Energy Efficient and Reliable Communication in IEEE 802.15.6 IR-UWB WBAN

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ENERGY EFFICIENT AND RELIABLE COMMUNICATION IN IEEE 802.15.6 IR-UWB WBAN

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***Abstract*—This paper presents an exhaustive study on the use of one-relay and two-relay cooperative communication schemes and 2-hop communication scheme for improving the energy efficiency and reliability of ultra-wideband based wireless body area networks (UWB WBANs). Various investigations have been performed to study the impact of the parameters like packet size, hop distance, transmit power and channel error rate on the energy efficiency and reliability. An optimal packet size is obtained for the maximization of energy efficiency for both on-body communication and in-body communication. The analytical and simulation results show enhanced reliability with cooperative communication than direct communication and 2-hop communication, for all values of source to destination distances. The results also depict a threshold behaviour for energy efficiency which separates the hoplength for direct transmission from the hoplength where cooperation and 2-hop communication will be useful. The simulation results reveal that if the channel conditions are poor, when the source to destination distance is larger than the threshold value, 2-hop communication gives higher energy efficiency compared with direct and cooperative communications.**

***Index Terms*—Ultra wide band, Wireless body area networks, Energy efficiency, IEEE 802.15.6, Incremental cooperative relaying, Optimum packet size, Reliability.**

I. INTRODUCTION

There is a huge necessity that future health care systems aid proactive health care managements. The wireless body area network (WBAN) concept comprises tiny intelligent sensors implanted on and/or in the human body to acquire critical physiological data which are further to be monitored by doctors or health practitioners. Approval of IEEE 802.15 TG6 physical (PHY) and the medium access control (MAC) specifications for WBAN was made in 2012 [1].

The domain of applications of UWB communication (large data rate-short distance or low data rate-long distance) is constrained to a great extend by the restrictions on the transmit power(i.e; the power limit is below 0.5mW). The transmit power constraint implies that multiple low energy UWB pulses need to be combined to transport one bit [2]. Higher number of pulses per bit implies lower data rate and, in turn, larger transmission distance. The interference of UWB signals on narrowband radio systems is very low because of its low power spectral density (PSD). The reduced size, cost and weight of the UWB transceivers due to the absence of modulator, demodulator, etc and the reduced power consumption of UWB systems make it preferred choice for WBANs. However, UWB communication is a field that needs further investigation.

To combat the multipath fading, and hence to improve the link reliability and throughput of WBANs, various techniques are presently being considered, of which, cooperative communication proposals are focussed more [3] which use relay mechanisms to improve the communication link efficiency. The traditional cooperative relaying mechanisms cause a wastage of the channel resources since the relays always forward the signal without taking into consideration the channel conditions. Usage of the orthogonal channels for communication by the relays and the source causes extra resources even though relaying is not required when successful direct communication is possible. The conservation of the channel resources form the main objective of incremental relaying schemes. If the source-to-destination link SNR is sufficiently high, an ack from the destination could be used to indicate that there exists a successful direct transmission link, and relaying is not needed [3,4]. In the case of an incremental relaying technique, the destination processes only a single signal at a time, and hence no need of co-phasing and combining, leading to simplified receiver units. Cooperative and multi-hop communications have been considered as effective methods to enhance the energy efficiency of BANS [5-6].The work in [5] proposes a model for energy efficiency in 2-hop communication and an optimal packet length to attain the maximum energy efficiency. In [6] authors propose a relay selection procedure for energy efficient cooperative communication. However, these works are for NB PHY layer.

Packet length is an important parameter which influences the reliability of transmission and energy consumption of a communication link. A long packet increases the packet error probability and thereby wasting the energy associated with the unsuccessful transmission. For smaller packet size the rate of transmission success is supposed to be increase, but short packet will lessen the system efficiency because of the packet overhead. In [4] the authors consider packet size optimization for the incremental relay based cooperative communication in WBANs based on NB PHY layer. The author in [7] also deal with the packet size optimization to enhance the eneygy efficiency for NB PHY layer. In[8] the authors study frame length optimization for UWB WBAN. The packet success rate corresponding to both PHY modes defined in the standard are derived. The work in [9] presents the use of 1-relay cooperative communication for optimizing the frame length in IEEE 802.15.6 UWB WBAN.

Different from the above works, in this paper we perform energy efficiency and reliability analysis of two-relay cooperative and two-hop UWB WBANs and compare their performance with direct link and one-relay UWB cases. For all four cases, we study the impact of packet size, hop length and packet error rate on reliability and energy efficiency. The rest of the paper is organized as follows: Section II describes the system model and the schemes that are analyzed. Section

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III gives the derivation of the packet success probabilities. Section IV provides a detailed analysis of energy efficiency and optimization of packet size. The simulation and analytical results are given in section V and the paper is concluded in Section VI.

