Effects of relaying on network lifetime in 2.4GHz IEEE802.15.4 based body area networks

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***Abstract*—Relaying is a major technique to increase network lifetime in wireless sensor networks (WSNs) and body area networks (BANs). The results of relaying studies highly depend on power consumption model of relay's transmitter and receiver radio, channel and mobility models. In this work, we study the effect of relaying with 2.4GHz IEEE802.15.4 modules on network lifetime. We analytically derive the energy expenditure of relays in which we use the path loss probability distribution function (PDF) over links, which is derived from our link characterization using micaZ motes, and the existing power consumption models. It turns out that in order for relaying to be beneficial to network lifetime and for the same transmitter power amplifier efficiency, receive power consumption of IEEE802.15.4 widely used RF modules, e.g., micaZ motes are required to be decreased. For instance, receive power of 17mW helps us achieve 25% more lifetime with 3-relay scheme than single-hop transmission over ankle-waist link during walking, whereas with the current receiver, we achieve 12% less lifetime compared to single-hop scenario.**

***Index Terms*—Body area networks, relaying, IEEE802.15.4, micaZ modules, convex function, power amplifier efficiency**

I. Introduction

WIRELESS body area network (WBAN) is a subclass of wireless sensor networks(WSNs) and consists of a set of sensing nodes or relays mounted on the human body or implanted into the tissues. Sensing nodes make observations of human body vital signs and send these observations to a centralized data monitoring and processing centre, i.e., an off-body base station or an on-body sink node usually mounted on the left waist, by means of wireless communications.

It is of utmost importance to increase WBANs lifetime since power resource constraints are more severe and batteries may not be easily accessible [1].

In order to decrease the transmit power consumption which results in increased lifetime in WBANs and WSNs, relaying techniques have been proposed. Previous works [2]–[4] take advantage of the non-linear behaviour of path loss versus distance, i.e., simple $1/d^n$ model to place the relays in desired locations along the route in order to cut down either aggregate power consumption or lifetime of the system. In [2], authors proposed a relay placement technique based on placing relays within line of sight (LOS) distances of each other and have concluded that relaying in WBANs cuts down the average energy consumption of sensor nodes significantly compared to single-hop routing. In [3] Braem et. al proposed cooperative relaying for BANs. Using multihop relaying, tree topology deployment on the body and cooperative relaying proved to be effective in order to provide fairness to power consumption of different tree stages and therefore increasing network lifetime. Shelby et. al studied power consumption of multihop routing in WSNs for two different relaying schemes, i.e., equidistant and optimal space relaying [4].

We believe that the assumptions used in [2]–[4] are not valid for WBANs. The aforementioned studies are all based on the path loss model introduced in [5], [6] and power consumption models introduced in [7], [8]. In [2], [3], the assumption is that the transmitter radio has a fixed power amplifier efficiency and transmitter power decays proportionally with $1/d^n$, where the path loss exponent n being classified to LOS and non-line-of-sight (NLOS) situations [5], [6]. Another assumption is that the studied RF module can take on any required transmit power level. These three assumptions cause relaying to raise network lifetime and lower aggregate power consumption in a considerable manner. It is noteworthy that propagation model proposed in [5] applies to ultra wide band (UWB) scenarios whereas the studied CC2420 chip is a narrowband ZigBee RF module. The model proposed in [6] applies to a specific half wavelength dipole antenna while the ones mounted on micaZ chips are integrated quarter wavelength monopoles. Some work was later proposed to address on-body propagation and path loss behaviour of ZigBee WBANs using micaZ motes [9], [10]. We noticed that there is a remarkable discrepancy between the path loss exponents, models extracted from [9], [10] and those obtained from [5], [6] and applied in [2], [3]. To the best of our knowledge how these channel models, receiver and transmitter power consumption models affect the network lifetime and whether they provide enough accuracy when estimating lifetime has not been studied.

In this work we study how realistic channel estimation and power consumption model affect the power efficiency of relaying mechanisms in IEEE802.15.4-based WBANs which shows that packet relaying may not always be a lifetime efficient strategy. Relaying in turn impacts the WBAN lifetime and power consumption in the network. We will express how different transmitter and receiver radio parameters can render relaying benefical or detrimental to lifetime of WBANs.

