An Energy Analysis of IEEE 802.15.6 Scheduled Access Modes

Christos Tachtatzis, Fabio Di Franco, David C. Tracey, Nick F. Timmons, Jim Morrison
WiSAR Lab
Letterkenny Institute of Technology
Port Road, Co. Donegal, Ireland
E-mail: {christos, fabio, david, nick, jim}@wisar.org

***Abstract*—Body Area Networks (BANs) are an emerging area of wireless personal communications. The IEEE 802.15.6 working group aims to develop a communications standard optimised for low power devices operating on, in or around the human body. IEEE 802.15.6 specifically targets low power medical application areas. The IEEE 802.15.6 draft defines two main channel access modes; contention based and contention free. This paper examines the energy lifetime performance of contention free access and in particular of periodic scheduled allocations.**

This paper presents an overview of the IEEE 802.15.6 and an analytical model for estimating the device lifetime. The analysis determines the maximum device lifetime for a range of scheduled allocations. It also shows that the higher the data rate of frame transfers the longer the device lifetime. Finally, the energy savings provided by block transfers are quantified and compared to immediately acknowledged alternatives.

I. Introduction

Developments in wireless communication technology have focussed on increasing the network throughput, but recently Wireless Sensor Networks (WSNs) and Personal Area Networks (PANs) shifted the focus to low power, low cost and short range operation. The importance of lifetime is even greater in Body Area Networks (BANs) where devices are expected to operate over a prolonged period e.g. implantable medical devices where battery replacement or charging is not feasible. The potential of IEEE 802.15.6 [1] to overcome the limitations of other Personal Area Network (PAN) standards, such as IEEE 802.15.1 [2] and 802.15.4 [3], should allow the wider implementation and deployment of Wireless Body Area Networks (WBANs).

IEEE 802.15.1 was the first standard to focus on the short range personal area networking environment and IEEE 802.15.4 traded throughput for low power operation. Previous work [4] has shown that IEEE 802.15.4 can only just meet the lifetime requirements of low rate medical applications whereas [5] claims that IEEE 802.15.4 provides a solution for medical applications although their study focusses on medical applications with higher rate to that studied in [4].

In April 2010 the IEEE 802.15.6 working group created the first draft of the standard and is continuing to develop it [1]. The early results presented here analyse the energy usage of certain modes of operation in the proposed standard.

This paper is organised as follows: Section II gives an overview of IEEE 802.15.6 physical and data link layers. Section III presents the analysis and assumptions used. Section IV presents the results and Sections V presents future work and conclusions.

II. IEEE 802.15.6 Overview

A. Physical Layer

The IEEE 802.15.6 specification defines Narrowband (NB), Ultra-Wide Band (UWB) and Human Body Communications (HBC) physical layers. The analysis presented here concentrates on the NB physical layer. The NB physical layer operates in seven different frequency bands and offers a variable number of channels, bit rates and modulation schemes.

The analysis presented here focuses on the sixth band of 2360-2400 MHz (newly reserved for use by medical devices) and the seventh band of 2400-2483.5 MHz, because it is the most commonly used license exempt ISM band. These bands operate at a symbol rate of 600 ksps while the modulation schemes, coding rates and spreading factors vary as shown in Table I. All the modes presented in Table I are mandatory.

Packet Component	Modulation	Code Rate (k/n)	Spreading Factor (S)	Data Rate (kbps)
PLCP Header	$\pi/2$-DBPSK	19/31	S_0: 4	R_0: 91.9
PSDU	$\pi/2$-DBPSK	51/63	S_1: 4	R_1: 121.4
PSDU	$\pi/2$-DBPSK	51/63	S_2: 2	R_2: 242.9
PSDU	$\pi/2$-DBPSK	51/63	S_3: 1	R_3: 485.7
PSDU	$\pi/4$-DQPSK	51/63	S_4: 1	R_4: 971.4

TABLE I
Physical Layer Parameters for Bands 6 and 7.

The structure of the Physical-layer Protocol Data Unit (PPDU) as defined by the IEEE 802.15.6 is shown in Figure 1. Where no transmission mode is specified in this paper, it is assumed that Physical Layer Service Data Units (PSDUs) are $\pi/4$-DQPSK modulated resulting in data rate of 971.4 kbps. The Physical Layer Convergence Protocol (PLCP) header is always $\pi/2$-DBPSK modulated with a coding rate of 19/31 and spreading factor equal to 4.

