-109.9</td>
<td>-109.9</td>
<td>-114</td>
</tr>
<tr>
<td>RX noise figure referred to the antenna terminal (( N_F ) [dB])</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Total noise power (( P_N = N + N_F ) [dBm])</td>
<td>-99.9</td>
<td>-99.9</td>
<td>-104</td>
</tr>
<tr>
<td>Required Minimum SNR (( S ) [dB])</td>
<td>0.2</td>
<td>8.4</td>
<td>11.4</td>
</tr>
<tr>
<td>Implementation loss (( L ) [dB])</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Link Margin (( M = P_T - P_R - S - L )) [dB]</td>
<td>44.1</td>
<td>45.9</td>
<td>37</td>
</tr>
</tbody>
</table>

A similar analysis could be performed for MBANs with a bandwidth less than 1 MHz. It should be noted that both the maximum radiated power and the noise power are proportional
to the bandwidth in that case and the link margin results will be the same as the above analysis. In summary, the proposed emission power limit for the 2360-2390 MHz band is sufficient to meet link robustness requirements of MBAN in-hospital applications. Moreover, such power limit is low enough to significantly alleviate possible in-band interference to incumbent users and facilitate frequency reuse inside healthcare facilities to support large-scale deployment.

2) Link budget Analysis for Home Monitoring Applications: In a home monitoring case, a long communication range is highly desirable to provide greater mobility to MBAN users within their homes and minimize the required base installation cost. In this scenario, a communication range of 10 meters is a reasonable design objective to allow single MBAN hub device to cover multiple rooms. Therefore, a higher emission power limit for the location independent sub-band is preferred from home healthcare perspective. Also, a higher power limit is needed to cope with an adverse event that may cause a patient to fall on the transmitter, causing significant signal attenuation. Moreover, a higher radiated power is helpful to counteract possible interference introduced by the OOBE from adjacent band users, e.g. ubiquitous high-power 2.4 GHz Wi-Fi devices.

Increasing the transmission power to 13 dBm would provide sufficient link margin for home monitoring applications, as demonstrated by the link budget analysis in Table VI. In this link budget analysis, the following assumptions are used: AWGN channel model, 10 meter communication range, 0 dBi TX and RX antenna gains, free-space path loss, central frequency of 2400 MHz (worst case), 10 dB noise figure and 6 dB implementation loss. Also a 30 dB loss is included to represent the human body blockage loss, which could happen when a patient falls on MBAN devices in an adverse event, and another 20 dB loss is included to cover extra attenuation introduced by barriers (e.g. walls and doors). Some barrier attenuation values can be found in the online document [9]. 20 dB is a practical choice to cover typical use cases. Since most of the home monitoring applications that require long ranges are usually low-rate applications, we assume the data rate is 31.25 kbps. Two typical modulation schemes are studied, O-QPSK and FSK with modulation index 0.5. It should be noted that the analysis does not include excess noise from adjacent band devices. In the both cases, more than 4 dB link margins are achieved. Therefore, with the proposed 13 dBm emission power limit in the 2390-2400 MHz, MBAN radios can provide reasonable coverage, link performance, and data rates for home monitoring applications and overcome out of band emission inference from nearby adjacent band devices.

IV. CONCLUSIONS

MBAN is a promising technology that has great potential to revolutionize health care delivery and convey ubiquitous monitoring services to patients. Due to its significant economic and social benefits, U.S., Europe, and China have already initiated regulation proceedings to address the spectrum needs of MBAN services. This paper studies a joint proposal developed by Philips Healthcare, GE Healthcare, and AFTRCC, which was submitted to the FCC for consideration. Radio requirements of in-hospital, home MBAN, and emergency ambulance applications are identified and used as guidelines to develop the proposed ruling parameters, including frequency band selection, emission bandwidth limit, amount of total spectrum, and transmission power limit. It is demonstrated by technical analysis and simulation results that the proposed scheme can address diverse MBAN needs while facilitating harmonized coexistence among different MBAN systems, protecting primary users, and allowing low-power low-cost MBAN implementation.

TABLE VI

<table>
<thead>
<tr>
<th>Parameter</th>
<th>O-QPSK</th>
<th>FSK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Information data rate ($R_d$) [kbps]</td>
<td>31.25</td>
<td>31.25</td>
</tr>
<tr>
<td>Average TX power ($P_T$) [dBm]</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>RX antenna gain ($G_{RX}$) [dBi]</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Center frequency ($f_c$) [MHz]</td>
<td>2400</td>
<td>2400</td>
</tr>
<tr>
<td>Path loss at 10 meter, $L_1 = 20\log_{10}\left[4\pi f_d d / (3 \times 10^8)\right]$ [dB]</td>
<td>60.1</td>
<td>60.1</td>
</tr>
<tr>
<td>Human body blockage loss ($L_{HB}$) [dB]</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>building attenuation ($L_A$) [dB]</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>RX antenna gain ($G_{RX}$) [dBi]</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>RX power ($P_R = P_T + G_T + G_R - L_1 - L_2 - L_3$)</td>
<td>-97.1</td>
<td>-97.1</td>
</tr>
<tr>
<td>Average noise power ($N = -174 + 10 \times \log_{10}(BW)$) [dBm]</td>
<td>-128</td>
<td>-129.1</td>
</tr>
<tr>
<td>RX noise figure referred to the antenna terminal ($N_{RF}$) [dB]</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Total noise power ($P_N = N + N_{RF}$) [dBm]</td>
<td>-118</td>
<td>-119.1</td>
</tr>
<tr>
<td>Required Minimum SNR ($S$) [dB]</td>
<td>8.4</td>
<td>11.4</td>
</tr>
<tr>
<td>Implementation loss ($I$) [dB]</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Link Margin ($M = P_R - P_N - S - I$), [dB]</td>
<td>6.5</td>
<td>4.6</td>
</tr>
</tbody>
</table>

REFERENCES