In order to do network lifetime analysis we need to know the behaviour of on-body links in terms of path loss during doing actions of interest. The on-body links are characterized using micaZ motes where received signal strength indication (RSSI) is recorded with a high sampling rate at the receiver end of the link during doing two highly mobile actions (brisk walking and jumping jack). This enables us to calculate path

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loss probability distribution function (PDF) and consequently average bit error rate (BER) and packet error rate (PER) for every considered on-body link at different transmit power levels. The rest of the paper is as follows. In section II we analytically derive the power consumption of relays that makes it possible to assign them transmit power levels at which relays consume the minimum power and network lifetime, route lifetime in this work, is maximized. The performance evaluation of our technique followed by measurement setup, lifetime efficient relaying with micaZ motes and results are explained and justified in III followed by the conclusion in IV.

II. On-body relaying scheme

In this section, we describe an analytical approach to obtain the transmit power levels of on-body nodes in order to maximize route lifetime for any relay placement scheme. In section II-A we define route lifetime based on literature and introduce the node which is decisive in route lifetime. In order for route lifetime to be calculated, the consumed average energy per packet for every node along the route is required, and this will be done in section II-B. In order to do so we need to know characteristics of channel, deployed communications standard along with receiver and transmitter power consumption model. The impact of channel and communications standard, i.e., IEEE802.15.4, translates to the relationship between transmit power level and packet error rate. This relationship will be explained in section II-C. Transmitter and receiver power consumption models which are proposed in literature are discussed in section II-D. Finally in section II-E, we describe the procedure to select transmit power levels so that the convex function of energy consumption derived in II-B becomes minimized.

A. The best m-relay route in terms of network lifetime

In this section we explain the procedure to come up with the best m-relay on-body route in terms of lifetime. Each route is a sequence of relays from the source to the sink, while m-relay route is a path which goes through sink, source and m on-body relays. In the literature, network lifetime is defined as the lifetime of the shortest-lasting relay as its death will cause disconnection in the network [11], [12]. In this study a fixed transmit power level is used for each link over time which makes sense since no real time link assessment was done. The objective is to study and calculate lifetime of routes with different relay placement setups along with optimum transmit power levels. Let us assume that for given on-body source and sink locations, we have a sample space of routes Ω. One question that is raised is the minimum distance between the relays. This is restricted by the near field distance of relays antennas in the sense that the distance between contiguous relays are set to be more than Fraunhofer distance which is less than 5cm for micaZ integrated antennas. In [2] $d_{LOS} = 30cm$ has been used as line of sight between nodes is the criterion. In this work we comply with this criterion plus the fact that the minimum distance between contiguous nodes should be close enough that the lowest micaZ transmit power level guarantees successful packet reception over the links. Since we study ankle-waist and wrist-waist routes, for a normal height male, placing the relays on the joints has the advantage of having LOS between every two adjacent relays even at the highest level of mobility. Even though in order to satisfy our second criterion we decide to consider mounting relays between joints as well. The detailed node placement will be explained in section III-A. Based on these criteria, we divide the source-sink path to n shorter hops or $n-1$ possible relays. Energy consumption per packet for each node is defined as the energy it consumes to receive and forward a data packet successfully including corresponding retransmissions, ACK or NACK packets. The energy consumption of source and relay nodes will be calculated in the next section. Let E^k_{max} denote the energy consumption per packet of the highest consuming node in the kth route of Ω. Assuming that BAN application requires r packets to be sent over the path every second, and every node is equipped with a battery which stores total energy of E_{tot}, one can conclude that lifetime of the kth route denoted by t^k_l can be calculated by $t^k_l = \frac{E_{tot}}{r.E^k_{max}}\cdot$ Note that BAN applications are mostly low data rate and we therefore neglect the possibility of congested channel. Nevertheless in this study, we are only concerned with single source cases and ignore the likeliness of two transmission attempts at a single time slot. From now on, the term best m-relay route is replaced by m-relay route.