B. Medium Access Control Layer

The IEEE 802.15.6 draft operates with one-hop star and two-hop restricted tree topologies. In the one-hop topology, frames are exchanged between nodes and hubs while in the

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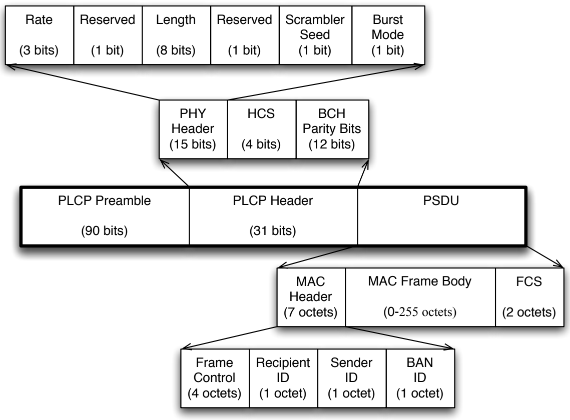

Fig. 1. IEEE 802.15.6 physical layer frame structure.

two-hop restricted tree, a hub and a node may use a relay node to exchange frames. This analysis concentrates on the one-hop topology.

The hubs are responsible for coordinating channel access by establishing one of the following three access modes:

- Beacon mode with beacon period superframe boundaries
- Non-beacon mode with superframe boundaries
- Non-beacon mode without superframe boundaries

The time base is divided into equal length beacon periods (also known as superframes) and each superframe is further divided into allocation slots. In the first two access periods the time base is common between hubs and nodes and it is dictated by the hub; i.e. the hub establishes superframe boundaries and defines the number of allocation slots in it. In the first access mode, the hub communicates the superframe structure via beacon frames or Timed frames (T-Poll). The second access mode does not transmit beacons and the superframe structure is enforced through the use of Timed frames (T-Poll). In the non-beacon mode without superframe boundaries each node establishes its own time base independently. The analysis in this paper concentrates on Beacon Mode with beacon period superframe boundaries.

The superframe structure, shown in Figure 2, starts with a beacon followed by two consecutive periods each consisting of an Exclusive Access Phase (EAP), Random Access Phase (RAP), Type I/II access phases, and an optional B2 frame that precedes the Contention Access Phase (CAP). It must be noted that the length of these phases is variable and their length is given in numbers of allocation slots. By setting any of these lengths to zero the access phases can be eliminated. This superframe structure allows three types of access:

1) Random access (Contention based): CSMA/CA or Slotted ALOHA for the narrowband and ultra-wide band physical layers respectively.
2) Improvised and unscheduled access: Post (i.e. a hub instruction) or Poll (i.e. a data request from the hub).
3) Scheduled access (Contention free): 1-period or m-periodic.

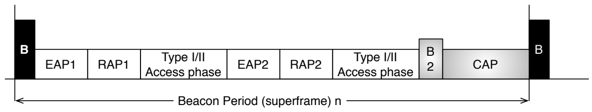

Fig. 2. Beacon mode with beacon period boundaries superframe structure.

The EAP1, EAP2, RAP1, RAP2 and CAP are random access phases. The EAPs are reserved for high priority traffic while the RAPs are used for non-recurring transfers using contention.

Type I/II access phases are set aside for scheduled transfers, unscheduled and improvised transfers. Devices that have type I/II scheduled allocations can start their transfer when the reserved allocation slot time has commenced, whereas devices with unscheduled and improvised access must be awake and wait for a poll or post frame from the hub, before they can transmit. Type I and Type II access cannot be mixed in each of the Type I/II phases in one superframe. Type I and type II phases differ in the units used to request reservations, with the device requesting allocation intervals in time (Type I) or in number of frames (Type II).

Scheduled allocation can be either 1-periodic or m-periodic. In 1-periodic allocations devices exchange frames with the hub in every superframe while in m-periodic allocation devices and hubs exchange frames every m superframes allowing the device to sleep between transfers. The allocations can be either uplink, downlink or bilink. In bilink, transfers occur in both directions and are initiated by the hub using post/poll frames.

