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Enhancing Reliability of IEEE 802.15.6 Wireless Body Area Networks in Scheduled Access Mode and Error Prone Channels

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Abstract This paper investigates reliability of wireless body area networks based on the IEEE 802.15.6 standard, for the scheduled access mode in an error prone channel. In scheduled access mode, during a time slot that is allocated for communication between a sensor node and the hub, the frame transmission fails if the link is in the deep fade state. To improve reliability of the network, we propose an efficient scheme for packet retransmission. The proposed scheme relies on allocation of spare slots for packet retransmissions in each superframe. We then present analytical models to find the energy efficiency and reliability of the network under the proposed retransmission scheme. Through analytical and simulation results, we establish that the proposed retransmission scheme can significantly improve the reliability of the network in the scheduled access mode, without causing degradation of energy efficiency.

Keywords Reliability · Retransmissions scheme · IEEE 802.15.6 · Scheduled access mode · Wireless body area networks

1 Introduction

Wireless body area networks (WBANs) have attracted attention of researchers due to their immense potential in many areas such as health care, sports, military, and entertainment. Such networks are formed by low-power, lightweight sensor nodes that are implanted in the human body or attached to the surface. The sensor nodes collects physiological data and transmits the information to a central device known as hub. WBANs consist of invasive devices as well as wearable devices communicating with a hub [1, 2]. Design of energy efficient protocol to improve lifetime of the network is a major challenge in WBAN research [2]. Another critical aspect is the reliability, which is highly application-

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dependent [2]. For example, medical applications that involve real time collection of patient's vital information require the packet delivery ratio to be almost 100 % [2]. However, the wireless link between the sensor and hub experience severe attenuation and shadowing that can result in very high outage probability [2, 4]. Therefore, efficient mechanisms should be devised to improve reliability along with low energy expenditure.

IEEE 802.15.6 standard defines the specifications for the physical (PHY) layer and medium access control (MAC) layer for WBANs [3]. A MAC layer is defined in common for three PHY layers. The different physical layers are Narrowband (NB), Ultra Wide Band (UWB), and Human Body Communications (HBC). The MAC layer supports both contention based as well as contention-free access schemes. Either slotted ALOHA or CSMA/CA mechanism can be used in contention phase based on the physical layer. Scheduled access as well as an improvised polling/posting based access are supported in contention-free access phase [3].

The scheduled access mode, is based on TDMA and is a very much suitable MAC scheme to reduce energy consumption due to overhearing, collisions and idle listening. In this case, time is divided into super frames, with each super frame further divided into a number of allocation slots that can be individually allocated to the sensor nodes. However, when the channel conditions are bad, scheduled allocation may lead to significant waste of energy. Specifically, during a time slot that is allocated for communication between a sensor node and the hub, if the link is in the deep fade state, frame transmission fails. To meet the network reliability requirements, the data frames that are not successfully delivered to the hub have to be retransmitted. However, the WBAN channel greatly influences the effectiveness of frame retransmission scheme. When a frame encounters transmissions failure in a scheduled allocation slot, the retransmission of the frame should be delayed until the corresponding link recovers from outage.

We present analytical models to find the energy efficiency and reliability of IEEE 802.15.6 WBAN employing scheduled access, taking into account the impact of channel error. We assume NB PHY for on-body communication in 2.4–2.4835 GHz and in-body communication at 402–405 MHz. We also determine the lifetime of WBAN node compliant to IEEE 802.15.6 in presence of channel error. To improve the reliability, we then propose a simple but efficient retransmission scheme which can be implemented by using the scheduled and the improvised access functionalities specified by IEEE 802.15.6 standard. The proposed scheme relies on allocating additional TDMA slots for frame retransmissions in each super frame and such slots are allocated to a sensor node only when the state of its link to the hub allows a successful data transfer.

The major contributions of this paper can be stated as below:

- We develop an analytical model to compute the energy efficiency and reliability of IEEE 802.15.6 based WBANs in scheduled access mode by including channel error and conduct an extensive study on the impact of hop distance and channel error on the energy efficiency and reliability.
- To improve the reliability, we then propose an efficient technique for the retransmission of failed frames using the functionalities available in the IEEE 802.15.6. Further, we present an analytical model for evaluating the energy efficiency and reliability of the network under the proposed retransmission scheme. We establish that, as compared to the legacy scheduled access procedure specified by IEEE 802.15.6 (which does not specify a strategy for frame retransmission), the proposed scheme improves the reliability without causing degradation of energy efficiency.

2 Related Work

Many works exist in the literature [5–9], that aim to improve the energy efficiency of WBANs. Work in [5], attempts to improve the energy efficiency using optimal power allocation. The authors of [6], analyse energy efficiency of cooperation schemes in WBANs. Selection of optimal packet size is considered in [7], to improve energy efficiency. The same problem is considered in [8] for a two hop communication system. In our earlier work [9], we have investigated energy efficiency and optimal packet size for cooperative WBANs with channel error. All these papers, however, does not consider MAC protocols according to IEEE 802.15.6 specifications. Many proposals [10–15] have appeared for energy efficient MAC design of WBANs. Recently, a few works [16–20] have appeared on the performance analysis of IEEE 802.15.6 MAC. The delay and maximum throughput of CSMA/CA protocol are evaluated in [16]. The throughput under saturation of CSMA/CA protocol is evaluated in [17]. In [18], energy efficiency, power consumption and throughput of CSMA/CA protocol are evaluated assuming unsaturated conditions. Performance of CSMA/CA protocol in terms of average delay, power consumption, reliability and throughput are evaluated in [19]. A preliminary study of the lifetime for the scheduled access mode, assuming an ideal channel has been conducted in [20].

According to the IEEE 802.15.6 proposals, to improve the reliability of the network in scheduled access, a node is required to retransmit a frame that was not delivered successfully to the hub in the first transmission attempt [3]; however the standard does not specify the mandatory procedure for retransmission. There have been many proposals for improving reliability in WBANs [21–32]. In [21], the authors present the design of an opportunistic MAC protocol, BANMAC, that try to mitigate signal strength variations to improve reliability of WBAN. Authors of [22] propose cooperative network coding for improving reliability of WBAN. Work in [23] propose temporal density coding, that applies diversity coding in time and space, to improve the robustness and reliability of WBANs. In [24], authors propose that transmit power control with switch-and-examine combining (SWC) can improve WBAN reliability. The authors of [25] adopt compressive sensing technology to improve data transmission reliability. Work in [26] applies the concept of cooperative communications to improve reliability in terms of outage probability and bit error. Work in [27] consider partitioning the WBAN into distinct regions, and selecting a leader for each region to enhance the reliability. Authors of [28] consider variable TDMA scheduling, instead of a fixed TDMA allocation, for mitigating the effect of packet loss in WBANs. In [29], the same authors consider the design of a strategy for packet retransmission under variable TDMA scheduling. The schedule of order of the nodes in a superframe depends on the result of previous round. A flipping strategy is adopted in which nodes that successfully delivered their packets in previous superframe are scheduled first, followed by nodes which were unsuccessful. In [30], the authors propose a cross-layer design to improve reliability in WBAN in presence of other coexisting networks. The gateway need to continuously probe the spectrum and require free control channel to announce free slots. The nodes access the hub using CSMA/CA and are assumed to contain passive radio-frequency module and require free control channel to inform the other nodes of completion of back off procedure when they initiate frame transmission. Work in [31] is based on the IEEE 802.15.4 superframe and uses fuzzy logic to adjust the length of back off window of CSMA/CA scheme. Reliability is improved by achieving fair access to the medium by the nodes varying the back off values. The back off calculations is based on the number of successful transmission attempts in past superframes. This scheme is not suitable for high data rate WBAN nodes due to the contention-based operation. Notice that none of the above papers consider protocol specifications according to the IEEE 802.15.6 proposals. Authors of [32] propose enhancements for the polling access scheme of the IEEE 802.15.6 baseline MAC to improve the packet reception ratio (PRR). The enhancement scheme allocates continuous polling slots to empty the buffer faster and use link adaptation to reduce the loss of Ack frames.

