Analysis of the Performance of IEEE 802.15.4 for Medical Sensor Body Area Networking

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Abstract—**For the first time, this paper presents an analysis of the performance of the IEEE 802.15.4 low power, low data rate wireless standard in relation to medical sensor body area networks. This is an emerging application of wireless sensor networking with particular performance constraints, including power consumption, physical size, robustness and security. In the analysis presented, the star network configuration of the 802.15.4 standard at 2.4 GHz was considered for a body area network consisting of a wearable or desk mounted coordinator outside of the body with up to 10 body implanted sensors. The main consideration in this work was the long-term power consumption of devices, since for practical reasons, implanted medical devices and sensors must function for at least 10 to 15 years without battery replacement. The results show that when properly configured, 802.15.4 can be used for medical sensor networking when configured in non-beacon mode with low data rate asymmetric traffic. Beacon mode may also be used, but with more severe restrictions on data rate and crystal tolerance.**

Keywords- wireless body area network; wireless sensor network; 802.15.4; power consumption

I. INTRODUCTION

The last few years have seen a significant increase in research study directed at ad-hoc wireless networks and wireless sensor networks. Terms such as pervasive computing, and smart spaces are being used to describe the future of computing and communications [1]. These concepts allude to our personal and business domains being densely populated with miniature sensors, which are constantly monitoring the environment and reporting the data to each other or to some central base station. Likewise, such sensors when equipped with sufficient processing power may be configured in a grid fashion – so-called 'microgrid' computing. However, the range of applications is even wider than this. One area of increasing interest is the adaptation of this technology to operate in and around the human body, connected via a wireless body area network (WBAN). There are many potential applications that will be based on WBAN technology, including medical sensing and control, wearable computing, location awareness and identification.

However, in this paper we consider only a WBAN formed from implanted medical sensors. Such devices are being and will be used to monitor and control medical conditions such as coronary care, diabetes, optical aids, bladder control, muscle stimulants etc. The advantages of networking medical sensors will be to spread the memory load, processing load, and improving the access to data. One of the crucial areas in implanting sensors is the battery lifetime. Batteries cannot be replaced or recharged without employing a serious medical procedure so it is expected that battery powered medical devices placed inside the body should last for ten to fifteen years. Networking places an extra demand on the transceiver and processing operations of the sensor resulting in increased power consumption. A network placed under a hard energy constraint must therefore ensure that all sensors are powered down or in sleep mode when not in active use, yet still provide communications without significant latency when required.

The IEEE 802.15.4 standard was specifically devised to support low power, low data rate networks where latency and bit rate are not so critical, and is a response to the growth in this area [2]. This paper addresses whether or not 802.15.4 can be applied to a WBAN where each sensor must operate for fifteen years without battery replacement or recharging. An 802.15.4 WBAN would go beyond the current state of the art where a 403 MHz medical implant communications service (MICS) [3] is used for implant to controller, point-to-point communication without networking support. The paper focuses on an analysis of the 802.15.4 standard configured as a star network where the coordinating device is external to the body, e.g., incorporated in a PDA, mobile telephone or in bedside monitoring station. The approach taken was to devise generic equations to model the average power consumption of a sensor in the range of modes available to the standard. These equations were then used to analyze the lifetime performance of 802.15.4 while changing important parameters such as data frame size, upload rate and crystal tolerance.

The next section introduces the relevant characteristics of the 802.15.4 standard. Section III sets out the main assumptions used in developing the analysis equations, including the transceiver and microcontroller characteristics used. An analysis of the Carrier Sense Multiple Access / Collision Avoidance (CSMA/CA) protocol and average number of back-offs in a given network is presented in section IV. Section V presents the network scenarios available and the power equations upon which the power analyses are based. The results are presented and discussed in section VI with the conclusions in section VII.

TABLE I. 802.15.4 PHYSICAL PARAMETERS

Frequency Band	**Bit Rate**	**Symbol Rate**	**DSSS Spreading Parameters**	
			Modulation	***Chip rate***
868-868.6 MHz	20 kb/s	20 ks/s	BPSK	300 kc/s
902-928 MHz	40 kb/s	40 ks/s	BPSK	600 kc/s
2.4-2.4835 GHz	250 kb/s	62.5 ks/s	O-QPSK	2 Mc/s

II. 802.15.4 OVERVIEW

A. Physical Layer

There are two physical layer variants in 802.15.4: 868/915MHz and 2.4 GHz (Table I). The standard defines the 868 MHz band as a single channel with a data rate of 20 kbps, the 915 MHz band as a single 40 kbps channel, while the 2.4 GHz band is divided into 16 channels each with a data rate of 250 kbps. For convenience, this work considers only 2.4 GHz.

B. Medium Access Control Layer

Two topologies are supported by 802.15.4: star and peer-to-peer, but in this work only star networks were considered. The main advantage of using a star network for medical sensor applications is that an external coordinator can be used with access to rechargeable power supply [4]. With the star topology there are two communication methods: beacon mode and non-beacon mode. In beacon mode, communication is controlled by the network coordinator, which transmits regular beacons for device synchronization and network association control. The network coordinator defines the start and end of a superframe by transmitting a periodic beacon. The length of the beacon period and hence the duty cycle of the system can be defined by the user between certain limits as specified in the standard [2]. The advantage of this mode is that the coordinator can communicate at will with the nodes. The disadvantage is that the nodes must wake up to receive the beacon.