The draft defines four acknowledgement policies: 1) not acknowledged frames (N-Ack), 2) immediately acknowledged (I-Ack), 3) block acknowledged later (L-Ack) and 4) block acknowledged (B-Ack).

III. Analysis

This analysis provides estimates of the device lifetimes for a range of 1-periodic and m-periodic scheduled allocations. The assumptions used in the analysis are:

- The network operates in a steady state, i.e. device association and resource negotiation is only performed when the device is powered up, after which it stays connected.
- Devices are granted enough time to complete their transfers including guard times.
- Current is only drawn by the radio transceiver. The effect of current drawn by the microcontroller and other peripherals will be significant in extended sleep modes, but this analysis concentrates on the effect that the energy consumption of the wireless transceiver has on the device lifetime.
- The devices use coin cell batteries of 560 mAh capacity that provide constant operating voltage during their lifetime. We do not consider battery effects such as self discharge that will reduce their actual lifetime.
- Where defined by IEEE 802.15.6, the RF transceiver characteristics used are those in Table II, but where

Tx-Rx & Rx-Tx turn around time	50	μs
Clear Channel Assessment (CCA)	63	symbols
Energy Detection (ED)	8	symbols
Short Inter-frame Space (SIFS)	50	μs
Minimum Inter-frame Space (MIFS)	20	μs

TABLE II
TRANSCEIVER CHARACTERISTICS DEFINED BY IEEE 802.15.6.

Voltage Supply		3	V
Receive current	no data (*state*=RxListen)	13.8	mA
	@ 600 ksps (*state*=Rx)	13.1	mA
Transmit current	@ 0 dBm (*state*=Tx)	11.3	mA
	@ -6 dBm	9.0	mA
	@ -12 dBm	7.5	mA
	@ -18 dBm	7.0	mA
Deep sleep current	(*state*=Stdby)	0.9	μA
Warm-up current	(*state*=Wup)	8.9	mA
Transmitter and receiver start up time including voltage reg, oscillator and PLL lock		3.13	ms

TABLE III
ASSUMED TRANSCEIVER CHARACTERISTICS.

not defined, the values in Table III are used. In the absence of IEEE 802.15.6 compliant transceivers, these are derived from experience gained in [6] and available RF transceivers such as the Nordic nRF24L01+.

- The current draw when the transceiver operates in modes R_0 to R_4 is assumed to be the same.

The following notation is used: t refers to the duration of frames and generally any quantity measuring time, T refers to fixed times defined by the data link layer, L refers to the length of frames in bytes, while N is used for lengths in bits.

The remainder of this section contains the analysis for computing the duration of the frames, the superframe duration, the required guard times and estimates of the lifetime for scheduled allocation transfers.

A. Frame Duration

The total time to transmit a frame with MAC payload length L_p bytes using transmission $mode \in [1,4]$ (as in Table I) is given by:

$$\begin{aligned} t_F(L_p, mode) =& t_{preamble} + t_{PLCP_{Header}} \\ &+ t_{PSDU}(L_p, R_{mode}) \end{aligned} \tag{1}$$

$$t_{preamble} = \frac{N_{preamble}}{SymbolRate} = \frac{90}{600 \cdot 10^3} = 0.15ms \tag{2}$$

$t_{PLCP_{Header}}$ is the time it takes to transmit the PLCP header with coded length of $N_{coded} = 31bits$.

$$t_{PLCP_{Header}} = \frac{N_{coded} \cdot S_{PLCP_{Header}}}{SymbolRate} = \simeq 0.20666ms \tag{3}$$

where $S_{PLCP_{Header}}$ the spreading factor for the PLCP header.

The MAC payload length (L_p) is 0-255 bytes as shown in Figure 1 and therefore the total PSDU length N_{PSDU} is $8 \cdot (L_{MAC_{Header}} + L_p + L_{FCS})$ bits. The PSDU is then passed through a scrambler and subsequently a BCH encoder. The number of parity bits added by the encoder are [1]:

$$N_{parity} = \left\lceil \frac{N_{PSDU}}{k} \right\rceil (n-k) \tag{4}$$

where n and k for that $mode$ are defined by the coding rate as shown in Table I.