Reliability (i.e., packet delivery rate) is highly critical for medical applications of WBANs. To achieve very high reliability, retransmissions of failed packets needs to be employed. The focus of the present work is to evaluate energy efficiency and reliability of WBANs operating in the scheduled access mode of IEEE 802.15.6, taking into account channel error, and to propose a retransmission scheme for improving the reliability. The organization of the remaining portion of the paper is as follows. In Sect. 3, we describe briefly the IEEE 802.15.6 standard. Section 4 analyses the energy efficiency taking into account the effects of packet error, and describes the proposed retransmission algorithm. Section 5 presents analytical and simulation results. The paper is concluded in Sect. 6.

3 IEEE 802.15.6: An Overview

A brief description of main features of IEEE 802.15.6 standard is given in this section. As shown in Fig. 1, the physical-layer protocol data unit (PPDU) consists of physical layer convergence protocol (PLCP) preamble, PLCP header and a physical layer service data unit (PSDU). The MAC header and frame check sequence (FCS) are added to the MAC frame body to create the PSDU. BCH code is used to encode the PSDU before transmission.

The IEEE 802.15.6 standard specifies beacon mode in which the hub transmits beacons which divides time into super frame structures. The super frame consists of allocation slots. Allocation interval of a node consists of a number of allocation slots assigned for scheduled access. The access mechanisms used are divided among three categories: random, improvised and scheduled access. In scheduled access, the nodes obtain allocation intervals based on exchange of connection request and assignment frames with hub. When

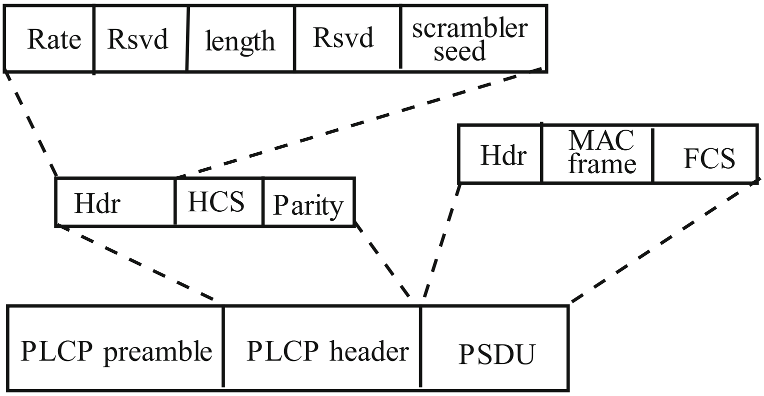

Fig. 1 The PPDU structure of narrow band PHY of IEEE 802.15.6 standard

the periodicity of allocation is 1-periodic, the nodes and hub exchange frames in every superframe [3]. In unscheduled and improvised access, resource allocation is done using poll/post frames. When immediate Ack policy is employed, the recipient acknowledges each data frame by sending back an IAck frame after a short inter frame spacing (SIFS).

4 Energy Efficiency Analysis

We consider a star topology for the WBAN. The nodes operate in the scheduled access mode and communicate directly to the hub in a single hop. Table 1 [3], lists the MAC parameters used throughout our analysis, while specifications of transceivers used for the analysis is given in Table 2 [33, 34]. For the energy efficiency analysis, we consider 1-periodic allocation with IAck scheme. We select allocation slot length to accommodate maximum data payload of 255 bytes. It is assumed that, in each super frame, a node can upload one data frame, and it receives IAck for the uploaded frame after SIFS duration, if the frame is correctly received at the hub. For analysis of energy efficiency in presence of channel error, we choose the channel model reported in [35–37].

4.1 Channel Model

Consider the communication link between the sensor node and the hub having a distance separation of d. The propagation path loss can be expressed as: [35]:

$$PL(d) = PL(d_o) + 10\alpha log\frac{d}{d_0} + X_\sigma \tag{1}$$

where $PL(d_o)$ represents the path loss at a reference distance of d_o, α is the path-loss exponent; and X_σ represents the shadowing component. Table 3 lists the channel parameters for in-body communication between implanted nodes and the hub [35], and for on-body communication betwen wearable node and the hub [37]. Considering a transmit power of P_T and an additive white Gaussian noise power of P_N, the signal to noise ratio (SNR) is obtained as: $\gamma(dB) = P_T - PL(d) - P_N$. Considering differential phase shift keying (DPSK) as the modulation scheme, the bit error rate (BER) is given by [38]: $P_b = \frac{1}{2}exp(-\gamma_b)$. Here, γ_b = E_b/N_o= γ. B_N/R represents the SNR per bit, R is the data rate

Table 1 MAC layer parameters [3]

MAC Parameter	value	MAC Parameter	value
$ClockRes$	4 μs	$HubClockPPMLimit$	40 ppm
SI_n	$8t_{SF}$	N_{Beac}	15 Bytes
N_{MAChdr}	7 Bytes	N_{FCS}	2 Bytes
N_{IAck}	Nil	N_{Poll}	Nil
$N_{DataMAX}$	255 Bytes	$AlocSltmin$	500 μs
$AlocSltResln$	500 μs	$ExtraIFS$	10 μs
$SIFS$	75 μs	time out	30 μs
$N_{preamble}$	90 bits	$N_{PLCPhdr}$	31 bits
$\lfloor log_2 n + 1 \rfloor$	6	t	2

Table 2 Specification of transceiver [33, 34]

Electrical parameter	nRF24L01 + (nordic)	zl70101(zarlink)
Voltage	3 V	3V
Current in transmit state (I_{TX} in mA)	7.5	5
Current in receive state (I_{RX} in mA)	13.1	5
Current in sleep state (I_{Sleep} in nA)	900	250
Current in idle state (I_{idle} in μA)	26	1000
Current to wakeup (I_{Wup}); 1.5 ms t_{Wup}	400 μA	–
Current to wakeup (I_{Wup}); 1.15 s t_{Wup}	–	250 nA
E_{add} (W/Hz)	$3.3 \times 10^{-14} \lfloor log_2 n + 1 \rfloor$	
E_{mult} (W/Hz)	$3.7 \times 10^{-14} \lfloor log_2 n + 1 \rfloor^3$	
Li-ion battery capacity	560 mAHr	

Table 3 Channel parameters [35, 37]

WBAN Scenario	In-body	On-body
Ref distance in cm (d_0)	5	10
Path loss at d_0 in dB (PL_0)	49.81	48.4
Path loss index (α)	4.22	5.9
Standard deviation indB (X_σ)	6.81	5
f (GHz)	.402–.405	3.1
Band width in MHz	0.3	1
Max data rate in kbps	562.5	1200
Transmit power in dBm	-10	-12
Noise power in dBm	-100	

(bps); B_N the noise power bandwidth (Hz); E_b is the energy per bit, and N_o is the noise power spectral density.

4.2 Packet Error Rate

The PSDU is converted into BCH encoded blocks of length n bits, by adding $(n-k)$ parity bits to every k bit of data. If the number of bits in error in a block is more than t (error correcting capability of the code), the block will be in error. Hence block error rate P_{blk} is given as [38]:

$$P_{blk} = \sum_{i=t+1}^{n} \binom{n}{i} P_b^i (1 - P_b)^{n-i} \tag{2}$$

The payload of N_{Data} bits is transformed into a PSDU of length $N_{DataPSDU}$ as described in section below and contains $\left\lceil \frac{N_{DataPSDU}}{k} \right\rceil$ blocks. If any of the blocks are in error, the packet will be in error. The packet error rate (PER) assuming independent block errors can be expressed as:

$$PER_B = 1 - (1 - P_{blk})^{\left\lceil \frac{N_{DataPSDU}}{k} \right\rceil} \tag{3}$$

If BCH coding scheme is not used, the packet will be in error if any of the bits comprising the $N_{DataPSDU}$ are in error and the corresponding PER is given by $PER = 1 - (1 - P_b)^{N_{DataPSDU}}$. We represent network reliability in terms of packet acceptance rate-*PAR* defined as $PAR = 1 - PER_B$. If coding is not used, PAR is equal to 1 − PER. Next, we compute the energy consumption in different states.