In non-beacon mode a network node can send data to the coordinator at will using CSMA/CA if required. However, to receive data from the coordinator the node must power up and poll the coordinator. To achieve the required node lifetime the polling frequency must be pre-determined by power reserves and expected data quantity. The advantage of non-beacon mode is that the node's receiver does not have to regularly power-up to receive the beacon. The disadvantage is that the coordinator cannot communicate at will with the node but must wait to be invited by the node to communicate.

In beacon mode, the superframe may consist of both an active and inactive period (Figure 1)[2]. The active portion of the superframe, which contains 16 equally spaced slots, is composed of three parts: a beacon, a contention access period (CAP), and a contention free period (CFP). The beacon is transmitted without the use of CSMA at the start of slot 0 and the CAP commences immediately after the beacon. The coordinator only interacts with nodes during the active period and may sleep during the inactive period. There is a guaranteed timeslot (GTS) option in 802.15.4 to allow lower latency operation. There are a maximum of 7 of the 16 available timeslots that can be allocated to nodes, singly or combined.

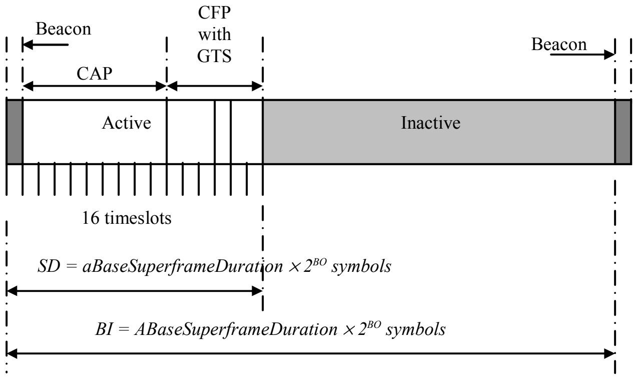

Figure 1. IEE 802.15.4 superframe structure.

When a node is allocated a timeslot it may only transmit data during that timeslot. GTS nodes must listen to the beacon to synchronize prior to communication within its allocated timeslot(s). The relative size of each of the active and inactive periods is determined by the values of the *macBeaconOrder* (*BO*) and the *macSuperframeOrder* (*SO*) and the overall superframe length (or *Beacon Interval*, *BI*) and active superframe duration (*ASD*) are calculated as follows [2]:

$$BI = (aBaseSlotDuration \times aNumSuperframeSlots \times 2^{BO})\ symbols$$

$$where \quad 0 \le BO \le 14,\ aBaseSlotDuration = 60\ symbols$$

$$and\ \ aNumSuperframeSlots\ (slots\ in\ a\ superframe) = 16$$

$$ASD = (\ aBaseSlotDuration \times aNumSuperframeSlots \times 2^{SO})\ symbols$$

$$where \qquad 0 \le SO \le BO \le 14$$

III. ANALYSIS ASSUMPTIONS

A. Sensor Specification

There are a variety of sensors that are currently being used or are planned for use in medical device body area networking. The particular characteristics of these devices can have a significant impact on the communication network in terms of bit rate, latency and quality of service. Table II describes the communications and networking requirements for a typical sensor and coordinating device. The highly asymmetric nature of implanted sensors lends itself to a power-constrained network. If the main data traffic is from the sensor to the coordinating device then, the receiver will be off most of the time. This will be borne out in the analysis.

In this analysis, the star coordinator was assumed to be an externally worn device that can gather data and forward it to the appropriate databases and systems via other networks. Since it is externally worn it was assumed to have a rechargeable battery and thus was not subject to the same hard energy constraint as the internal sensors. Other characteristics such as computing power, memory storage capacity are not discussed in this paper. For example, a personal digital assistant, mobile telephone or other wearable computing system could easily incorporate an 802.15.4 interface. Other external coordinating devices could be nearby fixed mains powered equipment such as hospital bedside monitoring stations or home telemedicine systems.

TABLE II. TYP. MEDICAL SENSOR CHARACTERISTICS

	Communication Needs	**Networking Needs**
Sensor e.g., insulin sensor Cranial pressure	Hourly uploads to controller device Emergency alert Battery status warning Simplex / highly asymmetric Defined data path to sink device	Range device >3 m / can communicate with bedside monitor or hospital WLAN automatic network associate / disassociate STAR or Peer to peer ultra-low mobility
Coordinating Device e.g PDA, Bedside monitor	Listen to all network devices Excess memory store for sensors, as required Can interrogate network devices (i.e. full or ½ duplex) Unknown and time-varying data path	Access to 2G, 2.5G, 3G, 802.11, bluetooth Provides a link to download data from body-centric network to main database automatic network associate / disassociate Defaults to controller in STAR configuration High mobility

B. *Hardware assumptions*

It was necessary to specify typical hardware parameters for the nodes in the medical sensor system. The sensors require an 802.15.4 radio transceiver. We assumed that the transceiver characteristics (Table III) were similar to a commercially available 2.4 GHz chipset from Chipcon, the CC2420 [5]. Likewise, the characteristics of the Motorola 8-bit microcontroller MC9508RE8 [6] were used as typical microcontroller operating parameters: with a supply voltage of 2.0 V, the active current with a 2 MHz clock was 4.5µA, while the standby current was 700 nA. For the purposes of this study we assumed that a Lithium coin battery was used in each node with a capacity of 560 mAh at 3.0 V.