II. System Model

According to the standard IEEE 802.15.6, a hub can handle up to 64 nodes. There are 11 channels defined for the UWB PHY in the 3.1- 10.6 GHz spectrum band, each with a bandwidth of 499.2 MHz.The nodes transmit in the orthogonal time slots. The standard emphasizes upon two modes for IR-UWB PHY: the Default mode and the High QOS (Quality of Service) mode. The default mode is used for nonspecific WBAN demands; and it features an on-off keying signaling (OOK) and BCH (63, 51) code for forward error correction. The high QoS mode is adopted for high-preference medical demands. A non-coherent receiver that is suboptimal in nature and is based on either energy detection (ED) or autocorrelation (AC) is considered because of the demand for the low complexity receivers. The type of the channel between the source and destination nodes in the sensor network can be on-body LOS, on-body NLOS, or in-body.

The in-body and on-body UWB communication path loss models are given by [10]:

$$L_{in}(d) = 10nlog(a_1.\frac{d}{d_o}) + L_{in} + X_{\sigma_0} \quad (1)$$

The on-body path loss model is expressed by [10] ,

$$L_{on}(d) = L_{on}(d_0) + 10nlog\frac{d}{d_0} + X_{\sigma_i} \quad (2)$$

Where $L_{on}(d_0)$ is the propagation path loss at a reference distance d_o, n is the path-loss exponent; X_{σ_0} and X_{σ_i} follow zero mean Gaussian distributions with standard deviation σ_0 and σ_i in dB. In-body and on-body channel parameters values are given in Table I and Table II, respectively. The semantics

TABLE I
In-Body UWB channel parameters

channel parameters	value
d_o(in mm)	1
L_{in}[in dB]	10
a_1	0.98
n	4.22
σ_0	7.8
P_t (in dBm)	-10

TABLE II
On-Body UWB channel parameters

channel parameters	NLOS	LOS
$d_o(mm)$	1	1
$L_{on}(d_o)$[in dB]	48.4	44.6
n	5.9	3.1
σ_i	5	6.1
P_t (in dBm)	-12	-12

of IEEE 802.15.6 UWB PPDU is illustrated in Fig:1. It includes the synchronization header (SHR), the physical layer header (PHR), and the physical layer service data unit (PSDU). The SHR contains a 63-bit Kasami sequence which is used in the start-of-frame delimiter (SFD); and a pool of 4 Kasami symbols in the preamble.This is being used inorder to assign 4 logical channels. The PHR is composed of PHY header (24

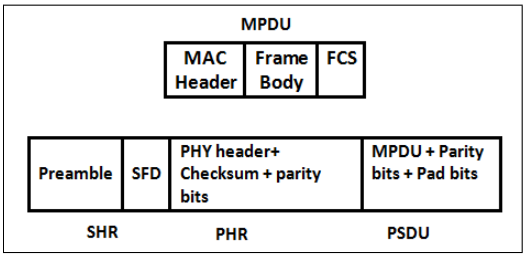

Fig. 1. IEEE 802.15.6 UWB PPDU format.

bits), check sequence (4 bits), plus 12 and 63 parity bits taken from a shortened BCH(40, 28) code in the default mode. The MPDU (MAC PDU) consist of 7 octets of header, 2 octets of frame checksum and a variable MAC frame body length of L_{fb} bits. The correct reception of PSDU unit implies the physical layer success probability. The MPDU utilize the BCH (63, 51) code. The MPDU is converted into blocks of length k = 51 bits, and it will be mapped to N_{cw} codewords of length n= 63 inorder to constitute a PHY frame. Therefore,

$$N_{cw} = \lceil \frac{72 + L_{fb}}{k} \rceil \quad (3)$$

If mod (72+L_{fb},k)≠0, then $Nbs = kN_{cw} -$ (72+L_{fb}) pad bits are added to the last codeword.
The SNR at the energy detection receiver can be written as [11],

$$SNR = \frac{2\frac{E_b}{N_o}}{4 + N_p 2TW\frac{N_o}{E_b}} \quad (4)$$

where E_b, W, N_p, N_o, T represent the integrated energy per bit, bandwidth of the signal, number of pulses per bit, noise power spectral density and integration interval per pulse, respectively. N_p is one of the optimized parameters. For the single pulse option, N_p=1 and for burst pulse case, $N_p \ \epsilon \ \{2, 4, 8, 16, 32\}$, this variable is employed to provide a balance between symbol rate and processing gain. We select the integration interval T=N_pT_p where T_p is the single pulse duration.

Relay node is to be placed at a distance that measures exactly half of the total distance between the source and destination nodes to provide a maximum energy efficiency [4]. Since the sensor nodes transmit in orthogonal time slots, the multi-access interference effect could be neglected. In direct communication scheme, only a direct transmission between the sensors and the hub is being permitted.