4.3 Computing Time to Transmit/Receive Frames

The duration of transmission and reception of a frame depends on the length of the PPDU formed according to the structure defined in the IEEE 802.15.6 NB PHY. For a given frame type having N_{Type}, the length of the PSDU (bits) is given by:

$$N_{TypePSDU} = N_{MAChdr} + N_{Type} + N_{FCS} \tag{4}$$

Here $Type \in$ {Data, IAck, Poll, Beac}. After employing BCH coding, the total number of bits for a frame type is:

$$N_{totalTypePSDU} = N_{TypePSDU} + N_{CW}(n - k) + N_{pad} \tag{5}$$

where N_{CW} is the number of code words and N_{pad} is the number of pad bits [3]. The coded bits are spread, interleaved, and scrambled before transmission. The PPDU is formed by adding header and preamble of $N_{PLCPhdr}$ and $N_{preamble}$ bits respectively. The duration of PPDU in symbols is given by [3]:

$$N_{TypePPDU} = N_{preamble} + N_{PLCPhdr} S_{PLCPhdr} + \frac{N_{totalTypePSDU}}{Log_2 M} S_{PSDU} \tag{6}$$

where, $S_{PLCPhdr}$ and S_{PSDU} are the spreading factors[3]. If the duration of a symbol is T_s, the total time duration the node or hub resides in the transmit or receive state (i.e., State ∈ {TX, RX}) for a frame can be expressed as:

$$t_{StateType} = T_s N_{TypePPDU} \tag{7}$$

4.4 Computing Energy Consumption in Different States

The energy consumption in the transmit and receive states depends on the time duration of frame transmission and reception. Let E_{TX_b} and E_{TX_s} be the energy consumption of the transceiver to transmit one bit and one symbol respectively. Let supply voltage and current in the transmit state be V and I_{TX} respectively. The energy consumed for transmitting a symbol E_{TX_s} can be expressed as $E_{TX\_s} = VI_{TX}T_s$. The total energy expenditure incurred by the node in an operating state and for a given frame type can be expressed as $E_{StateType} = VI_{State}t_{StateType}$, where I_{State} denotes the supply current in a given operating state and State ∈ {TX, RX, Idle, Wup}. Here, Wup represents the wake up state i.e., the transition from sleep state to the active state. Since ultra low power transceivers are used in WBAN, for simplicity of analysis the energy consumption in the sleep state is assumed to be negligible. The time spent by the node in TX and RX states for various frame types are given by (7); time duration in the idle state is given by (9) (described below); and the time to wake up is given in Table 2. The time taken by the node for transmission of data frame, as well for the reception of IAck and beacon frames can be written as:

$$\begin{aligned} t_{TXData} &= T_s N_{DataPPDU} \\ t_{RXAck} &= T_s N_{AckPPDU} \\ t_{RXBeac} &= T_s N_{BeacPPDU} \end{aligned} \tag{8}$$

The time spent in idle state by the node is computed next. After the data frame is transmitted, the node waits SIFS duration for the Ack. The duration the node resides in the idle state depends on the success or failure of the transmission. For an ideal channel, the Ack frame will be received after SIFS duration. The total time the node resides in the idle state is sum of SIFS duration and guard time (GT) computed as given in [3].

$$t_{Idle} = SIFS + GT \tag{9}$$

Next we compute the guard time, which is the time set aside to achieve synchronization of the clocks of the nodes and the hub. If the time elapsed after the last synchronization is less than eight superframes denoted as SI_n (Table 1), the guard time is computed as $GT_n = GT_o + 2D_n$. Here, GT_o is a quantity independent of clock drift; and D_n is the maximum drift during SI_n [3]. Let the accuracy of the clock and the node be HubClockPPM. If the time since last synchronization exceeds SI_n by a time duration SI_a, additional guard time is $GT_a = 2D_a$; where $D_a = SI_a HubClockPPM$ [3]. If time since last synchronisation is greater than SI_n, GT = $2GT_a + GT_n$ else GT = GT_n. The energy consumption of the node in different states are given by:

$$\begin{aligned} E_{TXData} &= VI_{TX} t_{TXData} \\ E_{RXAck} &= VI_{RX} t_{RXAck} \\ E_{RXBeac} &= VI_{RX} t_{RXBeac} \\ E_{Idle} &= VI_{Idle} t_{Idle} \\ E_{Wup} &= VI_{Wup} t_{Wup} \end{aligned} \tag{10}$$

In (10), the time duation the node resides in different states, i.e., TXData, RXAck, RXBeac, and Idle, are given by equations (8) and (9) respectively. The operating current in various states are listed in Table 2. We next describe the computation of super frame duration t_{SF}.

4.5 Computing the Duration of Super Frame

The duration of super frame depends on the slot duration and has to be selected to comply with the latency requirements. The slot duration is chosen to accommodate the total time required for the transaction of a frame of maximum length including the guard time. The allocation slot duration is given as [3]:

$$t_{Slot} = AlocSltmin + l.AlocSlotResln \tag{11}$$

where AlocSltmin and AlocSltResln are given in Table 1 [3], and l determines the duration of one allocation slot. From equations (1)–(6), transmission times of Ack, beacon are 0.437 and 0.557 ms respectively. At highest data rate, the transmission transmission for the maximum data size specified by the standard, is 2.5 ms. Taking into account the idle time and guard time, the allocation slot length t_{Slot} is computed as 3.5 ms and the duration of the super frame $t_{SF} = nslot\ t_{Slot}$, where $nslot$ is the number of slots in a super frame. The latency specified for medical applications in technical requirements document [39] is 125 ms. A super frame of 122.5 ms consisting of 35 slots is selected for the analysis.

4.6 Energy Consumption for Encoding/Decoding

The energy consumption for encoding is considered to be negligibly small [40]. When a BCH code of codeword length n and error correction capability t is used, the energy to decode a code word E_{dec} is given as [40]: $E_{dec} = (2nt + 2t^2)(E_{add} + E_{mult})$, where E_{add} and E_{mult} are given in Table 2 [40]. The energy consumption involved in decoding of various frames (i.e., Data, Ack, and Beac) are given by:

$$\begin{aligned} E_{decData} &= E_{dec}\left\lceil \frac{N_{DataPSDU}}{k} \right\rceil \\ E_{decAck} &= E_{dec}\left\lceil \frac{N_{AckPSDU}}{k} \right\rceil \\ E_{decBeac} &= E_{dec}\left\lceil \frac{N_{BeacPSDU}}{k} \right\rceil \end{aligned} \tag{12}$$

4.7 Energy Efficiency

To compute the energy efficiency, we find the total energy consumption as follows: A tagged node transmits in its regular scheduled allocation (SA) slot, which may be a success or may fail based on channel conditions. When frame transmission is successful, the node receives Ack and when transmission is a failure, the node experiences time out. The energy expenditure by the node and the hub depends on the success or failure of the transmission. Let the energy expenditure by the node and the hub for the two cases be $E_{Node}^{SA\_Success}$, $E_{Hub}^{SA\_Success}$, $E_{Node}^{SA\_Fail}$, and $E_{Hub}^{SA\_Fail}$ respectively. Next, we describe the computation of these energy consumption components. The node will first transmit in its regular SA slot. If this transmission is successful, the energy consumed by the node can be expressed as:

$$E_{Node}^{SA\_Success} = 2E_{Wup} + E_{RXBeac} + E_{decBeac} + E_{TXData} + E_{Idle} + E_{RXAck} + E_{decAck} \tag{13}$$

The hub incurs energy expenditure for transmitting beacon, receiving data frame and to transmit Ack frame. The total energy the hub incurs when the transaction of the frame is successful can be expressed as:

$$E_{Hub}^{SA\_Success} = E_{TXBeac} + E_{RXData} + E_{decData} + E_{TXAck} \tag{14}$$

The various energy consumption components can be computed as follows:

$$\begin{aligned} E_{RXData} &= VI_{RX}t_{RXData} \\ E_{TXAck} &= VI_{TX}t_{TXAck} \\ E_{TXBeac} &= VI_{TX}t_{TXBeac} \end{aligned} \tag{15}$$

Notice that t_{RXData} is equal to t_{TXData}; t_{TXAck} is equal to t_{RXAck}; and t_{TXBeac} is equal to t_{RXBeac} given by (8).