TABLE III. TRANSCEIVER PARAMETERS (CHIPCON CC2420)

Voltage supply		1.8 V
Receiver current	(active)	20 mA
	(standby)	1 µA
Transmitter and receiver start up time incl. voltage reg, oscillator and PLL lock		1.4 ms
Transmitter current	–24 dBm	8.5 mA
	–15 dBm	9.9 mA
	–10 dBm	11.0 mA
	–5 dBm	14.0 mA
	0 dBm	17.4 mA

C. *Implanted Sensor Link Budget*

To accurately determine the transmitter current for a body implanted medical sensor it was necessary to calculate the link budget. A body implanted RF source will suffer from a number of impairments including restricted (electrically small) antenna size, absorptive losses in tissue and losses due to reflection from the skin-air and other tissue interfaces [7][8]. Assuming a maximum 3 m range (free space path loss of 49.7 dB) and standard –85.0 dBm sensitivity, antenna and tissue losses of 29.7 dB (for an implant 20 mm below the surface), a 0 dBm 2.45 GHz transmitter will operate with a 5.6 dB margin.

D. *Description of network*

For most of the results shown, the star network consisted of the coordinator and 10 body implanted sensors. However, the CSMA/CA performance will be shown for much larger networks. The analysis was for a steady state network, as it did not take into consideration association or disassociation of sensors to or from the network.

IV. AVERAGE TRANSMISSION TIME WITH CSMA/CA

In IEEE 802.15.4, each node can employ a CSMA/CA protocol to avoid power-consuming collisions when multiple simultaneous transmissions may occur. The CSMA/CA protocol used in 802.15.4 can be slotted or unslotted. If a beacon is being used the slotted CSMA/CA is employed in the CAP part of the superframe. If a non-beacon network is used, or if the beacon is not detected, then unslotted CSMA/CA is employed. In slotted CSMA/CA the start of the first back-off period of each node is aligned with the start of the beacon. In unslotted CSMA/CA there is no link in time between the back-off periods of any node.

There are three variables maintained by each node for each transmission attempt: *NB*, *CW* and *BE*. *NB* is the number of back-offs permitted before declaring channel access failure and can be set between 0 and 5. *CW* is the contention window length and is only used in slotted CSMA/CA. This defines the number of back-off periods that need to be clear of channel activity before the transmission can commence. *CW* is set to 2 before each transmission attempt and reset to 2 each time the channel is busy. *BE* is the back-off exponent. The MAC sub layer shall delay for a random number of complete back-off periods in the range $0 \text{ to } 2^{BE}-1$. *BE* has a range from 0 to 5, with the minimum initial permitted value between 0 and 3 inclusive. The default minimum value is 3. If the channel is assessed to be busy using the Clear Channel Assessment (*CCA*), both *NB* and *BE* are incremented by 1. *BE* cannot be greater than 5 and the number of iterations is limited by *NB*, also with a maximum of 5. If *BE* is set to 0 CSMA/CA is switched off.

A. *Back-off periods*

The number of back-off periods is chosen randomly with equal probability, *x*, from the range, $0 \text{ to } 2^{BE}-1$ as given in Table IV. The back-off period in the standard is given as 20 symbols. The average number of back-off periods for each range is:

$$\sum_{i=0}^{i=n} x_i i \tag{1}$$

Substituting in the probability, the average back-off symbols in each range is then given by:

$$20 \times \sum_{i=0}^{2^{BE}-1} 2^{-BE} i \tag{2}$$

B. *Calculation of average transmission time*

We can establish an expression for the average transmission time in terms of the number of back-off periods, message time, and propagation time. There are up to five back-off periods possible before a transmission failure occurs. Table IV shows the average number of back-off periods for each value of *BE*.

TABLE IV. IEEE 802.15.4 CSMA/CA AVERAGE BACK-OFF

BE	Back-off intervals 0 to ($2^{BE}-1$)	Ave. no of back-off periods	Ave. back-off (symbols)
0	CSMA/CA OFF	n/a	n/a
1	0 to 1	0.5	10
2	0 to 3	1.5	30
3	0 to 7	3.5	70
4	0 to 15	7.5	150
5	0 to 31	15.5	310

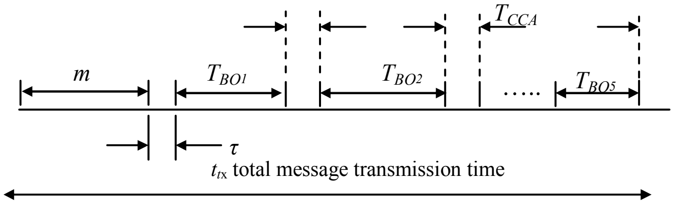

Figure 2. Calculation of message transmission time, CSMA/CA.