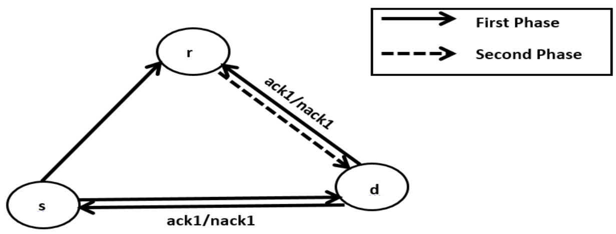

Fig. 2. One-relay incremental cooperative communication model (ack- acknowledgement; nack-negative acknowledgement)

In the second case a one-relay cooperative communication scheme is considered (see Fig 2). In the first stage of the communication, the source transmits a packet to the destination. As the broadcast medium is wireless, relay overhears the packet. In case the destination decodes the packet properly, it

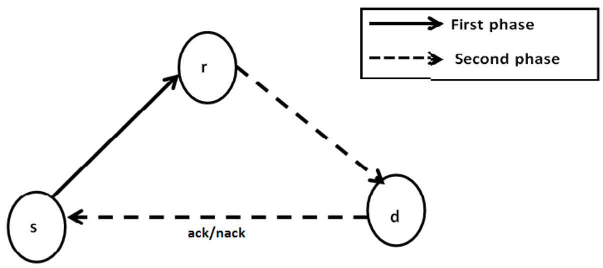

Fig. 3. 2-hop communication model

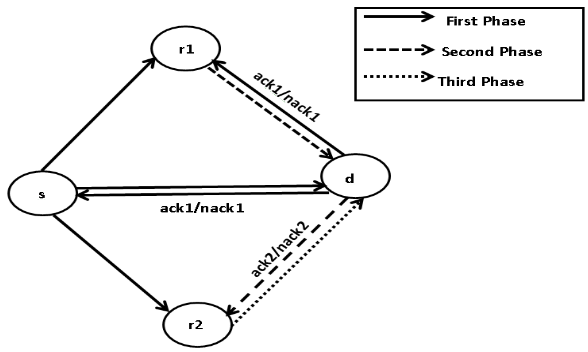

Fig. 4. Two-relay incremental cooperative communication model

sends ack and relay must remain inactive; and if destination does not decode packet properly, it sends nack to source. The relay, on hearing the nack, if it obtains the packet containing the data correctly in the first phase, it forwards the packet to the destination during the second phase. If the destination can correctly decode the packet then destination sends acknowledgment and there exists successful relaying. In a 2-hop communication (see Fig 3), in the 1st time slot source sends packets to relay node and relay node forwards the packet to destination in second time slot.

In the fourth case, a two-relay cooperative communication model is used which is illustrated in Fig 4 : Assume a given source with two potential relays r1 and r2 for help. The first phase of cooperation begins when the source transmits the data packet to destination and it is being overheard by the relays and they also attempt to decode this packet. If the destination is successful in decoding the packet, it will send back ack(ack-1) and therefore the relays remain inactive. But, if the decoding at the destination is not done properly, it will send back nack(nack-1) which the relays also receive. The second phase is initiated when the relay r1 forwards the data packet to the destination. As usual, if the destination is successful in decoding the packet, it will send back ack(ack-2). If once again the decoding is not done successfully, the destination will send back nack(nack 2), indicating the demand for another phase of communication. Upon over hearing nack 2, relay r2 forwards the data packet, initiating the third phase.

III. PACKET ERROR RATE

The expressions for the packet error rate (PER) for the four cases are presented in this section. The PER analysis is dependent on the channel models for WBAN. The code word error probability is given by

$$p_{\text{cw}} = \sum_{j=t+1}^{n} \binom{n}{j} (p_{bu})^{i} (1 - p_{bu})^{n-j}, \tag{5}$$

where t is the error correction capability and p_{bu} represents the uncoded bit error probability given by [12]

$$p_{bu} = Q(\sqrt{SNR^r}) \tag{6}$$

Note that SNR^r can be obtained by replacing E_b with rE_b from the formula for SNR given by Equation 4, where r denotes the code rate.
The coded bit error probability is [12]

$$p_b = \frac{1}{n} p_{cw} = \frac{1}{n} \sum_{j=t+1}^{n} \binom{n}{j} [p_{bu}]^j [1 - p_{bu}]^{n-j} \tag{7}$$

If l is the total length of the PSDU, then the packet-error probability is

$$p_{e,d} = 1 - (1 - p_b)^l \tag{8}$$

The packet error rate for the 1-relay cooperative communication scenario can be found as follows. Let assume $p_{e,sd}, p_{e,sr}, p_{e,rd}$ denotes the packet error probabilities for the s - d, s - r and r - d links, respectively. Packet error happen either when both s - d and s - r links fail, or when s - d and r - d links fail, at the same time s - r link is error free.