After encoding, the number of pad bits appended to ensure bit alignment on the symbol boundary is [1]:

$$\begin{aligned} N_{pad} =& log_2(M_{mode}) \left\lceil \frac{N_{PSDU} + N_{parity}}{log_2(M_{mode})} \right\rceil - \\ & (N_{PSDU} + N_{parity}) \end{aligned} \tag{5}$$

where M_{mode} is the modulation constellation size for the transmission $mode$.

Then the PSDU is subsequently passed to a spreader and the total length of the PSDU in bits after the spreading is [1]:

$$N_{total} = (N_{PSDU} + N_{parity} + N_{pad}) \cdot S_{mode} \tag{6}$$

where S_{mode} is the spreading factor for the transmission $mode$.

Finally the PSDU is passed to a bit interleaver which does not change its length and this is then mapped to symbols. Hence the time it takes to transmit a frame with MAC payload length L_p bytes at transmission $mode$ is given by:

$$t_{PSDU}(L_p, mode) = \frac{N_{total}}{log_2(M_{mode}) \cdot SymbolRate} \tag{7}$$

B. Superframe Duration

The duration of the superframe (T_{SF}) is given by the number of allocation slots within the beacon period ($nSlots$) and the duration of the allocation slots (T_{slot}) as follows:

$$\begin{aligned} T_{SF} =& nSlots \cdot T_{slot} \\ T_{slot} =& (pAllocationSlotMin + \\ & AllocSlotLength \cdot pAllocationSlotResolution) \end{aligned} \tag{8}$$

Where the $AllocSlotLength$ is defined by the hub and it takes a value from 0-255. Both the $pAllocationSlotMin$ and $pAllocationSlotResolution$ depend on the underlying physical layer and the draft specifies them equal to 1 ms for the NB physical layer [1].

Using these values in equation 8, the minimum and maximum allocation slot duration (T_{slot}) is in the range of 1 to 256 ms and consequently the superframe duration (T_{SF}) in the range of 1 ms to 65.536 s.

To put these timings in prospective consider a data frame exchange of with maximum payload. This exchange includes a data frame with MAC payload 255 bytes, an inter-frame space (SIFS), an immediate acknowledgement (I-Ack) and a nominal guard time.

For the narrowband physical layer the duration of a frame with maximum MAC payload using the slowest transmission mode is equal to 17.8 ms using equation 1. The SIFS is equal to 50 μs, the time to generate the I-Ack is 99.67 μs while the nominal guard time according to the draft is 1/10 of the allocation slot. Therefore, for T_{slot} in the range of 1 ms to 256 ms the nominal guard time will be in the range of 100 μs to 25.6 ms. This leads to total frame exchange duration between 18.05 and 43.55 ms after rounding to the specified MAC layer clock resolution ($\delta = 10\mu s$)

C. Guard Time

The draft defines the nominal guard time GT_n to be 1/10 of the allocation slot duration. GT_n should be used when the last synchronisation interval SI is less than a nominal SI_n, otherwise GT_a should be appended to it. The nominal SI_n is predetermined and it is a function of the clock accuracy (in ppm) and slot duration. Hence the guard time is a function of SI and after rounding to specified MAC layer clock resolution $\delta = 10\mu s$:

$$GT(SI) = \begin{cases} \left\lceil \frac{GT_n}{\delta} \right\rceil \cdot \delta & \text{if } SI < SI_n \\ \left\lceil \frac{GT_n + GT_a}{\delta} \right\rceil \cdot \delta & \text{if } SI \geq SI_n \end{cases} \tag{9}$$

This shows that devices with m-periodic allocation ($SI = m \cdot T_{SF}$) shall commence the beacon reception at least $GT(m \cdot T_{SF})$ prior to beacon reception. When a device has an uplink allocation it shall initiate the frame transmissions at the nominal start time if SI is less than SI_n, otherwise it shall initiate the frame transmission at least GT_a after the nominal start time. For downlink or bilink allocations, the node must be ready to receive frames at least GT_n prior to the nominal guard time, if SI is less than SI_n and at least $GT_n + GT_a$ otherwise.