The total transmission time can be given as:

$$t_{tx} = m + \tau + RT_{CCA} + f\left(R, T_{BO(a)}\right) \tag{3}$$

where m is the message length in time, τ is the propagation time, R is the average number of back-of intervals, $T_{BO(a)}$ is the average back-off time for each back-off interval, T_{CCA} is the clear channel assessment (CCA) time and $f\left(R, T_{BO(a)}\right)$ is the total average back-off time as a function of R and $T_{BO(a)}$.

To find the value of R we derive an analysis a based on a model described by Schartz [9]. The overall back-off time can be comprised of up to 5 back-off intervals plus associated CCA periods (depending on the value of *NB*). Depending on the initial value of *BE* the average length of each back-off is given in Table IV. The probability of a clear channel after the first back-off interval is p. Therefore, with up to five back-off intervals possible the probability, s, of transmission is:

$$s = \sum_{k=1}^{k=5} p(1-p)^{k-1} \tag{4}$$

Then the average number of back-offs, R:

$$R = \sum_{k=1}^{k=5} kp(1-p)^{k-1} \tag{5}$$

Expanding (5) for a possible 5 back-off periods gives:

$$R = 15p - 40p^2 + 45p^3 - 24p^4 + 5p^5 \tag{6}$$

Now, finding the probability p that a channel is clear at the end of a back-off interval we consider n sensors in the network. The probability that the channel is clear in a CCA period is then:

$$p = (1-q)^{n-1} \tag{7}$$

where q is the probability that a sensor transmits in a CCA period. If we know the average transmission time of a node in its transmission period (defined by the designer) then the probability of a sensor transmitting at any time is:

$$q = \frac{\textit{average channel occupation time in a fixed time period}}{\textit{fixed time period}} \tag{8}$$

q is calculated for beacon and non beacon networks using the equations in section IV. For a given number of nodes we can determine p and then R. In (3), the function $f\left(R, T_{BO(a)}\right)$ is a function of R and the average of each back-off interval. However, as each back-off interval has a unique average length the algorithm shown in Figure 3 is required to calculate $f\left(R, T_{BO(a)}\right)$ for a given network size. For example, if the average number of back-offs R was calculated to be 2.5, then average back-off time is:

$$f(R, T_{BO}) = (1 \times T_{BO1}) + (1 \times T_{BO2}) + (0.5 \times T_{BO3}) \tag{9}$$

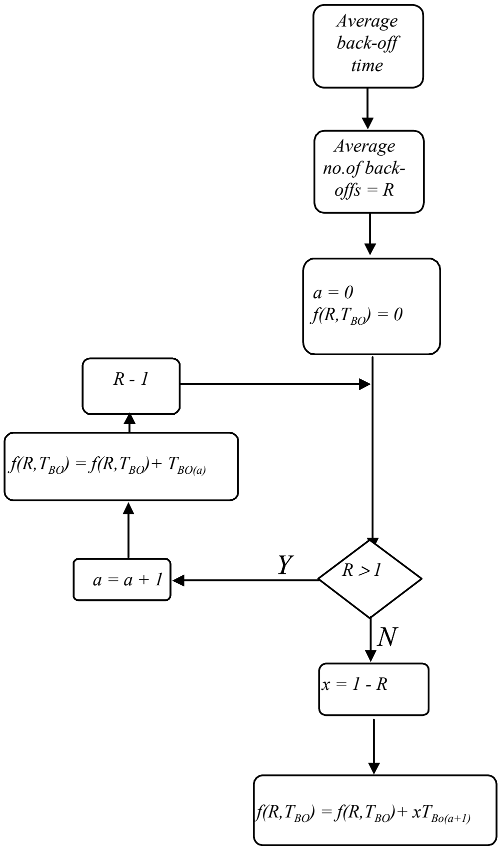

Figure 3. The Average Back-off Algorithm.

V. NETWORK SCENARIOS AND POWER ANALYSIS

The data transfer mechanisms specified in 802.15.4 were used to derive a set of equations that express the power consumption for network scenarios. The equations were then used with the assumptions given in section III to investigate the power consumption and, in turn, the lifetime of sensors in a 802.15.4 medical sensor body area network.

A. *Sensor power consumption with beacon reception*

The sensor devices within a beacon network have to wake up to receive the beacon from the coordinator. Depending on crystal tolerances, the receiver in each of the sensors must be on long enough to ensure that the beacon frame is not missed. As receiver ON time is critical for power consumption the following analysis uses the crystal tolerance to calculate the required duty cycle for a sensor receiver for each beacon frame. For optimum power saving the beacon interval is assumed to be as long as possible, $BO = 14$. From (1),

$$BI = (60 \times 16 \times 2^{14}) \times T_S \tag{10}$$

where T_S = symbol duration. Therefore, the transmit duty cycle is:

$$Beacon\ duty\,cycle = \frac{frame\,duration}{BI} \tag{11}$$

We must take into account the time-base tolerance of the transmitter and the receiver when defining the duty cycle for the receiver. Therefore, the receiver must be on for the period of beacon frame plus the transmitter and receiver tolerances:

$$\text{Receiver ON time} = (2\varepsilon_{TX} + 2\varepsilon_{RX})BI + T_{BF} \tag{12}$$

Where, T_{BF} is the beacon frame time in s, and ε_{TX} and ε_{RX} are the transmitter and receiver timebase tolerances, respectively.