Therefore, the packet error probability for 1-relay cooperative communication can be written as,

$$p_{e,1-cc} = p_{e,sd} p_{e,sr} + p_{e,sd}(1 - p_{e,sr}) p_{e,rd} \tag{9}$$

Packet error rate for 2-hop communication is obviously,

$$p_{e,2-hop} = p_{e,sr} + (1 - p_{e,sr}) p_{e,rd} \tag{10}$$

Two potential relays, r1 and r2, are assumed to be available to help the source for two-relay cooperative communication. Let packet error rates of source-to-relay r1 (s - r1), source - to - relay r2 (s - r2), relay r1 - to -destination (r1 - d) and relay r2-to-destination (r2 - d) links be represented by $p_{e,sr1}, p_{e,sr2}, p_{e,r1d}$ and $p_{e,r2d}$, respectively. The two-relay transmission fails if :

(1)All three links fail, ie; s - d, s - r1 and s - r2 fail.
(2) The direct link and the first - stage relaying (through r1) fail; also, relay r2 cannot decode and forward the data packet because of the s - r2 link failure.
(3) The direct link and the first- stage relaying (through r1) fail and relay r2 successfully decodes and forward the data packet; however r2-d link fails.
(4) The s - d and s - r1 links fail but s - r2 link is error free; so r2 decodes and forwards but the transmission fails as a result of channel error in r2 - d link.

Therefore, packet error rate for two - relay cooperative communication can be written as,

$$\begin{aligned} p_{e,2-cc} = {} & p_{e,sd} p_{e,sr1} p_{e,sr2} + p_{e,sd}(1 - p_{e,sr1}) p_{e,r1d} p_{e,sr2} + \\ & p_{e,sd}(1 - p_{e,sr1}) p_{e,r1d}(1 - p_{e,sr2}) p_{e,r2d} + \\ & p_{e,sd} p_{e,sr1}(1 - p_{e,sr2}) p_{e,r2d} \end{aligned} \tag{11}$$

IV. ENERGY CONSUMPTION MODEL AND ANALYSIS

Typically the uplink energy consumption cost, i.e, from the sensors to the hub, is higher compared with that of the reception on the downlink.

Let E_{enc}/E_{dec} represents the energy needed for data encoding/decoding. Also let E_{tx-ack}/E_{rx-ack} denotes the energy needed for the transmission/reception of acknowledgment packets. We denote by C_{r-dl}, C_{t-dl}, C_{r-ul} and C_{t-ul}, the energy consumption costs for reception and transmission on the downlink and uplink scenarios respectievely. Let E_{tx-p} represents the total energy needed for the pulse transmission (includes the processing energy of the electronic circuit and radiation energy) and E_{rx-p} represents the total energy utilized by electronic circuits for the pulse reception. Let R represents the coding rate of data payload, indicated as number of bits per symbol and β be modulation index (1/2 for on-off signalling and 1 otherwise).

A. Direct communication

The energy needed for transmitting a packet of l bits is given by [8]:

$$E_{tx-d} = \frac{\beta N_p E_{tx-p} C_{t-ul}}{R} l + C_{t-ul} E_{enc} \tag{12}$$

The encoding energy for BCH code can be calculated as,

$$E_{enc} = (2nt + 2t^2)(E_{add} + E_{mul}) \tag{13}$$

where n is the codeword length, t is the error correcting capability,E_{add} is the addition energy consuption E_{mul} is the multiplication energy consumption.

Similarly the energy utilized to receive the packet is,

$$E_{rx-d} = \frac{N_p E_{rx-p} C_{r-ul}}{R} l + C_{r-ul} E_{dec} \tag{14}$$

The decoding energy for BCH code can be calculated as,

$$E_{dec} = (4nt + 10t^2)E_{mul} + (4nt + 6t^2)E_{add} + 3tE_{inv} \tag{15}$$

where E_{inv} is the energy consumed for inversion operation.
Similarly, the energy utilization related with transmission and reception of acknowledgment packets of size l_{ack} bits are given by,

$$E_{tx-ack} = \frac{\beta N_p E_{tx-p} C_{t-dl}}{R} l_{ack} \tag{16}$$

$$E_{rx-ack} = \frac{N_p E_{rx-p} C_{r-dl}}{R} l_{ack} \tag{17}$$

Let E_0 represents the total energy that is needed for transmission and reception of the acknowledgment packets and data encoding and decoding ,

$$E_0 = E_{tx-ack} + E_{rx-ack} + C_{t-ul}E_{enc} + C_{r-ul}E_{dec} \tag{18}$$

Therefore, the total energy spent for transfering a data packet of size l bits for the direct communication (1-hop) can be expressed as,

$$E_{total}^{1-hop} = \frac{\beta N_p E_{tx-p} C_{t-ul}}{R} l + \frac{N_p E_{rx-p} C_{r-ul}}{R} l + E_o = x(N_p l/R) + E_o \tag{19}$$

where $x = \beta E_{tx-p}C_{t-ul} + E_{rx-p}C_{r-ul}$.
Energy efficiency is formalized as the fraction of favorable energy for successful communication of a packet of L_{fb} bits to the total energy consumed, it can be computed as,