When data transmission results in a failure, the node experiences time out. We first evaluate the energy consumption in the idle state when time out occurs. After transmitting the data frame, the node listens for a duration of SIFS for Ack frame. The node then listens for a time $t_{preamble} = N_{preamble}\ T_s$ expecting the PHY preamble and further waits for $t_{timeout}$. Total time spent in idle state when the node experiences timeout is given by $t_{Idle}^{timeout} = SIFS + t_{preamble} + t_{timeout} + GT$. The energy the node spends in the idle state when the transmission is a failure $E_{Idle}^{timeout}$ is:

$$E_{Idle}^{timeout} = VI_{Idle} t_{Idle}^{timeout} \tag{16}$$

Next, we compute the energy expenditure by node and the hub when transmission in scheduled allocation slot becomes a failure denoted by $E_{Node}^{SA\_Fail}$ and $E_{Hub}^{SA\_Fail}$ respectively. The energy incurred by the node when the first transmission attempt is unsuccessful involves the energy consumed to wake up to receive beacon, sleep till the scheduled allocation slot, wake up again to transmit the data frame and wait til time out. The energy consumption of the node can be written as:

$$E_{Node}^{SA\_Fail} = 2E_{Wup} + E_{RXBeac} + E_{decBeac} + E_{TXData} + E_{Idle}^{timeout} \tag{17}$$

The energy consumed in the idle state when the transmission attempt fails is given by (16). In scheduled allocation, data frames do not suffer collisions since transmissions are coordinated by the hub. When data frame received by hub is in error, Ack is not transmitted. The energy consumption of the hub includes the energy consumed in transmitting the beacon and energy for receiving and decoding the data frame given as:

$$E_{Hub}^{SA\_Fail} = E_{TXBeac} + E_{RXData} + E_{decData} \tag{18}$$

The total average energy consumed by the node and the hub when channel is error prone can be expressed as:

$$E_{Total}^{error} = PAR\,(E_{Node}^{SA\_success} + E_{Hub}^{SA\_success}) + (1 - PAR)(E_{Node}^{SA\_Fail} + E_{Hub}^{SA\_Fail}) \tag{19}$$

We define energy efficiency as ratio of useful portion of the energy consumption to the total energy consumption. The useful part of the energy consists of $\left\lceil \frac{N_{Data}}{k} \right\rceil$ blocks of length n each, and can be expressed as: $E_{useful} = xn\left\lceil \frac{N_{Data}}{k} \right\rceil$. Here x=$(E_{TX\_b} + E_{RX\_b})$, where $E_{TX\_b} = \frac{E_{TX\_s}}{log_2 M}$ and $E_{RX\_b} = \frac{E_{RX\_s}}{log_2 M}$ respectively represent the energy required to transmit and receive a bit. The energy efficiency for transmission of N_{Data} data bits when 1-periodic allocation with IAck policy is employed, when channel is error prone is given as:

$$\eta^{error} = PAR\,\frac{x\left\lceil \frac{N_{Data}}{k} \right\rceil\, n}{E_{Total}^{error}} \tag{20}$$

In Sect. 5, we describe the results for energy efficiency and PAR; which are affected significantly by the channel error. For reliable data exchange, the packets which are received in error need to be retransmitted. Next, we propose a retransmission scheme which can be implemented using the functionalities available in the IEEE 802.15.6 specifications.

4.8 Proposed Retransmission Scheme

We present an efficient scheme for packet retransmission for nodes in WBAN operating under the scheduled access mode. In the scheduled access mode, the sensor node normally stays in the sleep state. It wakes up to receive or transmit frames at the slots scheduled by the hub and to listen for Ack. When the hub successfully receives a data frame sent by the node in the scheduled allocation slot, it transmits an Ack frame. Mean while, if the node fails to get the Ack within the time out interval, the data frame is considered to be in error and thus need to be retransmitted. The basic steps involved in the proposed retransmission scheme are given in Algorithm 1 and 2 (for the node and hub respectively).

The WBAN channel greatly influences the effectiveness of the frame retransmission scheme. Recent empirical measurements and related studies have reported that, for the narrow band PHY layer, the WBAN channel essentially exhibits slow and flat fading [2, 4, 34–36]. Extensive measurements of WBAN channels corresponding to various kinds of human activities in the 2400 MHz ISM band have reported channel coherence time value ranging from 100-400 milliseconds (i.e., a bad link will remain bad for some time). The proposed retransmission scheme takes into account the temporal correlation exhibited by WBAN links due to slow fading. The proposed retransmission scheme relies on allocating spare TDMA slots for frame retransmissions in each super frame. When a frame encounters transmission failure in a scheduled allocation slot, the retransmission of the frame should be delayed until the corresponding link recovers from deep fade conditions. In the proposed scheme, this is ensured by allocating retransmission slots to the node only when the state of its link to hub allow successful data transfer. We assume that a few reserve slots are available to handle the retransmission requirements. Further, it is assumed that the hub maintains a list containing sequence numbers of data frames received in error from the nodes and it is capable of allocating spare slots for frame retransmissions.

When the hub successfully receives a data frame from a tagged node in the scheduled allocation slot, it checks the list containing sequence numbers of data frames received in error from the node during previous allocation slots. If the list is empty, it immediately transmits the Ack frame for the successfully received frame in the current slot. However if the list is non-empty, the hub sends an IAck plus poll frame to the tagged node. The inclusion of the poll along with IAck means that a slot would be assigned for a polled frame transaction in one of the reserve slots by setting appropriate value for the poll-post window field and the next field within the MAC header of the IAck plus poll frame. The poll-post window is used to indicate the allocation slot number in which the hub will send a future poll, and the next field is used to indicate the super frame in which this allocation slot is located. The node then wakes up at the assigned slot to receive the poll frame, and will retransmit the pending frame after SIFS duration.

Notice that, in the proposed scheme, retransmission can occur in the immediate or in a later super frame depending on when the corresponding link recovers from bad state. However, retransmission is not permitted in the scheduled allocation slot; it can happen only during the spare retransmission slots allocated by the hub. Thus depending on the average fade duration/coherence time of the corresponding fading channel, retransmission can occur as soon as the channel conditions favour successful delivery.

Algorithm 1: Proposed retransmission scheme procedure at the node

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Basic steps at Node: In superframe K, Node i has regular data with
seq. no. j to be transmitted and earliest data pending retransmission
with seq. no. k and transmission attempts p;
Step 1 : Wake up in SA slot, transmit data with seq. no. j ;
Step 2: wait SIFS for Ack of j;
if Ack received, then
    go to step 1, transmit data with seq. no. j+1 in superframe K+1;
else if Ack +Poll received, then
    Save Frame.no. L and Slot.no F of polled allocation.  if $L>K$ then
        go to step 1
    else
        go to step 3
    end
else
    Timeout, keep frame j for retransmission, increment transmission
    attempt count; go to step 1;
end
Step 3: Wake up in PA slot F, receive poll, wait SIFS and transmit
data k ;
Step 4: wait SIFS for Ack;
if Ack received then
    remove k from retransmission list; go to step 1;
else
    Timeout, increment transmission attempt count of k; go to step 1;
end
```

Algorithm 2: Proposed retransmission scheme procedure at the Hub