Including the transmitter and receiver warm-up times the receiver ON time is:

$$= (2\varepsilon_{TX} + 2\varepsilon_{RX})BI + T_{BF} + T_{TX\_wu} + T_{RX\_wu} \tag{13}$$

The average beacon duty cycle (DC) of the receiver is:

$$DC = \frac{(2\varepsilon_{TX} + 2\varepsilon_{RX})BI + T_{BF} + T_{twu} + T_{rwu}}{BI} \tag{14}$$

B. *Data Transfer Mechanisms*

In the beacon star network the node wishing to send data to the coordinator must listen for a beacon. If it has a GTS assigned it will send the data frame within the appropriate timeslot (assumption that data frame can be sent within a single timeslot). If no GTS is assigned the sensor transmits its data frame in the CAP, using the CSMA/CA protocol, if enabled. After receiving the data frame the coordinator sends back an acknowledgement frame to the sensor device, which completes the procedure.

When the coordinator wishes to send data to the sensor it sets a flag in the beacon frame indicating that a message is pending for a particular sensor. On receipt of this the appropriate sensor will transmit, using CSMA/CA, a data request MAC command frame, indicating to the coordinator that it may transmit the data. The coordinator will send an acknowledgment frame followed by the data frame. If it has a GTS assigned it will send the data frame within the appropriate timeslot. If no GTS is assigned the sensor transmits its data frame in the CAP, using the CSMA/CA protocol, if enabled. Upon receipt of the data frame the sensor will transmit an acknowledgment frame to the coordinator, ending the process. Using these message sequences, together with the frame durations, equations can be determined for the transmitter and receiver duty cycles in a given time period. Similarly the microcontroller timings can also be defined.

When communicating from the node to the coordinator, the node receiver is active for the beacon with a duty cycle (*DC*) as derived in (14). A receiver is active to receive acknowledgment from every data transfer. The duty cycle for this sequence depends on how often a data upload is required and is therefore application dependent. For the remainder of the time the receiver will be in standby mode which will have a much lower average current consumption but which is significant because of the long time involved. The average receiver power used in communication from sensor to coordinator is then given by:

$$P_{RX\_AV} = \left(DC + \frac{T_{AF} + (2+R)T_{RX\_wu} + 2RT_{CCA}}{T_U} \right) P_{RX} \tag{15}$$

where $T_{u,}$ is the upload period, P_{RX} is the active receiver power consumption, T_{AF} is the acknowledgement frame duration, T_{RX_wu} is the receiver warm-up time and T_{DF} is the average time duration of the data frame.

The following equation similarly describes the average power consumption of the sensor transmitter when responding with the data frame. Again, the frequency of the transmission depends on the sensor upload period, T_u.

$$P_{TX\_AV} = \left(\frac{T_{DF} + T_{TX\_wu}}{T_U} \right) P_{TX} \tag{16}$$

where T_{TX_wu} is the transmitter warm-up time.

When communication is from the coordinator to a node, the node receiver is active for the acknowledgment and the data frame, depending on the frequency of data downloads. After the acknowledgement frame an interframe space (IFS) is transmitted which is either 12 or 40 symbols depending on the length of the following data frame. If the data frame is less than or equal to 18 octets then the IFS is 12 symbols, otherwise it is 40 symbols. Equation (17) describes average receiver power consumption for a process using slotted CSMA/CA for the data frames.

$$P_{RX\_AV} = \left(\frac{T_{AF} + (2+R)T_{RX\_wu} + T_{IFS} + 2RT_{CCA} + f\left(R, T_{BO(a)}\right) + T_{DF}}{T_U} \right) P_{RX} \tag{17}$$

where $T_{D,}$ is the download period.

If GTS is selected the receiver is active for the full duration of the timeslot so (17) is adjusted accordingly giving:

$$P_{RX\_AV} = \left(\frac{T_{AF} + 3T_{RX\_wu} + T_{IFS} + yT_{GTS}}{T_D} \right) P_{RX} \qquad (18)$$

where, T_{GTS} is the time duration of a timeslot, and the value of y lies between 1 and 7 inclusive depending on the number of slots, if any, which have been combined to make the GTS. The node transmitter is powered up twice, once for the data request command frame, and then for the final acknowledgement frame, neither of which use CSMA/CA:

$$P_{TX\_AV} = \left(\frac{T_{DR} + T_{ACK} + 2T_{TX\_wu}}{T_D} \right) P_{TX} \qquad (19)$$

where T_{DR} is the duration of the data request command frame.