D. Scheduled Allocations

The device lifetime can be estimated from the total average current consumption (I_{total}) and the battery capacity (Q).

$$T_{life} = \frac{Q}{I_{total}} \tag{10}$$

I is used to refer to average current consumption while i is used to refer to instantaneous current draw. The total average current consumption is given by:

$$I_{total} = I_{Rx} + I_{Tx} + I_{RxListen} + I_{Wup} + I_{Stdby} \tag{11}$$

Where I_{Rx} and I_{Tx} are the average current consumptions when the device receives and transmits data, $I_{RxListen}$ is the average current drawn for idle listening, I_{Wup} the average current when the device moves from standby to receive or transmit states and finally, I_{Stdby} the average current consumption when the device is in sleep state. The average current consumption in each *state* described above, can be found using:

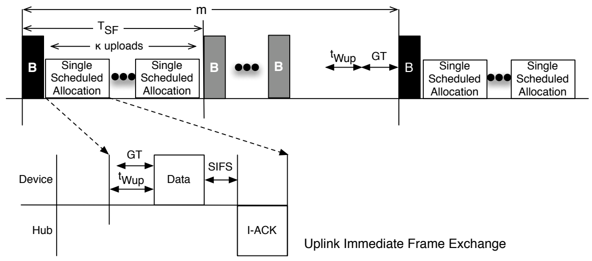

Fig. 3. m-periodic transfer with κ uploads, immediately acknowledged.

$$I_{state} = \frac{T_{state} \cdot i_{state}}{m \cdot T_{SF}} \tag{12}$$

where T_{state} is the total time the device spends in a *state* during $m \cdot T_{SF}$ and i_{state} is as specified in Table III.

Two frame exchange patterns are considered; immediately acknowledged and block acknowledged transfers. An m-periodic transfer with κ immediately acknowledged uploads is shown in Figure 3.

The time in each state for an immediately acknowledged uplink transfer consists of a one time warm-up t_{cal} (as in Table III), guard time $GT(m \cdot T_{SF})$ in the RxListen state and t_{Beacon} in Rx state for the beacon reception (see equation 1).

Each frame exchange consists of one warm-up t_{cal}, t_{Data} in Tx for the frame transmission, RxListen for the duration of the interframe spacing T_{SIFS} and t_{I-Ack} in Rx state to receive the acknowledgement. All the remaining time is spent in sleep state. Therefore the total time in each state for κ uploads including the times for beacon reception is:

$$\begin{aligned} T_{Rx} &= t_{Beacon} + \kappa \cdot t_{I-Ack} \\ T_{Tx} &= \kappa \cdot t_{Data} \\ T_{RxListen} &= GT(m \cdot T_{SF}) + \kappa \cdot T_{SIFS} \\ T_{Wup} &= (\kappa + 1) \cdot t_{cal} \\ T_{Stdby} &= m \cdot T_{SF} - T_{Rx} - T_{Tx} - \\ &\quad - T_{RxListen} - T_{Wup} \end{aligned} \tag{13}$$

For κ downlink allocations the roles of the hub and the device are swapped and the times the transceiver spends in each state is determined in a similar fashion. It is also necessary to include the appropriate guard time in the RxListen state. This guard time was not included for the uplink allocations, because the device initiated those transfers and so can remain in sleep state for the duration of the guard time. This is not true for downlink allocations, because the device must be ready to receive frames prior to the nominal start of its allocated slot.

An uplink block transfer of κ blocks is shown in Figure 4. This consists of a single device warm-up (t_{cal}), followed by the transmission of κ frames, each one of time t_{Data}. The device remains in RxListen for $\kappa - 1$ minimum interframe spacing (T_{MIFS}) and one short interframe space (T_{SIFS}). Finally, the device remains in Rx state for the duration of the acknowledgement frame t_{B-Ack}. The time spent in each state is:

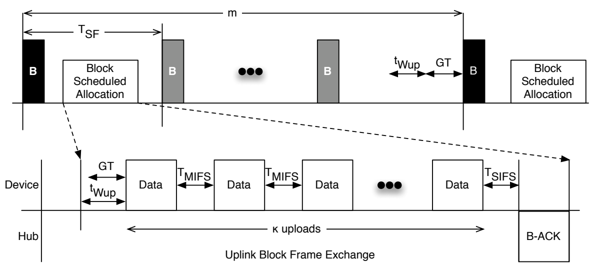

Fig. 4. An example of an m-periodic allocation with block transfers.