B. Relay and source node power consumption in multihop packet forwarding

In this section, we calculate the average energy per packet that each node consumes to forward a packet successfully. Based on the discussion in section II-A, each route in Ω is comprised of one source, one sink and a number of relays varying from 0, i.e., single-hop transmission, to $n-1$. Sink is assumed to be connected to an infinite power supply and therefore we are not concerned with its energy expenditure. First, we start with calculating the energy consumption for a given relay node. For a given route, there are two links emanating from the lth relay; one is incoming, lth link, and the other is outgoing, $(l+1)$th link. We assume that each relay sends a NACK packet in the event of not receiving the data packet successfully. Let $P^{(l)}_T$ and $P^{(l)}_{T_{NACK}}$ denote the transmitter power consumption to transmit the data and NACK packets over the lth link along the route respectively. The lth relay energy consumption can be divided to the incoming and outgoing link energy consumption, $E^{in}_{rel,l}$ and $E^{out}_{rel,l}$ respectively. Moreover, $E^{in}_{rel,l}$ consists of receiving the data packet and transmitting NACK packet, whereas transmitting data packet and receiving NACK contribute to $E^{out}_{rel,l}$. For a given route, let $\delta^{(l)}_{P_{Tx}}$ denote PER over lth link when transmit power level P_{Tx} is adopted and let P_R represent receiver power consumption. The relationship between $\delta^{(l)}_{P_{Tx}}$ and P_{Tx} will be elaborated in section II-C. In this study we assume that data packet length, t_p is fixed and length of NACK packet is α times that of data packet. The relay outgoing average energy consumption $E^{out}_{rel,l}$ can then be derived by

$$E^{out}_{rel,l} = t_p.\Bigg[(1-\delta^{(l+1)}_{P_{Tx}})[P^{(l+1)}_T]+ \delta^{(l+1)}_{P_{Tx}}(1-\delta^{(l+1)}_{P_{Tx}})[2P^{(l+1)}_T+\alpha P_R]+\dots\Bigg], \tag{1}$$

and $E^{in}_{rel,l}$ can be calculated by

$$E^{in}_{rel,l} = t_p \cdot \Bigg[(1-\delta^{(l)}_{P_{Tx}})[P_R] + \delta^{(l)}_{P_{Tx}}(1-\delta^{(l)}_{P_{Tx}})[2P_R + \alpha P^{(l)}_T] + \dots \Bigg], \tag{2}$$

where for the sake of simplicity, it is assumed that $P^{(l)}_T = P^{(l)}_{T_{NACK}}$ which is based on symmetric links assumption. The ith term in the right hand term of above sums represents the scenario in which i transmissions are needed to successfully forward the packet. The derivation of geometric series helps us simplify the above equations to

$$\begin{aligned} E^{out}_{rel,l} &= t_p \cdot \frac{P^{(l+1)}_T + \alpha \delta^{(l+1)}_{P_{Tx}} P_R}{1-\delta^{(l+1)}_{P_{Tx}}}, \\ E^{in}_{rel,l} &= t_p \cdot \frac{P_R + \alpha \delta^{(l)}_{P_{Tx}} P^{(l)}_T}{1-\delta^{(l)}_{P_{Tx}}}. \end{aligned} \tag{3}$$

The average energy consumption per packet per relay can then be expressed by

$$E_{rel,l} = E^{out}_{rel,l} + E^{in}_{rel,l}. \tag{4}$$

Source energy consumption is slightly different in the sense that it is only connected to the outgoing link which simplifies source energy consumption to

$$E_{source} = E^{out}_{source}. \tag{5}$$

C. Bit and packet error rate calculation of on-body links

In this section we explain how measurements help us derive on-body links bit error rate (BER) and packet error rate (PER) and discover their relation with transmit power level. Based on [13] provided that PDF of signal to noise ratio (SNR) values for an arbitrary channel and when ith transmit power level P^i_{Tx} employed is $f^i(\gamma_s)$ and bit error rate of additive white Gaussian (AWGN) channel for $SNR = \gamma_s$ is given by $P^{AWGN}_b(\gamma_s)$, BER of desired link can be calculated by

$$P^{(i)}_b = \int_{-\infty}^{+\infty} P^{\mathrm{AWGN}}_b(\gamma_s) f^i(\gamma_s) d\,\gamma_s. \tag{6}$$

According to [14], BER of 2.4GHz IEEE802.15.4 for AWGN channel can be calculated by

$$P^{\mathrm{AWGN}}_b = \frac{8}{15} \times \frac{1}{16} \times \sum_{k=2}^{16} (-1)^k \binom{16}{k} e^{20 \times \mathrm{SINR} \times (\frac{1}{\mathrm{k}}-1)}. \tag{7}$$