```
Basic steps at Hub Has to receive regular data with seq. no. j and
earliest data pending retransmission with seq. no. k with transmission
attempt p from Node i ;
if data j from Node i received in SA slot then
    if FCS check gives valid result then
        if data retransmission pending then
            if maximum retries not exceeded for packet k then
                $Frameno. \leftarrow L$, $Slotno, \leftarrow F$; transmitted in Ack+Poll,
                increment transmission attempt count of node i, packet k
            else
                Packet k retransmission fail
            end
        else
            data j received, transmit Ack; increment seq.no of Node i
        end
    else
        packet j received with errors, add to retransmission list ;
        increment transmission attempt count of node i, packet j
    end
else
    packet j not received, add to retransmission list ; increment
    transmission attempt count of node i, packet j
end
```

4.9 Energy Efficiency and Reliability Analysis Under the Proposed Retransmission Scheme

Here, we present an analytical model to find the energy efficiency and reliability of the network when the proposed retransmission scheme is employed. Let r denote the maximum permissible retransmission attempts. We evaluate the energy expenditure due to S transmissions where $S \leq r$. This assumption is reasonable since in the retransmission scheme, the notification regarding the future poll (to retransmit the frames in error) is given along with the IAck packet corresponding to a successfully transferred data packet. The node and the hub incurs energy expenditure in each of the S transmission attempts spread over different super frames. The first transmission of a data packet from a tagged node is in the regular scheduled allocation (SA) slot. This attempt can be a success or a failure depending on channel error. When the first attempt fails, the node will retransmit the data packet in the polled allocation (PA) slot. This transmission attempt also can be a success or a failure. Let the energy expenditure by the node and the hub for the two cases be $E_{Node}^{PA\_Success}$, $E_{Hub}^{PA\_Success}$, $E_{Node}^{PA\_Fail}$ and $E_{Hub}^{PA\_Fail}$ respectively. We now describe the models to find the energy consumption corresponding to the PA slot. For the polled allocation slots, the energy expenditure incurred by the node for the successful transmission attempt will consist of wake up to receive the poll, wait for SIFS duration to transmit the data, listen for SIFS duration to receive the Ack and can be expressed as:

$$E_{Node}^{PA\_Success} = E_{Wup} + E_{RXPoll} + E_{decPoll} + E_{IdleSIFS} + E_{TXData} + E_{Idle} + E_{RXAck} + E_{decAck} \tag{21}$$

Here E_{RXPoll} and $E_{decPoll}$ respectively represent the energy consumption to receive and decode the poll frame. Since both Ack as well as poll frames have the same size, E_{RXPoll} and $E_{decPoll}$ are computed using (10) and (12) respectively. Further, $E_{IdleSIFS}$ represents the idle energy consumption for SIFS duration and can be expressed as: $E_{IdleSIFS} = VI_{Idle}SIFS$. The energy consumed by the hub for the successful transmission attempt in the polled allocation slot will consist of beacon energy, energy to transmit a poll frame, receive and decode the data frame and transmit the Ack. This quantity can be expressed as:

$$E_{Hub}^{PA\_Success} = E_{TXBeac} + E_{TXPoll} + E_{RXData} + E_{decData} + E_{TXAck} \tag{22}$$

For the polled allocation slots, the energy consumed by the node for the unsuccessful transmission attempt will consist of energy expenditure to wake up, to receive the poll frame, wait for SIFS duration to transmit the data frame and to listen for $t_{Idle}^{timeout}$ duration. This quantity can be expressed as:

$$E_{Node}^{PA\_Fail} = E_{Wup} + E_{RXPoll} + E_{decPoll} + E_{IdleSIFS} + E_{TXData} + E_{Idle}^{timeout} \tag{23}$$

The energy consumption by the hub for the unsuccessful transmission attempt in polled allocation slot consists of energy to transmit the beacon, the poll frame, and for receiving and decoding the data frame and can be expressed as:

$$E_{Hub}^{PA\_Fail} = E_{TXBeac} + E_{TXPoll} + E_{RXData} + E_{decData} \tag{24}$$

The total energy consumed by the node, and the hub depends upon the requied number of attempts to successfully transfer the data frame. In each attempt; the data frame transmission is successful with probability PAR. The total average energy consumption for all the S transmission attempts can be expressed as:

$$E_{Total}^{Retn} = PAR\left(E_{Node}^{SA\_success} + E_{Hub}^{SA\_success}\right) + (1 - PAR)\left(E_{Node}^{SA\_Fail} + E_{Hub}^{SA\_Fail}\right) + \sum_{i=1}^{S-1}(1 - PAR)^{i}\left[PAR\left(E_{Node}^{PA\_success} + E_{Hub}^{PA\_success}\right) + (1 - PAR)\left(E_{Node}^{PA\_Fail} + E_{Hub}^{PA\_Fail}\right)\right] \quad (25)$$

The first term in (25) represents the energy expenditure for a successful data frame transmission in the scheduled allocation slot. The second term represents the energy expenditure for the unsuccessful transmission attempt of the data frame in the scheduled allocation slot. The third term represents the total average energy expenditure for $(S - 1)$ attempts in the polled allocation slot.

Due to retransmissions, the reliability or the overall packet acceptance rate improves. The total reliability or PAR under the proposed retransmission scheme PAR_{Retn}, can be expressed as: $PAR_{Retn} = \sum_{i=1}^{S}(1 - PAR)^{(i-1)}PAR$. Here, the ith term (i = 1,....S) represents the probability that the frame will be delivered successfully in the ith transmission attempt, when all the previous transmissions were not successful.

Now, in the energy efficiency expression with retransmission, the useful fraction of the data transmitted will be $x\left\lceil\frac{N_{Data}}{k}\right\rceil n$ multiplied by the overall packet acceptance rate PAR_{Retn}. The total energy consumption is given by (25). Hence, energy efficiency under the proposed retransmission scheme can be expressed as:

$$\eta_{Retn}^{error} = PAR_{Retn}\,\frac{x\left\lceil\frac{N_{Data}}{k}\right\rceil n}{E_{Total}^{Retn}} \quad (26)$$

4.10 Lifetime of Node Under the Proposed Retransmission Scheme