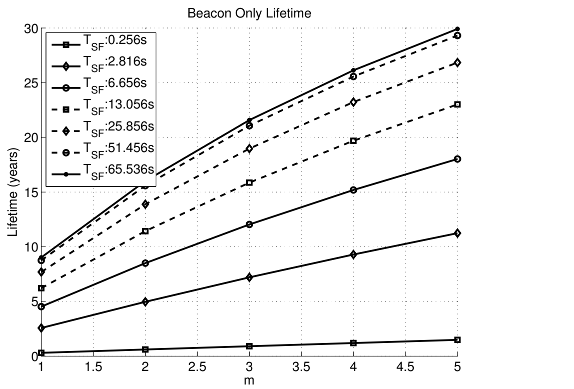

Fig. 5. Lifetime for a device that receives only beacons every m periods for different superframe lengths.

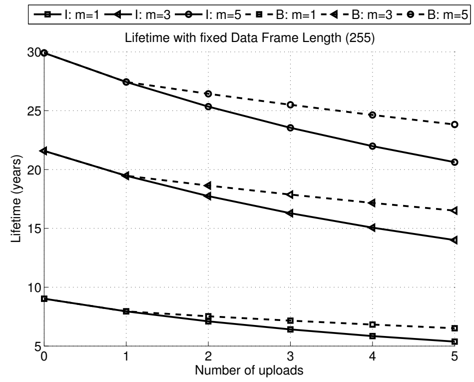

Fig. 6. Comparison of immediately and block acknowledged transfers for various number of uploads and periods m.

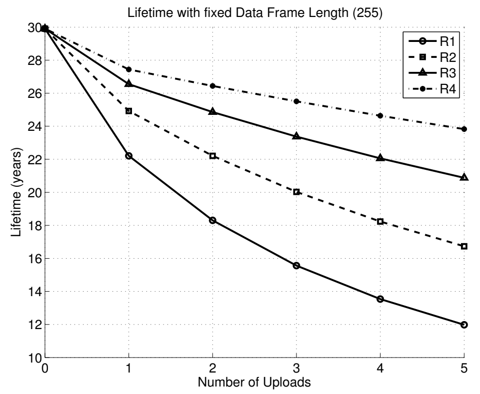

Fig. 7. The effect of physical layer transmission rate in device lifetime.

$$
\begin{aligned}
T_{Rx} =& t_{Beacon} + t_{B-Ack} \\
T_{Tx} =& \kappa \cdot t_{Data} \\
T_{RxListen} =& GT(m \cdot T_{SF}) + (\kappa - 1) \cdot T_{MIFS} + T_{SIFS} \\
T_{Wup} =& 2 \cdot t_{cal} \\
T_{Stdby} =& m \cdot T_{SF} - T_{Rx} - T_{Tx} - \\
& - T_{RxListen} - T_{Wup}
\end{aligned} \tag{14}
$$

Block downlink allocation times are computed in a similar fashion with the roles of the device and the hub swapped.

IV. Device Lifetime Results

The effects on lifetime of the superframe duration T_{SF} and the periodicity m at which devices receive transmissions are shown in Figure 5. All superframes shown are 255 slots long.

This graph shows maximum device lifetime when the device receives beacons with periodicity m. As expected, it can be seen that increases in periodicity m result in increased device lifetime and that keeping the periodicity constant and increasing the superframe duration also improves the lifetime.

Figure 6 shows the effect on lifetime of block transfers versus immediately acknowledged ones. When a single upload is considered the block transfer and immediately acknowledged transfer give identical lifetimes as expected, as the block transfer becomes immediately acknowledged for a single upload. It can be seen that the two transfer mechanisms diverge as the number of uploads increase. For example, block and immediately acknowledged transfers have lifetimes of 23.83 and 20.63 years respectively for a periodicity of 5 (a difference in lifetime of 13.4%). The lifetime for block transfers can be improved further by bundling more data frames. It must be noted that as the periodicity gets lower the absolute increase in the device lifetime is reduced, but the blocked transfers always offer higher lifetimes. From these observations it is concluded that block transfers offer the potential for improved lifetime compared to immediately acknowledged ones.