When the receiver is not required it can be placed in standby mode, which allows power savings. The following equation provides the average power consumption due to the receiver being powered down.

$$P_{RX\_AV\_STB} = \left[1 - \left(DC + \frac{T_{AF} + (2+R)T_{RX\_wu} + 2RT_{CCA}}{T_U} \right) + \left(\frac{T_{AF} + (2+R)T_{RX\_wu} + T_{IFS} + 2RT_{CCA} + f(R, T_{BO(a)}) + T_{DF}}{T_D} \right) \right] \times P_{RX\_STB} \qquad (20)$$

where P_{RX_STB} is receiver power used on standby

In a non-beacon enabled network data frames are transmitted using unslotted CSMA/CA. Average values for the back-off times and clear channel assessment (CCA) times are incorporated into the equations developed to calculate average power consumption.

When communication is from the node to the coordinator, the coordinator acknowledges successful reception of the data frame by sending back an acknowledgement frame. The average receiver power consumption is defined by (21), where the receiver is active for the CCA as part of the unslotted CSMA/CA process to transmit data. It also remains active to receive the acknowledgment frame.

$$P_{RX\_AV} = \left(\frac{RT_{CCA} + (R+1)T_{RX\_wu} + T_{AF}}{T_U} \right) \times P_{RX} \qquad (21)$$

Average transmitter power consumption is defined by equation (22):

$$P_{TX\_AV} = \left(\frac{T_{DF} + T_{TX\_wu}}{T_U} \right) P_{TX} \qquad (22)$$

When the coordinator wishes to send a data frame to a node in a non-beacon network, it must wait until it receives a data request from the sensor.

$$P_{RX\_AV} = \left(\frac{2RT_{CCA} + f(R, T_{BO(a)}) + T_{DF} + (R+1)T_{RX\_wu} + T_{AF}}{T_D} \right) P_{RX} \qquad (23)$$

$$P_{TX\_AV} = \left(\frac{T_{DR} + T_{ACK} + 2T_{TX\_wu}}{T_D} \right) P_{TX} \qquad (24)$$

The average standby power for a receiver in non-beacon mode is given by:

$$P_{RX\_AV\_STB} = \left[1 - \left(\frac{RT_{CCA} + (R+1)T_{RX\_wu} + T_{AF}}{T_U} \right) + \left(\frac{2RT_{CCA} + f(R, T_{BO(a)}) + T_{DF} + (R+1)T_{RX\_wu} + T_{AF}}{T_D} \right) \right] \times P_{RX\_STB} \qquad (25)$$

VI. RESULTS

The equations in section V were used to analyse the power consumption performance of an 802.15.4 network. Using a spreadsheet, all the variable parameters are included in the analysis, including the probability of collisions and the CSMA effect. The analysis allowed the identification of the key parameters affecting battery lifetime in this type of network. The results give us a picture of the viability of the 802.15.4 networks and the constraints under which they perform to give sufficient lifetime of greater than fifteen years for body implanted medical devices. All the results measuring lifetime assumed a battery of capacity 560 mAH.

A. Average Back-off

For a body area network of 10 implanted medical sensors the first objective was to see if the CSMA/CA protocol was necessary by working through the equations given in section IV. The probability of finding the channel free and therefore finding the average number of back-off periods *R*, was calculated and plotted against varying upload/download rates and packet sizes. Figs. 4 and 5 depict beacon and non-beacon network, respectively. Note that that the CSMA/CA protocol in 802.15.4 automatically backs-off initially when a transmission is imminent, therefore the minimum value of *R* is 1.

These results demonstrate, that with a small number of sensors that are effectively off most of the time, the probability of a channel being free is greater than 99 %. Therefore, for the relatively small number of sensors used in the WBAN networks explored here, it would be more economical to keep the CSMA/CA switched off. This is to ensure that the automatic initial back-off is avoided.

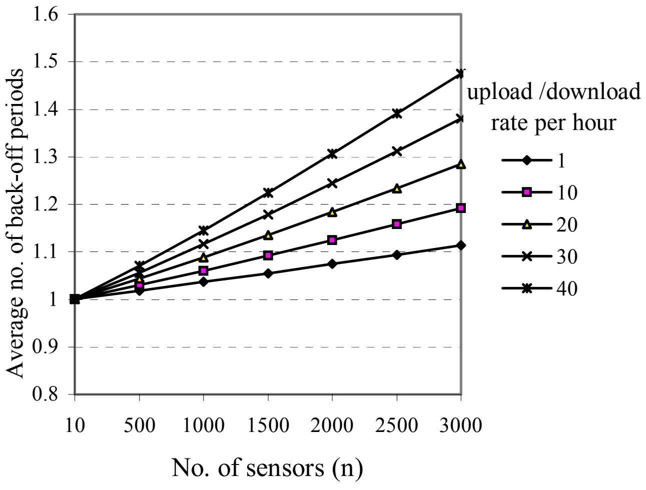

Figure 4. Effect of number of sensors on the average number of back-offs for a beacon network with a fixed data frame of 1000 bits.