We assume that each node is powered by lithium-ion cell [41] of capacity Q mAHr. The lifetime of WBAN node can be expressed as:

$$Node_{life} = \frac{Q}{I_{Totalavg}} \quad (27)$$

where $I_{Totalavg}$ is the total average current consumption in mA / hour [20]:

$$I_{Totalavg} = I_{RXavg} + I_{TXavg} + I_{Idleavg} + I_{Wupavg} \quad (28)$$

Here I_{RXavg}, I_{TXavg}, $I_{Idleavg}$, and I_{Wupavg} are the average current consumption of the transceiver in each state. If t_{state} is the total time the device spends in a state during the super frame, and I_{state} is as specified in Table 2, thenthe average current consumed in a state can be expressed as:

$$I_{stateavg} = \frac{t_{state}I_{state}}{t_{SF}} \quad (29)$$

The average current consumed of the node in a state depends upon the time it resides in that state, which in turn depends upon the number of transmission attempts S. First we compute the time spent in transmit and wake up states by the node for S transmission attempts. The total average time spent in the transmit state by the node can be expressed as:

$$t_{TX}^{Retn} = \sum_{i=1}^{S} (1 - PAR)^{(i-1)} t_{TXData} \tag{30}$$

The total average time duration spent in the wake up state by the node can be expressed as:

$$t_{Wup}^{Retn} = 2t_{Wup} + \sum_{i=1}^{S-1} (1 - PAR)^{i} t_{Wup} \tag{31}$$

Next we compute the total average time spent by the node in the idle state for S transmission attempts. If the ith transmission attempt is successful, the node spends a time duration in the idle state equal to t_{Idle} to receive the Ack. The probability of this event is $(1 - PAR)^{i-1} PAR$. If the ith attempt is unsuccessful, time out occurs, and the node spends a time duration in the idle state equal to $t_{Idle}^{timeout}$. The probability of this event is $(1 - PAR)^{i}$. Hence the total average time duration for which the node stays in the idle state can be expressed as:

$$t_{Idle}^{Retn} = \sum_{i=0}^{S-1} (1 - PAR)^{i} \left(PAR t_{Idle} + (1 - PAR) t_{Idle}^{timeout} \right) \tag{32}$$

Next we find the total average time the node resides in the receive state for S transmission attempts. If the ith transmission attempt is successful, the node spends a time duration in the receive state equal to t_{IAck} to receive the Ack. If the ith attempt is unsuccessful, no Ack is received. Hence the total average time duration spent in the receive state has sum of S terms for Ack, and $S - 1$ terms for Poll and one term corresponding to beacon reception and can be expressed as:

$$t_{RX}^{Retn} = \sum_{i=0}^{S-1} (1 - PAR)^{i} PAR t_{Ack} + \sum_{i=1}^{S-1} (1 - PAR)^{i} t_{RXPoll} + t_{RXBeacon} \tag{33}$$

Using equations (30)–(33) in (29), we can obtain the average current consumption for a given state. The node lifetime can then be computed using equations (27) and (28).

4.11 Comments on Number of Retries and Spare Slots

We have selected the slot duration to be 3.5 ms and the number of slots as equal to 35, which gives a super frame duration of 122.5 ms. According to IEEE 802.15.6, the maximum number of nodes in WBAN shall be limited to 64 [3]. However, the number of nodes depends on the patient's condition as well. Depending on the application, some nodes may require only one slot per super frame, whereas nodes with high data rate application require more slots per super frame. To calculate the percentage of spare slots required for retransmission purpose, we assume that infinite retransmissions are allowed. In this case, the expected number of retransmissions can be considered as the mean of a geometric distribution given by $\frac{1}{1 - PER_B}$. For on-body communication, at a hop distance of 29 cm and for a payload size of 1000 bits, the PER_B is approximately equal to 0.089 and the expected number of retransmission required is 1.097. (note that these PER values are obtained from models of Sects. 4.1 and 4.2) This means that a 10 % spare slot allocation will be sufficient, if the PER_B is of this order.

5 Analytical and Simulation Results

The analytical and simulation results for the energy efficiency, PAR and the node lifetime are presented in this section. The analytical results correspond to the mathematical models presented in Sect. 4. Coherent BPSK is considered as the modulation scheme. Simulations were done on Castalia-3.2 [42], an open-source event-driven simulator based on the OMNeT++ platform. Castalia implements the baseline MAC for WBAN, proposed by the IEEE 802.15 Task Group 6. The configuration for different simulation scenarios are defined, using eight nodes with scheduled slots and their coordinates varied to reflect variation in hop distance. The initial energy of the nodes with a battery of capacity 560 mAHr; is taken as 6048 J. Table 1 gives the paremeters of header and overheads for the radio and MAC layers. The maximum value of hop distance is limited to 3 m and maximum value of payload size is 255 bytes as per the IEEE802.15.6 standard [3].

Figure 2 shows the PER for the in-body communication as well as the on-body communication. The payload is selected as 1000 bits and the PER is obtained for different values of distance separation between the node and the hub (i.e., hop distance). When hop distance increase, PER increases significantly (because of higher path loss). Further, at a fixed hop distance, the PER for in-body communication is higher compared to that of the on-body communication. Moreover, use of BCH coding scheme extends the hop distance at which a given PER performance can be satisfied. For example, considering on-body communication, use of BCH coding scheme increases the hop distance by 5 cm as compared to that of the uncoded system for a desired PER equal to 3×10^{-4}. The hop distance improvement for a desired PER for different cases are summarized in Table 4.

Figure 3 shows the variation in energy efficiency against the hop distance for a payload of 1000 bits. When the hop distance increases, the energy efficiency degrades significantly. When the hop distance is small, the energy efficiency for the uncoded case is slightly

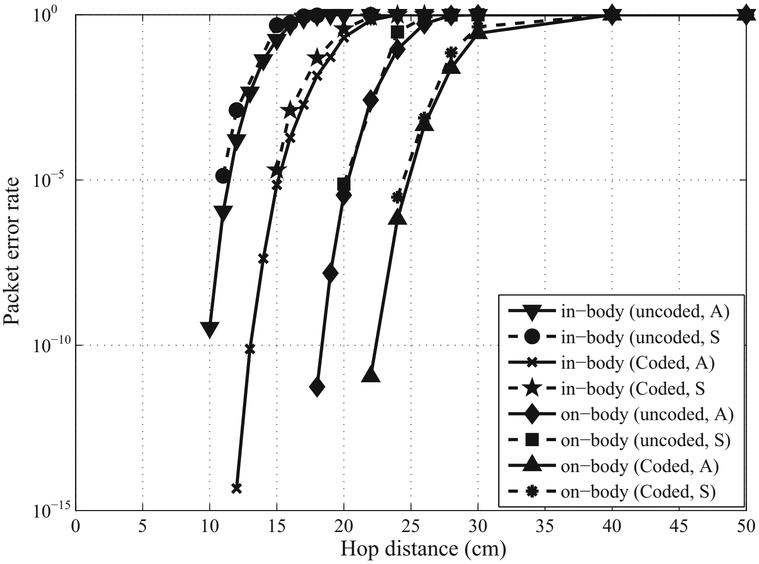

Fig. 2 Packet error rate when the hop distance between node and hub is varied for in-body and on-body propagation models for a payload size of 1000 bits (*A* analysis, *S* simulation)