For block transfers (using the maximum superframe size and periodicity of 5), Figure 7 shows the effect on the device lifetime for the four defined transmission data rates versus the number of uploads.

This graph shows that the higher the data rate, the higher the device lifetime, because for higher data rates the radio chip spends less time transmitting the frames. By bundling more data frames in the block transfers, the benefit of the higher rate becomes even greater, e.g. Figure 7 shows the device lifetime of the highest transfer rate is more than double that of the lowest transfer rate for 5 uploads. It must be noted, however, that this finding relies on a perfect channel and that no frames are received in error. For an imperfect channel, the higher data rates may result in failed transfers leading to frame retransmissions and reduce this beneficial effect of block transfers on device lifetime. Consequently, it is reasonable to

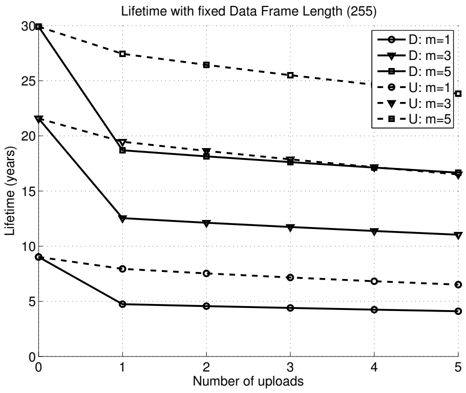

Fig. 8. Comparison of device lifetime for the same number of uploads and downloads.

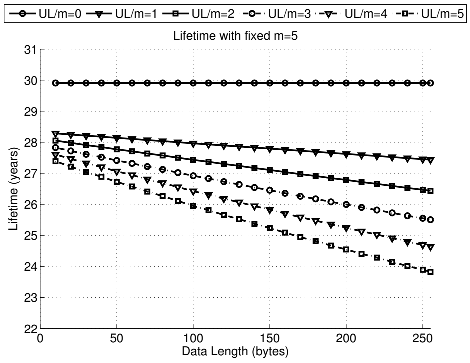

Fig. 9. Device lifetime for variable number of uploads with variable frame sizes.

state that rate adaptation will be important in increasing the device lifetime.

Figure 8 shows that downlink transfers are more expensive than uplink transfers. This is reasonable given that downlink allocations require its radio transceiver to remain in RxListen state for the additional duration of the guard band. As the number of transfers increases, the additional energy spent in the guard time becomes less significant because the device's radio transceiver has higher current consumption when receiving than when transmitting (Table III). In general it can be seen that it is preferable for a device to transmit frames to the hub rather than receive.

Figure 9 shows the device lifetime for variable number of frame lengths and number of uploads. When the number of uploads is zero the device spends all its energy receiving beacons. As the number of uploads increases, the device lifetime decreases due the volume of data uploaded. From Figure 9 it can be observed that is preferable to bundle the data in as few frames as possible, e.g. transferring 200 bytes as four uploads of 50 bytes each, gives a lifetime of 27.06 years, while two uploads of 100 bytes each gives 27.43 years and a single upload of 200 bytes gives 27.63 years.

V. Conclusions and Future Work

This first study of the IEEE 802.15.6 draft scheduled access modes has produced estimates of BAN device lifetimes for a range of parameter settings. It has verified that uplink allocations are less energy demanding than downlink ones. It has shown that bundling data into as few frames as possible and transmitting data using block transfer extends device lifetime. It has also shown that the device lifetime can be extended by increasing the transmission rate.

We believe that these findings are important in determining the manner in which to use the proposed standard for BAN devices and applications where lifetime will be a key requirement, such as in a number of medical applications.

Although the results presented in this analysis indicate the lifetimes achievable under ideal channel conditions, future work will be necessary to characterise the claims under non-ideal channels. This would form the basis for the development of power and rate adaptation mechanisms as well as fragmentation techniques in order to provide the optimum performance. Additionally, future work will investigate the effects on lifetime due to the different current consumption of the operating modes on Table I. Finally, to fully characterise the IEEE 802.15.6 draft we intend to validate this work using simulations and extend it to include random access and improvised unscheduled access for all three physical layers defined by the draft standard.

Acknowledgment

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