Note that in this work, we assume there is no interference present in the network, which means there is never more that one node taking up a time slot to forward a packet. In highly mobile BANs, $f^i(\gamma_s)$ is not analytically known since we do not know the fading distribution due to the complex environment, multipath effects, and other factors effecting $f^i(\gamma_s)$. Therefore, based on SNR measurements during doing actions and for different transmit power levels, P^i_{Tx}, we estimate (6) by

$$P^{(i)}_b = \sum_{j=-\infty}^{+\infty} P^{\mathrm{AWGN}}_b(\gamma_{s_j}) Pr^i(\gamma_{s_j}), \tag{8}$$

in which $Pr^i(\gamma_{s_j})$ is the probability that SNR falls within $[\gamma_{s_j}, \gamma_{s_{j+1}}]$ when $\gamma_{s_{j+1}} - \gamma_{s_j}$ is small enough and ith transmit power level is adopted. From (8), and assuming that data packets are f-bit long, provided that CRC which is being used in RF modules of interest is only able to do error detection, $\mathrm{PER} = 1-(1-\mathrm{P_b})^{\mathrm{f}}$. Therefore, as can be seen above we make use of measurements to find $Pr^i(\gamma_{s_j})$ for every transmit power level P^i_{Tx}. Note that the sampling interval of path loss instances from which $Pr^i(\gamma_{s_j})$ is calculated is chosen to be more than approximate coherence time of the channel.

D. Transmitter and receiver radio power consumption model

Transmitter and receiver power consumption model plays a key role in energy consumption of the nodes and consequently lifetime of the route. Wang et. al have proposed power consumption model for CC2420 modules, which are widely used in IEEE802.15.4 studies [15]. The transmitter power consumption, $P_T(d)$, which denotes the power consumption of the transmitter's radio in order to have a desired SNR at distance d and P_R which indicates receiver's radio power consumption have been modelled by

$$\begin{aligned} P_T(d) &= P_{T_0} + P_A(d), \\ P_R &= P_{R_0}, \end{aligned} \tag{9}$$

where P_{T_0} is the power which is dissipated in the module electric circuit and is a fixed term, whereas $P_A(d)$ is the power consumed at power amplifier and is a function of transmit power $P_{Tx}(d)$ which is the required transmit power in order to have the desired SNR at distance d. Note that P_R is a fixed term and is independent of the received signal power and other factors. Power amplifier's power consumption and transmit power level are related with amplifier drain efficiency η, $P_A(d) = P_{Tx}(d)/\eta$. Amplifier drain efficiency may increases with output power level [15], [16] for some RF modules, e.g., CC2420, CC1000. Moragrega et. al have proposed a linear fitting model for η and P_{Tx},

$$\eta = a_1 + a_2 P_{Tx}, \tag{10}$$

which yields acceptable results in terms of modelling data sheet and measured values [16].

E. Optimum transmit power selection for maximum lifetime

In order to maximize the route lifetime while having the aggregate power consumption minimized, we will try to minimize (4), (5) for every relay and also the source. Based on our experiments and calculations, we discovered that $E^{out}_{rel,l}$ and $E^{in}_{rel,l}$ in (3) are convex functions of $P^{(l+1)}_{Tx}$ and $P^{(l)}_{Tx}$ respectively. In fact, it can be intuitively seen that $E^{out}_{rel,l}$ starts to increase while $P^{(l+1)}_{Tx}$ exceeds the optimum point, moreover $P^{(l+1)}_T$ keeps increasing with a higher rate compared to other terms in the fraction which are functions of $P^{(l+1)}_{Tx}$, since packet error rate gets close to 0. On the other hand $E^{in}_{rel,l}$ mostly flattens out while $P^{(l+1)}_{Tx}$ keeps increasing since P_R is almost a fixed term and independent of received packet power for IEEE802.15.4 RF modules. Thereby we simplify the problem of minimizing (4) to minimizing $E^{out}_{rel,l}$ in (3). Moreover, it was observed that minimizing $E^{out}_{rel,l-1}$ provides us with a $P^{(l)}_{Tx}$ that renders $E^{in}_{rel,l}$ almost flattened and consequently minimized since it is a convex function of $P^{(l)}_{Tx}$.

III. Performance evaluation of on-body relaying with IEEE802.15.4 RF modules

As discussed and shown in section II, parameters of RF module's receiver and transmitter radio affects the average energy per packet consumption and consequently route lifetime. In this section, first we describe our measurement setup to collect path loss samples from the on-body links in III-A. In section III-B, we embark on deriving parameters of receiver and transmitter power consumption model, i.e., transmitter's power amplifier efficiency η and receiver power P_R, that can make relaying optimum in terms of route lifetime. We also discuss whether micaZ CC2420 or nRF24L01 motes are suitable for on-body relaying.