Table 4 Hop distance improvement for a desired PER of 3×10^{-4} (Payload size: 1000 bits)

Scenario	Un-coded (cm)	Coded (cm)	Improvement (cm)
In-body	12.12	16.03	3.91
On-body	21.07	26	4.93

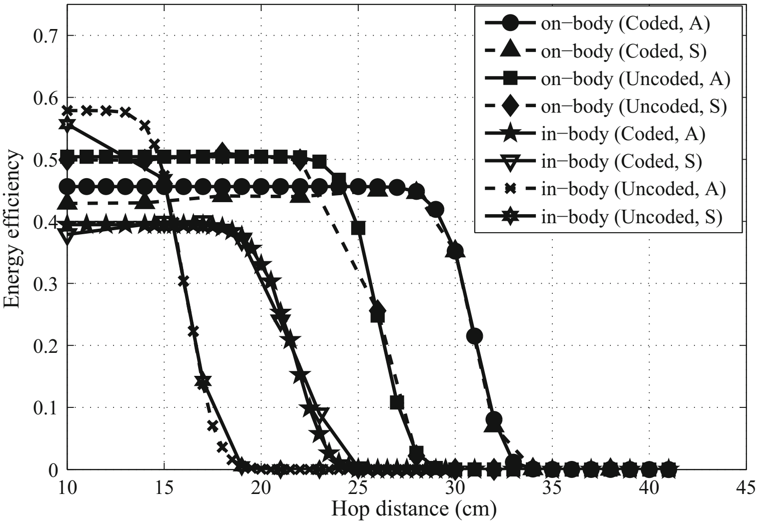

Fig. 3 Energy efficiency when the hop distance between node and hub is varied for in-body, on-body propagation models for a payload size of 1000 bits (*A* analysis, *S* simulation)

higher as compared to that of the coded system. This is because, when the hop distance is small, the channel conditions are better. Thus introducing redundancy by coding reduces the energy efficiency due to extra energy consumption associated with the overhead. A threshold is observed which separates regions where uncoded transmission is better from regions where BCH coded transmission is more benefitial in terms of energy efficiency. When the hop distance exceeds this threshold, the PER of the uncoded case is so high that the corresponding energy efficiency is drastically reduced. In this region, use of BCH coding improves the energy efficiency. Hence adopting BCH coding extends the hop distance over which energy efficient communication can be achieved.

5.1 Finding Optimal Packet Size

Figure 4 shows the results for energy efficiency when payload size is varied for the in-body channel model for different hop lengths. Results show that, when BCH coding is used optimal packet size that maximizes the energy efficiency exists when the hop distance is approximately equal to 21 cm. When packet size is less than the optimal payload size, energy efficiency decreases because of the effect of larger overhead compared to payload. When payload size exceeds the optimal value, energy efficiency decreases once again because of increase in PER. However, when the hop length is reduced the energy efficiency

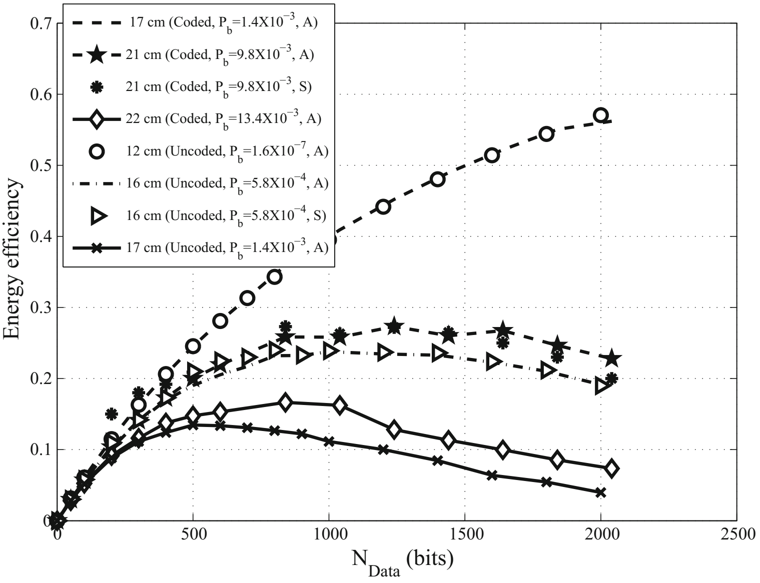

Fig. 4 Energy efficiency against payload size at different hop distances for coded system as well as uncoded system for a WBAN with in-body propagation channel (*A* analysis, *S* simulation)

Table 5 Optimal packet size improvement with coding

Communication scenario	With BCH coding			Un-coded case		
	Optimal packet size (bits)	Hop distance (cm)	PER	Optimal packet size (bits)	Hop distance (cm)	PER
In-body	700	22	0.89	600	17	0.92
On-body	850	31	0.8	750	26	0.8

increases with pay load size as can be observed for an ideal channel. For the uncoded case, the channel becomes error prone at lower hop distance because of the higher PER values. In this case, the optimal behavior is observed at a lower hop distance equal to 16 cm. Table 5 gives a list of optimal payload size obtained for different WBAN scenarios. It is observed that the optimal payload size which results in energy efficient communication is higher when BCH coding is employed as compared to that obtained for the uncoded case. Similar results are obtained for the on-body communication model.

We have evaluated the impact of different parameters (the distance d, the path loss exponent α and the shadow fading standard deviation X_σ) on the optimal packet size. Table 6 shows that, the optimal packet size reduces when the hop distance increases. This is because of the larger path loss causing the channel to be increaingly error prone. An increase in packet size causes further increase in PER which results in poor energy efficiency. Tables 7 and 8 shows the optimal packet size, when path loss exponent α and shadow fading standard deviation X_σ are varied.

Table 6 Impact of hop distance: (On-body, α: 5.9, X_σ (dB): 5)

Hop distance (cm)	30	31	32	33	34
Optimal packet size (bits)	1500	900	400	300	200

Table 7 Impact of path loss index (On-body, hop distance: 30 cm, X_σ (dB): 5)

α	5.9	6.0	6.1	6.2	6.3
Optimal packet size (bits)	1600	1200	800	500	400

Table 8 Impact of shadow fading standard deviation (On-body, Hop distance: 30 cm, α: 5.9)

X_σ (dB)	5	5.5	6	6.5	7
Optimal packet size (bits)	1500	900	500	300	200

5.2 Evaluation of Reliability, Energy Efficiency and Lifetime Under the Proposed Retransmission Scheme

Figure 5 shows the results for PAR where it is plotted against hop distance for the on-body communication scenario. We select the payload size as 1000 bits and find the PAR by varying the number of transmission attempts. As the hop distance increases, the PAR reduces owing to the higher path loss. Further, the proposed retransmission scheme improves the PAR significantly. For example, when the hop distance is equal to 30 cm, and assuming that retransmission is not permitted, the PAR is equal to 0.737 while if the retransmission scheme is employed (with $S = 2$) the PAR becomes 0.983.

Figure 6 shows the total energy consumption as a function of number of transmission attempts (S) for various channel models. Results show that the total energy consumption increases with the number transmission attempts. Figure 7 illustrates the impact of hop distance as well as the number of transmission attempts on the energy efficiency under the proposed retransmission scheme. The energy efficiency is observed to be almost independent of the number of transmission attempts. This happens because, the increase of energy expenditure due to the retransmissions (shown in Fig. 6) is compensated by an equivalent improvement in PAR.

5.3 Comparison of the Proposed Retransmission Scheme with Other Schemes

In this section, we compare the performance of the proposed retransmission scheme against that of the schemes reported in [29] and [32]. Recall that the retransmission scheme proposed in this paper relies on allocation of spare TDMA slots by means of polling. First all we compare our scheme the results for reliability with the TDMA scheme described in [29]. The authors of [29] propose a retransmission scheme based on variable TDMA scheduling, where the slots are flipped based on the outcomes of previous transmissions. The authors approximate the WBAN channel by a two state Markov model consisting of good and bad states. In fact this channel model is an approximation to the WBAN channel

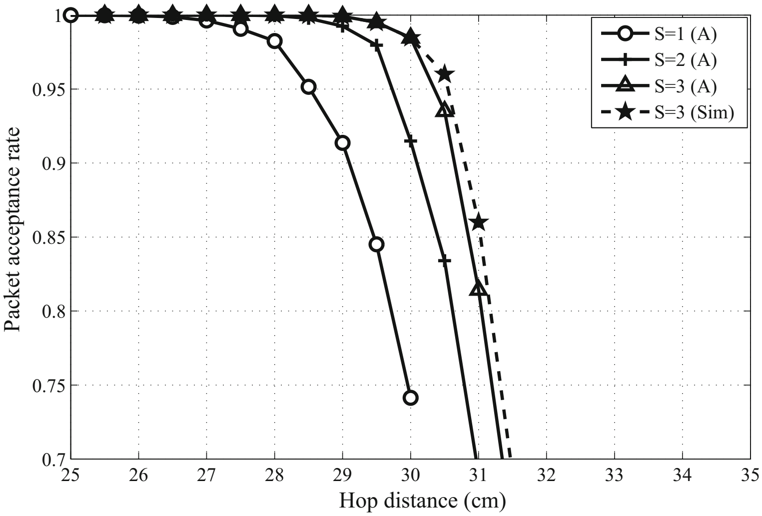

Fig. 5 Reliability: Packet acceptance rate at the hub when hop distance is varied for on-body communication for a payload size of 1000 bits for different transmission attempts (S) (*A* analysis, *Sim* simulation)

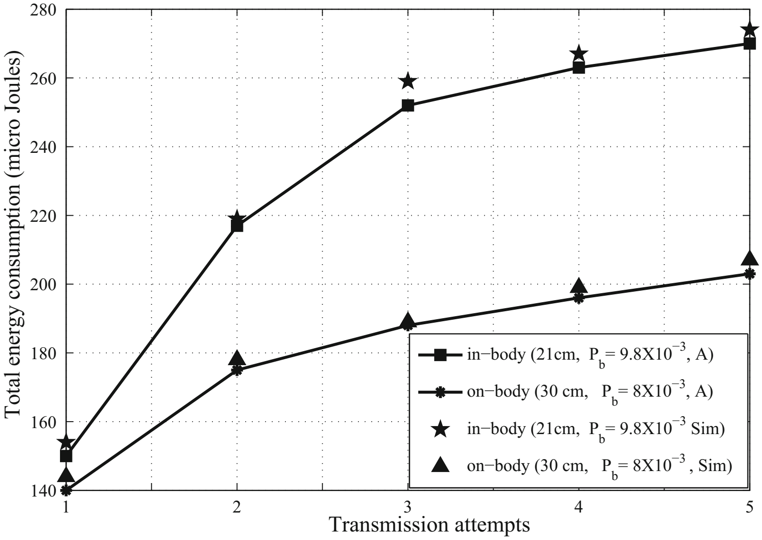