$$\eta_d = \frac{x(N_p L_{fb}/R)}{x(N_p l/R) + E_o}(1 - p_{e,d}) \tag{20}$$

B. Single-relay cooperative communication

To compute the average total energy consumption per bit of cooperative communication three events are taken into consideration. The first event is the transmission success of source to destination link (s-d) in the 1st time slot and it occurs with probability $(1 - pe_{sd})$ .The energy spent is

$$E_1 = E_{tx-d} + 2E_{rx-d} \tag{21}$$

The second event considered is the transmission failure of source to destination link(s-d) and source to relay link (s-r) in the first time slot together, which spend an energy E_2; this event occurs with probability $pe_{sd}pe_{sr}$. E_2 can be expressed as,

$$E_2 = E_{tx-d} + 2E_{rx-d} \tag{22}$$

The third event considered is the transmission failure of source to destination link, and the successful transmission of source to relay link in the first time slot with probability $pe_{sd}(1-pe_{sr})$. The energy spent can be expressed as,

$$E_3 = 2E_{tx-d} + 3E_{rx-d} \tag{23}$$

Therefore, total energy expenditure of cooperative communication on an average can be expressed as,

$$E_{total}^{1-cc} = E_1(1 - p_{e,sd}) + E_2 p_{e,sd} p_{e,sr} + E_3 p_{e,sd}(1 - p_{e,sr}) \tag{24}$$

The total energy spent for the transmission of acknowledgment packets in 1-relay cooperative communication can be written as,

$$E_{cc,ack}^1 = (E_{tx-ack} + 2E_{rx-ack})[1 + p_{e,sd}(1 - p_{e,sr})] \tag{25}$$

Here $E_{cc,ack}^1$ is total energy expenditure related with transmission of either ack or nack by the destination in first and second phase.Transmission of ack/nack in the second phase happens with probability $p_{e,sd}(1 - p_{e,sr})$.
Therefore, energy efficiency for single -stage cooperative scheme can be written as,

$$\eta_{1-cc} = \frac{x(N_p L_{fb}/R)}{E_{total}^{1-cc} + E_{cc,ack}}(1 - p_{e,1-cc}) \tag{26}$$

C. 2-Hop communication

Energy efficiency calculation of 2 - hop communication for narrowband WBAN communication is proposed in [5]. We do similar calculation for impulse radio UWB PHY in order to compute the total energy utilization of 2-hop communication, two events are taken into account: the first event is the successful transmission from source to relay link in the first time slot and it consumes energy E_1; this event occurs with probability $(1-p_{e,sr})$. Second event is the transmission failure of source to relay link in the first time slot that utilize an energy E_2 with probability $p_{e,sr}$. E_1 and E_2 can be written as,

$$E_1 = 2E_2 = 2\{E_{tx-d} + E_{rx-d}\} \tag{27}$$

The total average energy consumption of 2 - hop communication is expressed as,

$$E_{total}^{2-hop} = E_1(1 - p_{e,sr}) + E_2 p_{e,sr} \tag{28}$$

The total energy spent for transmission of acknowledgment packets in 2-hop communication $(E_{2-hop,ack})$, can be written as,

$$E_{2-hop,ack} = (E_{tx-ack} + E_{rx-ack})[1 - p_{e,sr}] \tag{29}$$

Here $E_{2-hop,ack}$ is the energy spent for the transmission of either ack or nack by the destination when the relay decodes and forwards the packet to the destination (occurs with probability $(1-p_{e,sr})$).

Therefore energy efficiency of 2-hop communication can be written as,

$$\eta_{2-hop} = \frac{x(N_p L_{fb}/R)(1-p_{e,2-hop})}{E_{total}^{2-hop} + E_{2-hop,ack}} \quad (30)$$

D. Two-relay cooperative communication

Energy efficiency calculation of 2-relay cooperative communication for narrowband WBAN communication is done in [4], which is extended to IR-UWB PHY. Inorder to compute the energy efficiency, we take into consideration the different events for successful packet transmission as follows: (1) Direct communication is sucessful, with probability (1-pe_{sd}), and because of the broadcast nature of the medium the two relays overheard the data sent from sourse. Therefore, total energy consumed in this case is $(E_{tx-d} + 3E_{rx-d})$

(2)The s - d link fails, whereas s-r1 link is error free, and the relay r1 decodes and forwards the packet with probability $p_{e,sd}(1-p_{e,sr1})$, causing an energy expenditure in total as $(2E_{tx-d} + 4E_{rx-d})$

(3) Both s - d and s - r1 links fail, whereas s-r2 link is error free. The probability corresponding to this event is $p_{e,sd}p_{e,sr1}(1-p_{e,sr2})$ and the energy expense is same as in case 2.

(4) The s - d link fails, whereas s-r1 link is error free, and relay r1 forwards the packet after decoding, but r1 - d link and s - r2 are in error and the packet is discarded at the relay r2. The probability corresponding to this event is, $p_{e,sd}(1-p_{e,sr1})p_{e,r1d}p_{e,sr2}$ and the energy expense is same as in case 2.