A. Measurement setup and problem assumptions

Measurements are done with CC2420 RF modules in a fairly large room which was sparsely occluded with tables and desks. Subject person, who is the second author of this paper, is a 27 year old male with an athletic build of 178cm height and 78kg weight. In Fig. III-A, each of the links on the H1-T1 route ($\binom{8}{2} = 28$ links) and on L1-T1 route ($\binom{6}{2} = 15$ links) were tested with 16 different transmit power levels and for 5 minutes each. The reason we are studying H1-T1 and L1-T1 routes is that sink is assumed to be placed on left waist (T_1) for most WBAN applications and also these two routes go under lots of variations during doing most body actions. Two

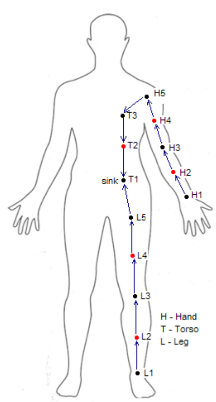

Fig. 1. Relay placement setup on-body

actions of brisk walking and jumping jack are studied. For walking, the subject person walked at approximately 6km/hr and jumping jack was done at roughly one cycle per second. The motes were set to transmit 44-byte packets with 27 bytes allocated to payload and 17 bytes to the header as in [17]. For L1-T1 route, motes are basically placed on ankle (L1), knee (L3), L1-L3 middle point (L2), groin (L5), L3-L5 middle point (L4) and abdominals (T1). Whereas for H1-T1 route study motes are placed on wrist (H1), antecubital space (H3), H1-H3 middle point (H2), shoulder (H5), H3-H5 middle point (H4), chest (T3), T1-T3 middle point (T2). This placement satisfies the criteria discussed in section II-A.

B. Results

Based on the discussion in section II, for the best m-relay route in terms of lifetime let $P_{Tx}^{(m)}$ denote the transmit power level assigned to the most power consuming node. We estimate

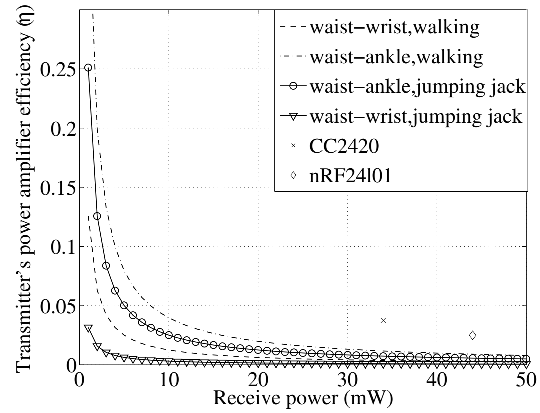

Fig. 2. Suitable region for relaying for two actions and two links of interest

$E_{rel,l-1}^{out}$ and $E_{rel,l-1}^{in}$ in (3) for this relay with $P_T^{(l+1)}$ and P_R respectively as packet error rate is small for the selected transmit power levels. For the sake of consistency in notations let $P_T^{(m)}$ represent $P_T^{(l+1)}$ and for single-hop transmission case with no relaying, let $P_{Tx}^{(SH)}$ represent the transmit power level assigned to the source node. In the following, on-body relaying for two actions of jumping jack and brisk walking and for two drain efficiency (η) models explained in II-D are discussed and plotted.

1) Fixed power amplifier efficiency: For a fixed power amplifier efficiency, based on the estimation discussed in section III-B in order for m-relay routing to outperform single-hop transmission in terms of route lifetime,

$$P_T^{(m)} + P_R < P_T^{(SH)}, \tag{11}$$

which according to the model discussed in II-D translates to

$$P_{T_0} + P_{Tx}^{(m)}/\eta + P_R < P_{T_0} + P_{Tx}^{(SH)}/\eta. \tag{12}$$

Simplifying (12) yields $\eta P_R < P_{Tx}^{(SH)} - P_{Tx}^{(m)}$. In case $P_{Tx}^{(SH)} >> P_{Tx}^{(m)}$ which holds for mobile routes with stable links between contiguous relays, $\eta P_R < P_{Tx}^{(SH)}$ is the condition which needs to hold in order for relaying to be beneficial to route lifetime. In this condition, based on our discussion in section II, $P_{Tx}^{(SH)}$ can be calculated for both links and actions of interest, i.e., ankle-waist and wrist-waist during brisk walking and jumping jack, therefore is a fixed term for each of these cases. In Fig. 2, the region below the graphs indicates region for which relaying helps us achieve more lifetime for these two highly mobile links (waist- wrist, waist-ankle). It can be seen that relaying with CC2420 and nRF24L01 modules does not help us achieve more lifetime.