Fig. 6 Total energy consumption of the node and hub when number of transmission attempts are varied for a payload size of 1000 bits for different WBAN channels (*A* analysis, *Sim* simulation)

model reported in [35] where the states of the on- body channel are classified based on dwell times into three good states (S1, S2, and S3) and two bad states (S4 and S5). In [35], these states are described as follows: (1) S1: unstable error-free state-good channels which lasts for <20 ms; (2) S2: semi-constant error-free state-good channel which lasts for over 20 and <400 ms; (3) S3: constant error-free state-good channel which lasts for over

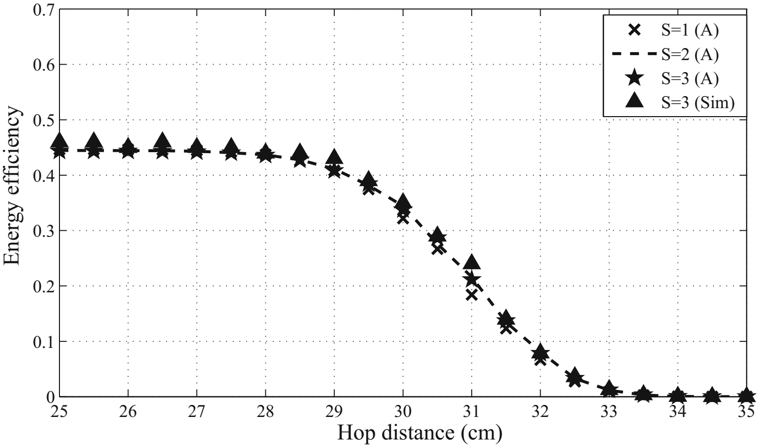

Fig. 7 Energy efficiency against hop distance with the proposed retransmission scheme, for on-body communication for a payload size of 1000 bits

400 ms; (4) S4: unstable error state- bad channel which last for <20 ms, and (5) S5: semi-constant error state-bad channel which lasts for <400 ms. For the approximate two state Gilbert model, the authors of [29] assume the long term average fraction of good slots to be above 90 %, based on public data set available for WBAN radio channel [43]. For comparing the results of our proposed scheme against that reported in [29], we try to ensure the channel-uptime to be above 90 % of the total simulation time. For this, we select the path loss parameters (which include path loss exponent as well as the shadow fading deviation) such that the channel remains as good for more than 90 % of the time. Based on the parameters for on-body communication, we set the average path loss to be <70 dB to simulate good channel conditions. We find the network reliability by averaging the results over 5000 superframes and is plotted in Fig. 8 for a given energy constraint. The proposed scheme shows improved reliability over the TDMA flipping scheme proposed in [29]. This happens because the TDMA flipping scheme relies on the ordering of slots by the hub in a span of 50 ms which is taken as the length of the super frame. For WBAN, the fading effects can last much longer (10–300 ms) which reduces the effectiveness of this scheme. In our proposed scheme, retransmission is not permitted until channel recovers from outage conditions. Thus for a given energy constraint, our proposed scheme results in higher reliability.

Next we compare our proposed scheme with the Enhanced polling scheme in [32]. Five sensor nodes are given different coordinates to represent different locations on the body (i.e., two on the wrists, two on the ankles and one on the chest). The nodes transmit packets of 1000 bits to the hub. The average path loss map given in the Castalia is used. The data rate is selected as 1024 Kbps; receiver sensitivity is assumed as equal to −87 dBm. As mentioned in Sect. 4.5, the slot duration is set as 3.5 ms and the superframe consists of 35 slots. Fig. 9 shows the PAR corresponding to all the nodes at the hub. The proposed scheme shows improvement over the enhanced polling scheme proposed in [32]. This happens because our proposed scheme combines both TDMA as well as polling. The regular transmission occurs in the scheduled access phase and for the failed packets, the hub allocates polled slots according to the channel conditions. Thus the proposed scheme thus adds the flexibility of polled allocation to pre-allocated scheduled allocation.

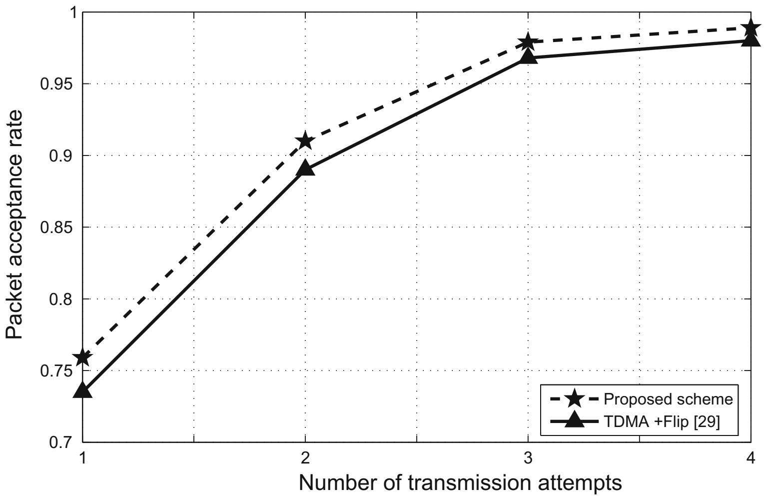

Fig. 8 Packet acceptance rate of proposed scheme and TDMA flipping scheme for different transmission attempts

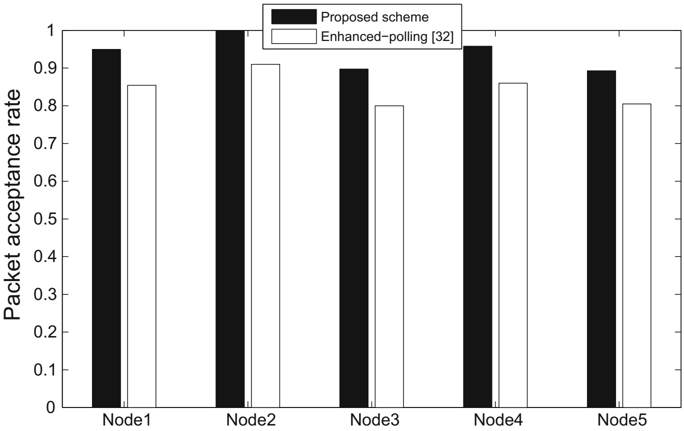

Fig. 9 Packet acceptance rate of proposed scheme and the enhancement polling scheme

The enhancement polling scheme does not include scheduled slots, and all the nodes are served through polling.

We now compare the performance of the proposed retransmission scheme with a scheme in which retransmission is done in the scheduled allocation slot of the immediate super frame. In the latter case, if a frame with sequence number j transmitted in super frame k fails, the frame is retransmitted in the scheduled allocation slot of the node during super frame k + 1. Figure 10 shows the reliability of the two retransmission strategies. Results show that, as compared to our scheme, retransmission in the immediate super frame is not beneficial. This happens because, in the latter case, the node does not wait for the allocation of retransmission slot by the hub and retransmits the frame immediately. Since a bad link may remain bad for some time, the retransmission attempt may fail again,

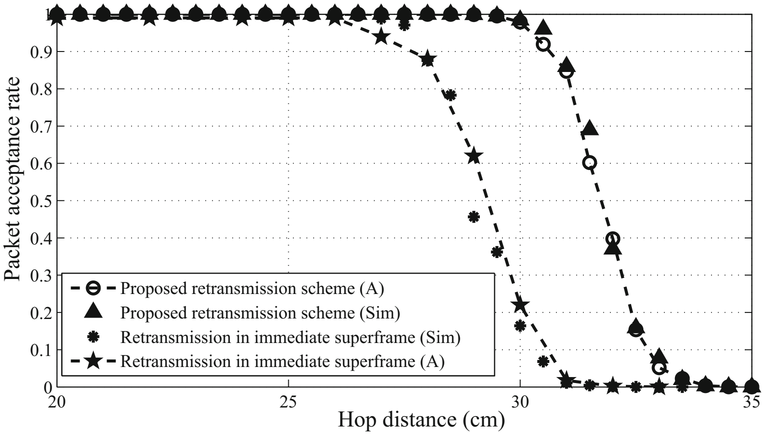

Fig. 10 Packet acceptance rate against hop distance with the proposed retransmission scheme, and retransmission in immediate super frame (*A* analysis, *Sim* simulation)

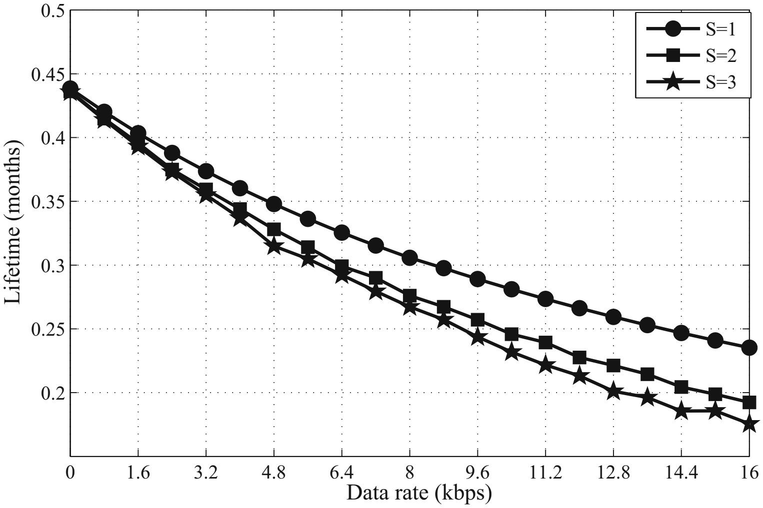

Fig. 11 Lifetime of the sensor nodes under the proposed retransmission scheme, for on-body communication at a hop distance of 30 cm

leading to degraded energy efficiency. However, in the proposed scheme, retransmission can happen only when the corresponding link favors a successful data transfer.

Figure 11 shows the lifetime of the node when the number of transmission attempts and the payload sizes are varied. Here we select the hop distance for the on-body communication scenario to be equal to 30 cm so that PER is significantly higher. When transmission attempts are increased, the lifetime decreases due to increased total energy consumption. Further, for larger payload lengths, the lifetime gets reduced significantly.

6 Conclusion

In this paper, we have proposed an efficient scheme for packet retransmission for improving reliability of wireless body area networks (WBANs) in the scheduled access mode. We have also presented analytical models to find the energy efficiency and reliability of the network under the proposed retransmission scheme. The proposed scheme was implemented using Castalia-3.2. The analytical and simulation have established that the proposed retransmission scheme can significantly improve the reliability without causing degradation of energy efficiency. The reliability of proposed scheme is compared with the TDMA based and polling based scheme in the literature.

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