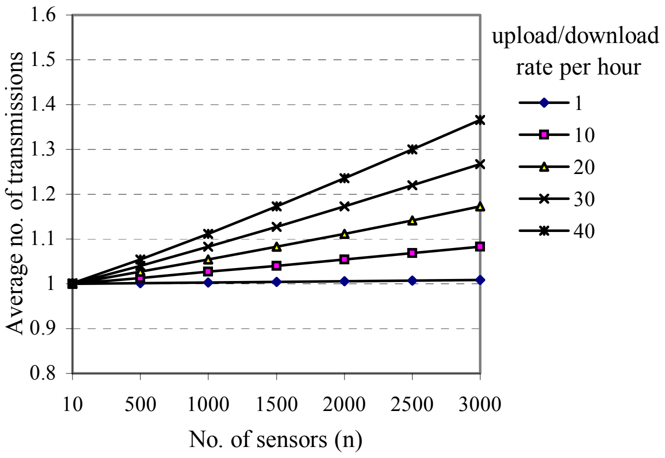

Figure 5. Effect of number of sensors on the average number of back-offs for a non-beacon network with a fixed data frame of 1000 bits.

B. *Node Lifetime in Beacon Networks*

In beacon networks each sensor must awake to receive the beacon from the coordinator, in all cases setting *BO* to 14 sets the beacon period to a maximum. However, it can be seen from Figure 6 that the effect of crystal tolerance on the lifetime of a 2.4 GHz sensor with symmetric communication is significant. The less stable the crystal the greater receiver on time required to capture the beacon. This impacts on power consumption, and therefore the lifetime of the sensor.

Figure 7 illustrates the effects of an asymmetric beacon network, which would be commonly found in sensor applications where most of the data moves from the sensor to the coordinator. The download rate is fixed at 1/hour and the lifetime of the network is measured against crystal tolerance for a range of upload rates. For a particular crystal tolerance, Figure 7 shows that a 15-year lifetime may only be obtained for very low upload rates. Although both symmetric and asymmetric beacon networks will provide a lifetime of 15 years it is under very limited data rate conditions and a tight tolerance crystal, which typically must be better than 25 ppm.

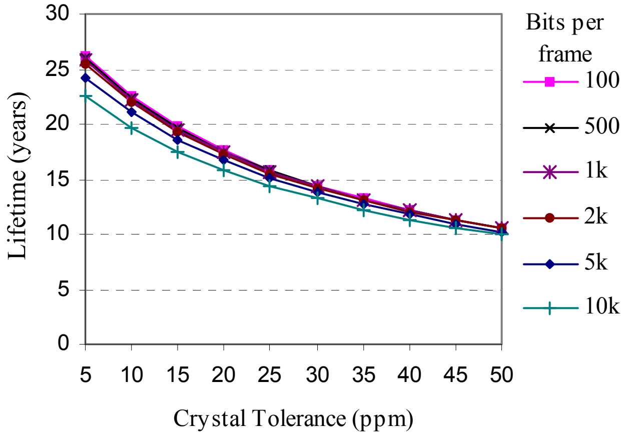

Figure 6. Effect of crystal tolerance on the lifetime of a sensor in a symmetric beacon network, with communication rate 1/hour.

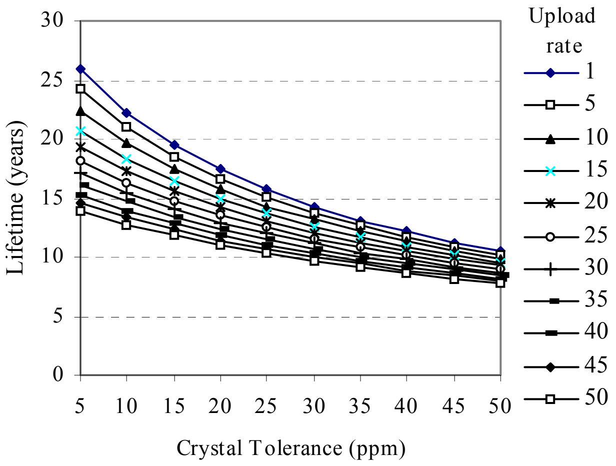

Figure 7. Effect of crystal tolerance on asymmetric sensor lifetime in a beacon network, with fixed packet size of 1000 bits and 1/hr download rate.

C. *GTS Option*

The main drawback of using GTS is that the receiver in the sensor remains on for the duration of the timeslot regardless of the size of the data packet. Figure 8 shows an example of timeslot versus lifetime for a sensor with a fixed data frame of 1000 bits, upload rate 5/hour, and download rate of 1/hour. The timeslot is adjusted by setting the value of *SO* between 0 and 14. For example, consider a GTS timeslot of 7.68 ms and a data frame of 4 ms, the lifetime of the beacon with GTS is 23.5 years as opposed to 24.2 years for the beacon without GTS.

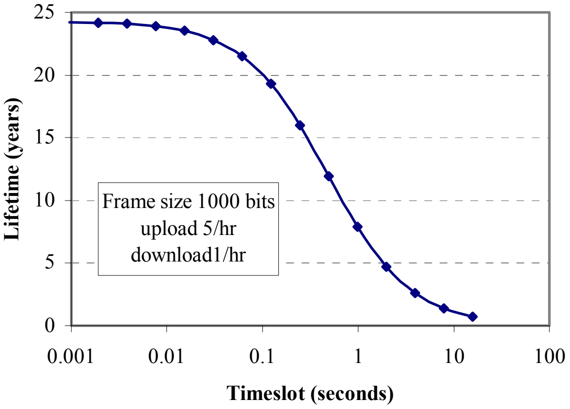

Figure 8. Effect of GTS timeslot on sensor lifetime.