2) Linear power amplifier efficiency: As discussed in section II-D for some RF modules, e.g., micaZ motes, a linear fit is proposed to model amplifier's drain efficiency η with respect to transmit power levels P_{Tx} as expressed in (10). Let η^{SH} and η^m denote efficiency corresponding to $P_{Tx}^{(SH)}$ and $P_{Tx}^{(m)}$ respectively, $\eta^{SH} = a_1 + a_2 P_{Tx}^{(SH)}$ and $\eta^m = a_1 + a_2 P_{Tx}^{(m)}$. The condition for m-relay route to outperform single-hop transmission is given by

$$P_R + \frac{P_{Tx}^{(m)}}{a_1 + a_2 P_{Tx}^{(m)}} < \frac{P_{Tx}^{(SH)}}{a_1 + a_2 P_{Tx}^{(SH)}}, \tag{13}$$

to single-hop.

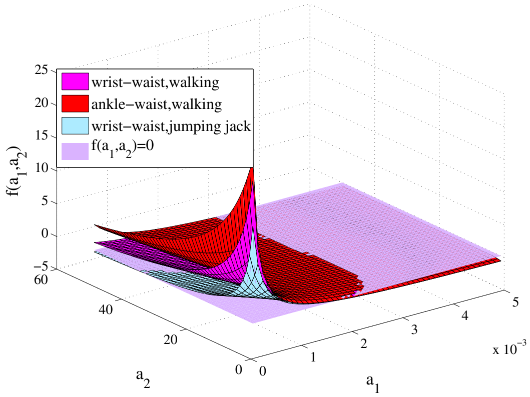

Fig. 3. $f(a_1, a_2)$ plane for three different links during doing actions and P_R=34mW

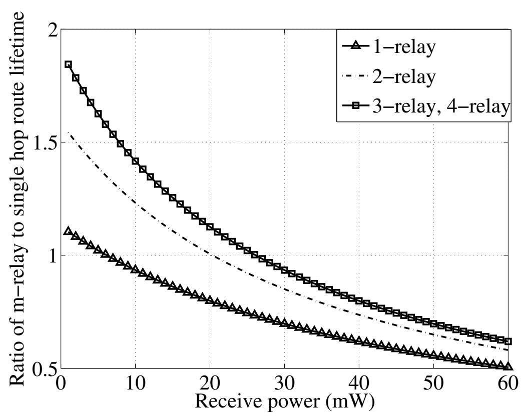

Fig. 4. ratio of route lifetime of m-relay scheme to that of single-hop transmission over ankle-waist link during walking

which can be simplified to

$$\frac{a_1 P_{Tx}^{(SH)}}{P_R(a_1 + a_2 P_{Tx}^{(m)})(a_1 + a_2 P_{Tx}^{(SH)})} - 1 > 0. \qquad (14)$$

Let $f(a_1, a_2)$ denote the left-hand side of (14) for a given route and action which translates to a given $P_{Tx}^{(m)}$ and $P_{Tx}^{(SH)}$. In Fig. 3, $f(a_1, a_2)$ for the best 3-relay routes over wrist-waist link during doing walking, jumping jack and ankle-waist link during walking and for $P_R = 34mw$, i.e., receive power for micaZ mote, is illustrated. It can be seen that lower a_1 and a_2 values will make relaying suitable whereas this requires low amplifier efficiency in the transmitter which generally causes waste of power. In Fig. 4, ratio of m-relay route lifetime to single-hop scenario, for $a_1 = 0.0013$, $a_2 = 31.96$ which correspond to CC2420 module is illustrated. The effect of receive power P_R can be seen on every m-relay graph, whereas the difference between graphs for every P_R value shows the importance of number of relays, m, and consequently transmit power level $P_{Tx}^{(m)}$. It can be seen that 4-relay transmission does not help us achieve more lifetime over 3-relay since in both scenarios the highest consuming node is already using the lowest $P_{Tx}^{(m)}$. One can also conclude that even for 3-relay and 4-relay cases, receive power of more than 27mW will cause relaying to degrade route lifetime compared to single-hop.

IV. Conclusion

In this paper we used measurement-based path loss models to study the impacts of IEEE802.15.4 on-body relaying on network lifetime compared to the single-hop transmission scenario. We showed that receiver power consumption and different models of transmitter's power amplifier efficiency play a major role in relaying analysis. As a widely used RF module, micaZ motes were studied for fixed and varying transmitter's power amplifier efficiency η. Based on our analysis, receive power of IEEE802.15.4 RF modules play an important role in relaying efficiency. Since well known 868MHz modules have lower receive power, we will extend our analysis to these motes in a future study.

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