(5) The s - d link fails, whereas s - r1 link is error free, and the relay r1 forwards the packet after decoding, but r1 - d link is in error and first-stage relaying fails. Though, the s - r2 link is error free, and the relay r2 forwards the packet after decoding. The probability of this event is $p_{e,sd}(1-p_{e,sr1})p_{e,r1d}(1-p_{e,sr2})$ and the energy consumed in this case is $(3E_{tx-d} + 5E_{rx-d})$

(6) The s-d link, s-r1 link and s-r2 link all fail with probability $p_{e,sd}p_{e,sr1}p_{e,sr2}$ and the energy consumed in this case is $(E_{tx-d} + 3E_{rx-d})$.

Therefore, the average energy consumption in total for the data packet transmission can be calculated as,

$$\begin{aligned} E_{total}^{2-cc} &= (E_{tx-d} + 3E_{rx-d})(1-p_{e,sd}) + \\ &(2E_{tx-d} + 4E_{rx-d})p_{e,sd}(1-p_{e,sr1}) + \\ &(2E_{tx-d} + 4E_{rx-d})p_{e,sd}p_{e,sr1}(1-p_{e,sr2}) + \\ &(2E_{tx-d} + 4E_{rx-d})P_{e,sd}(1-p_{e,sr1})p_{e,r1d}p_{e,sr2} + \\ &(3E_{tx-d} + 5E_{rx-d})p_{e,sd}(1-p_{e,sr1})P_{e,r1d}(1-p_{e,sr2}) \\ &+ (E_{tx-d} + 3E_{rx-d})p_{e,sd}p_{e,sr1}p_{e,sr2} \end{aligned} \quad (31)$$

Likewise, the energy consumption in total for transmission of ack/nack packet can be calculated as,

$$\begin{aligned} E_{cc,ack}^{2} &= (E_{tx-ack} + 3E_{rx-ack}) + \\ &(E_{tx-ack} + 3E_{rx-ack})p_{e,sd}(1-p_{e,sr1}) + \\ &(E_{tx-ack} + 2E_{rx-ack})p_{e,sd}(1-p_{e,sr1})p_{e,r1d}(1-p_{e,sr2}) \\ &+ (E_{tx-ack} + 2E_{rx-ack})p_{e,sd}p_{e,sr1}(1-p_{e,sr2}) \end{aligned} \quad (32)$$

Therefore, energy efficiency of two-stage cooperative communication can be calculated as :

$$\eta_{2-cc} = \frac{x(N_p L_{fb}/R)}{E_{total}^{2-cc} + E_{cc,ack}^{2}}(1-p_{e,2-cc}) \quad (33)$$

E. Optimal packet size

The optical packet size is charecterized by the payload size that maximizes the energy efficiency, and can be derived by taking $\frac{d\eta}{dL_{fb}} = 0$ where η denotes the energy efficiency of the respective communication scheme. In the case of direct communication, the optimal packet size can be derived as [9],

$$L_{1-hop}^{Opt} = -\frac{v}{2} + \frac{1}{2}\sqrt{v^2 - \frac{4v}{ln(1-p_e)}} \quad (34)$$

where $v = \frac{E_o R}{xwN_p}$, w=1+$\frac{r}{k}$, $r = \frac{k}{n}$ is the code rate. The expressions of optimal packet size for cooperative communication and 2-hop communication schemes cannot be obtained in closed form. However, we can obtain them using numerical methods. UWB system parameters and values employed for numerical results are given in Table III.

TABLE III
UWB SYSTEM PARAMETERS [13], [14], [15]

N_p	32
W	499.2MHz
T	2ns
C_{t-ul}	0.9
C_{r-ul}	0.1
C_{r-dl}	0.9
C_{t-dl}	0.1
E_{tx-p}	20pJ
E_{rx-p}	2.5nJ
l_{ack}	144
$N_0(dBm)$	-100

V. RESULTS AND DISCUSSION

The analytical and simulation results for the PER of direct, 1-relay and 2-relay cooperative communication and 2-hop communication are shown in Figs 5, 6 and 7 for on-body NLOS, in-body and on-body LOS channels respectively. It is noticed that the packet error rate of cooperative communication is lesser when compared to direct communication and 2-hop communication, irrespective of the source to destination distance. A direct link when not reliable, the cooperative communication leads to lowering of the PER because of the possibility of an alternative independent faded path through relay. Thus co-operative phenomenon can extend the hop length, for which a reliable communication can be attained. Another important comparison is the impact of the channel model on each communication scheme. For a given source-destination distance, on-body LOS has the least impact and in-body channel has the worst impact, which is quite intuitive.That is, for a given packet error rate, on-body LOS channel gives the maximum hop length and the in-body channel gives the minimum hop length. It is also observed that PER is lower when two relays are made use for cooperative communication.