D. *Non-Beacon Networks*

Figure 9 demonstrates the performance of a symmetric non-beacon sensor network in terms of lifetime versus data rate. Increasing the average data frame size and/or increasing the rate of communication between sensor and coordinator varies the data rate. Compared with the beacon network, the non-beacon network demonstrates a much better performance in terms of lifetime and available data rate.

Figure 10 shows that the maximum possible performance is obtained in non-beacon mode for asymmetric traffic. The lifetime is plotted against data frame size for a range of upload rates while fixing the download rate at 1/hour.

VII. CONCLUSION

In the first study of its kind, the low power performance of three modes of the IEEE 802.15.4 standard were evaluated in relation to a body area network of implanted medical sensors. The modes evaluated were beacon, beacon plus guaranteed timeslots and non-beacon, all at 2.4 GHz.

It was shown that beacon operation was only possible under very tight data rate restrictions and with a crystal tolerance of better than 25 ppm. Crystal tolerance larger than this resulted in a lifetime of less than fifteen years regardless of how minimal the data traffic. The overall bit rates possible are in the order of 10 bps for 2.4 GHz, although the nature of the traffic is bursty because nodes need to be powered down for most of the time. The beacon periods were also kept to a maximum (251 s) to reduce the number of times the receiver powers up.

The use of GTS was also tested and found to have a slight penalty over beacon operation because the receiver stays on for a full slot regardless of the size of the data packet. Therefore, if GTS is used slot size should be selected as close as possible to the packet size to minimise power wastage. As expected non-beacon operation provides the best performance, as the node receiver does not periodically power up to receive a beacon frame. Generally larger packets and a higher upload and download rate were possible for a lifetime of at least fifteen years. An overall bit rate of approx 20 bps was possible. It was also shown that with highly asymmetric data traffic, as is likely with some sensors, lifetime could be extended.

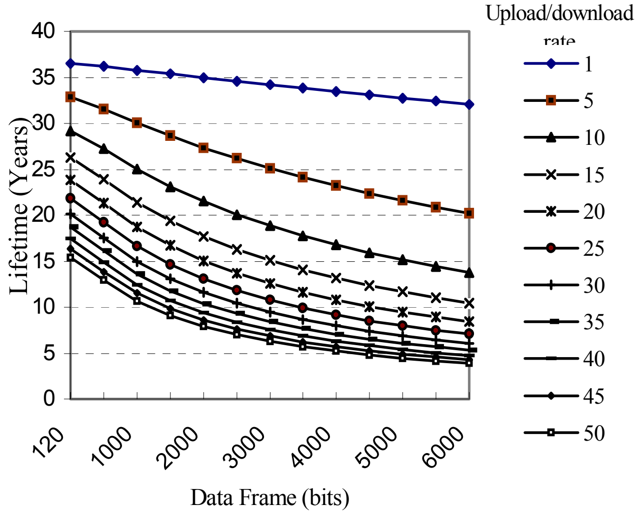

Figure 9. Lifetime of a symmetric sensor in a non-beacon network, with increasing frame size, and a range of upload download rates.

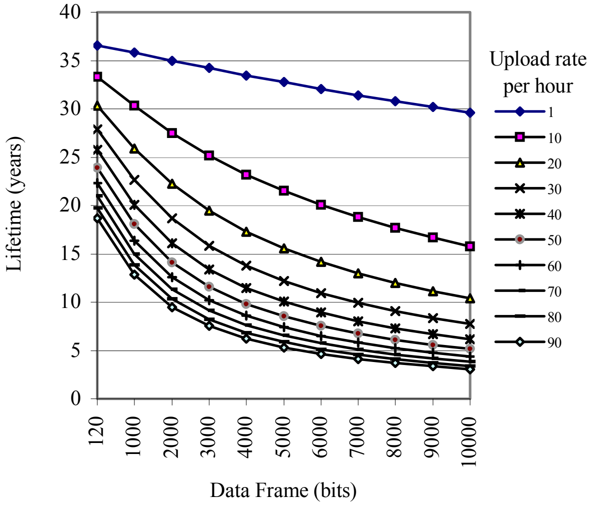

Figure 10. Lifetime of an asymmetric sensor in a non-beacon network over a range of upload rates. Download rate fixed at 1/hr.

An analysis of the CSMA/CA protocol was also presented. It was shown that for the limited number of sensors, say 10, that switching the CSMA/CA protocol off was the most power saving option as the average number of back-offs required due to a busy channel was tending to zero. The average number of back-offs required only becomes significant for a greatly increased number of sensors.

As a solution to the challenge of the body area network, the IEEE 802.15.4 standard would provide a limited answer in its non-beacon form. Sensors that do not have large amounts of data to transfer could be used, i.e., small packets of data several times per hour.

Future research will extend this work by considering 802.15.4 as the basis for a self-organising body area network for medical sensors.

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