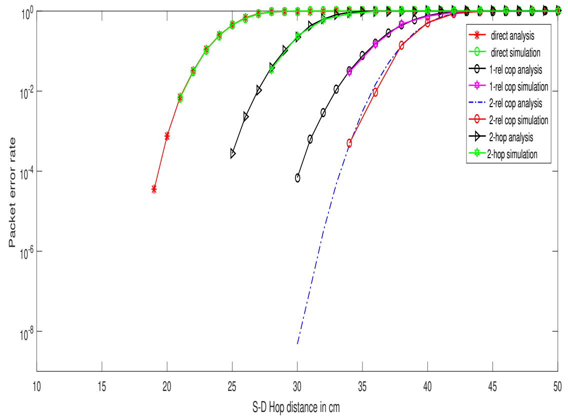

Fig. 5. Packet error rate vs source to destination hop distance for on-body NLOS channel (packet size 500 bits):1-relay, 2-relay and 2-hop communication

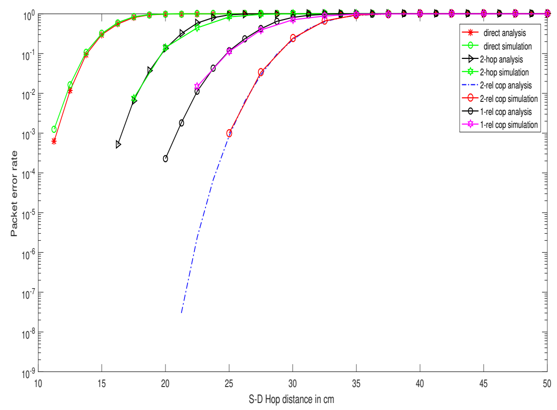

Fig. 6. Packet error rate vs source to destination hop distance for in-body channel (packet size 500 bits):Direct, 1-relay, 2-relay, 2-hop communication.

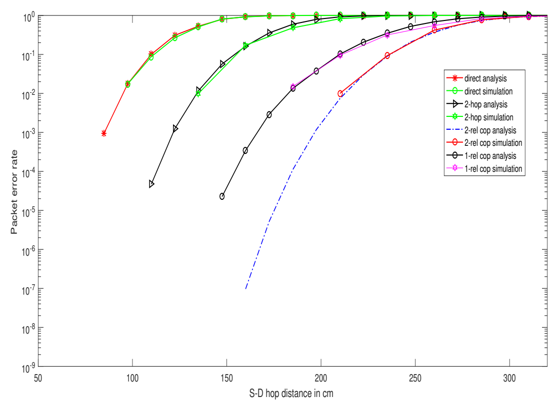

Fig. 7. Packet error rate vs source to destination hop distance for on-body LOS channel (packet size 500 bits):Direct, 1-relay, 2-relay, 2-hop communication.

Figs 8, 9 and 10 depict energy efficiency vs packet size for in-body, on-body NLOS and on-body LOS channels respectively with two different hop lengths. Below an optimal packet size, the energy efficiency decreases due to the overhead proportion that is high when compared with the payload size. If the size of packet is larger than an optimal value, energy efficiency decreases due to the rise in PER. But for better channel conditions, an optimal behavior is not seen. In such scenario, the PER is comparatively low thus the energy efficiency is not influenced by a packet size variation. But if the size of the packet is very small, then there is an increased overhead in each packet which will limit the energy efficiency. When the source to destination distance is increased to large values, an optimal behaviour is not exist for direct communication and the energy efficiency is approximately equal to zero, because the PER of direct communication become one at this distance. Similarly, an optimal behavior is not seen in the case of small PER. Obviously, in error-prone channel, the cooperative communication will support a higher packet size and thus maximum energy efficiency is obtained. Figs 11, 12 and 13 show simulation results of the energy efficiency against the source-to-destination hop distance for a fixed payload size. There exists a threshold distance which separates the area in which direct communication is superior from the area where cooperative communication is more beneficial. Below the threshold, eventhough the cooperative communication increases the reliability (lower PER), the energy efficiency is affected more by the extra amount of -

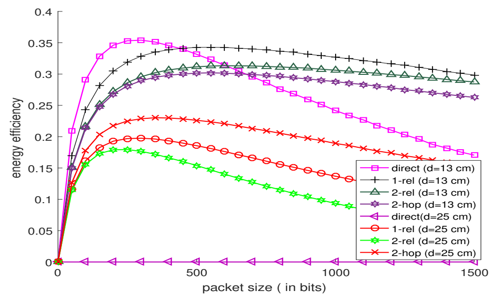

Fig. 8. Energy efficiency vs packet size for in-body channel

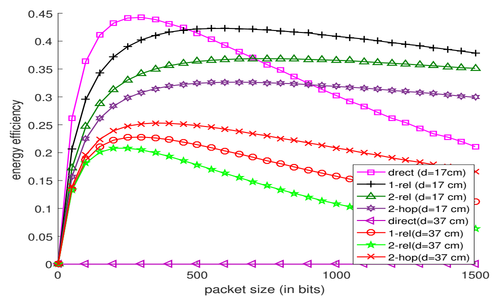

Fig. 9. Energy efficiency vs packet size for on-body NLOS channel

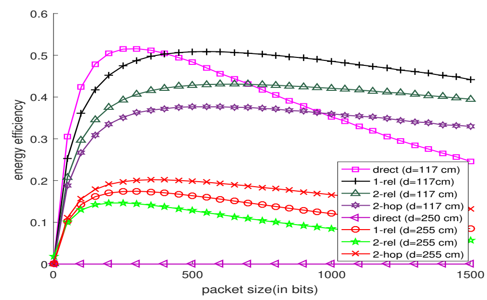

Fig. 10. Energy efficiency vs packet size for on-body LOS channel

transmissions and decoding aspects by the relays. Fig 11 reveals that for in-body communication the energy efficiency diminishes considerably at a hop length of 20 cm for direct communication while a one-relay and two - relay cooperation enhance the hop distance to about 35 cm and 2-hop communication extends the hop distance to about 42 cm. The values corresponding for on-body LOS communication are 210 cm, 430 cm and 600 cm. Tables IV and V consolidate the optimal packet size and threshold hop lengths for the various cases. We have not shown the results of impact of transmit power because of paper length constraint.

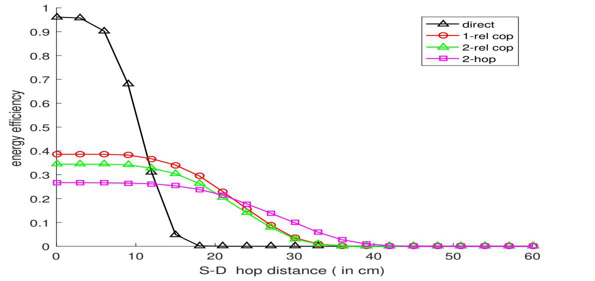

Fig. 11. Energy efficiency vs source to destination hop distance for in-body channel (packet size 350 bits).

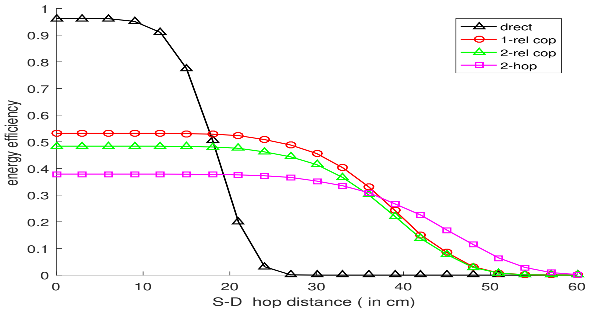

Fig. 12. Energy efficiency vs source to destination hop distance for on-body NLOS channel (packet size 350 bits).

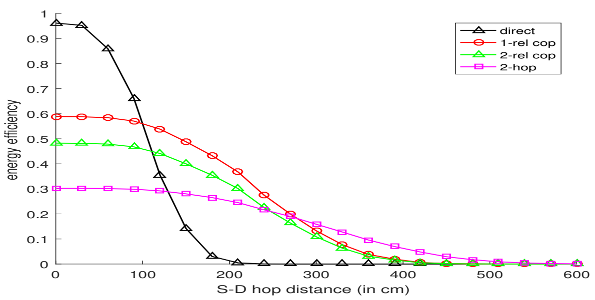

Fig. 13. Energy efficiency vs source to destination hop distance for on-body LOS channel (packet size 350 bits).

TABLE IV
COMPARISON OF OPTIMAL PACKET SIZE (BITS)

WBAN Scenarios	in-body	on-body (NLOS)	on-body (LOS)
Direct	300	300	300
1-relay Cooperative	600	650	500
2-relay Cooperative	700	800	680
2-hop	550	650	600

TABLE V
THRESHOLD VALUE OF SOURCE TO DESTINATION HOP LENGTH FOR PACKET SIZE=350 BITS .

WBAN Scenarios	Threshold distance(in cm)
in-body	14
on-body (NLOS)	19
on-body (LOS)	130

VI. CONCLUSION

The energy efficiency and the reliability aspects of IEEE 802.15.6 based WBANs with UWB PHY layer, for direct communication as well as single-relay and two-relay incremental cooperative communication and 2-hop communication scenarios have been investigated. With the help of analysis and simulation, we obtain the parameter settings for which the incremental relay based cooperative transmission techniques increase the reliability of the communication as well as the energy efficiency. The results also show that there is a threshold hop length which separates the regions of the direct transmission from the regions where cooperation is advantageous with respect to the energy efficiency. The results obtained give guidelines in finding out if cooperation technique is to be used,which relay is to be chosen, and what is the optimal number of relays for a given communication scenario.

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