Multi-hop Cooperative Relaying for Energy Efficient *In Vivo* Communications

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***Abstract*—This paper investigates cooperative relaying to support energy efficient *in vivo* communications. In such a network, the *in vivo* source nodes transmit their sensing information to an on-body destination node either via direct communications or by employing on-body cooperative relay nodes in order to promote energy efficiency. Two relay modes are investigated, namely single-hop and multi-hop (two-hop) relaying. In this context, the paper objective is to select the optimal transmission mode (direct, single-hop, or two-hop relaying) and relay assignment (if cooperative relaying is adopted) for each source node that results in the minimum per bit average energy consumption for the *in vivo* network. The problem is formulated as a binary program that can be efficiently solved using commercial optimization solvers. Numerical results demonstrate the significant improvement in energy consumption and quality-of-service (QoS) support when multi-hop communication is adopted.**

***Index Terms*—Body area network, *in vivo*, energy efficiency, relaying, multi-hop.**

I. Introduction

Nowadays, health care systems demand accurate and continuous monitoring of patients' health status. Such a monitoring is currently enabled through wireless body area networks that adopt low-powered sensor nodes which can be deployed inside the human body (*in vivo*) or on the body to measure all physiological data of interest.

A major challenge for *in vivo* communication is the requirement to support energy efficient communications with a quality-of-service (QoS) guarantee. This objective is motivated by the low power supply available for the *in vivo* sensor nodes and the associated difficulties with replacing the batteries of the *in vivo* implanted nodes. In most cases, it may not be feasible to support energy efficient *in vivo* communication given the high path loss, which may also lead to QoS outage. As a result, deploying on-body relay nodes can result in satisfying the target QoS and energy efficiency requirements. Thus, multiple *in vivo* sensor nodes can use multiple on-body relay nodes to forward the physiological signal information towards an on-body destination node that further transmits all gathered information to the hospital server for continuous monitoring and processing. Furthermore, a single on-body relay node can be used by multiple *in vivo* source nodes through a frequency division multiple access (FDMA) scheme among source nodes. However, most of the existing research focus mainly on single-hop relaying. On the other hand, multi-hop relaying can further enhance the resulting energy consumption as it enables shorter transmission range than single-hop relaying. In this context, two questions must be answered in order to achieve the target benefits. First, what is the optimal transmission mode (i.e., direct transmission, single-hop, or multi-hop relaying) for each source node in order to enhance the *in vivo* network energy efficiency? Second, given this optimal transmission mode, what is the optimal relay assignment for the source nodes that adopt cooperative relaying? In this paper, we aim to provide answers to such questions. In specific, we formulate a binary program that determines the optimal transmission mode selection and relay assignment that minimizes the total average energy consumption per bit of the *in vivo* wireless network.

The rest of this paper is organized as follows. The next section reviews the related work. Section III describes the system model. Section IV presents the problem formulation. Numerical results are discussed in Section V. Finally, conclusions are drawn in Section VI.

II. Related Work

Several work in literature have investigated energy efficient communication in wireless body area networks via signal processing [1], [2], modulation [3], [4], medium access control (MAC) [5], [6], transmission control protocol (TCP) [7], routing [8] - [10], and cooperative relaying [11] - [14].

Data compression is one of the most common signal processing techniques adopted in literature to support energy efficient communications in body area networks [1]. Both lossless and lossy compression are applied with tradeoffs between data reconstruction and energy saving percentage. Moreover, given the sparse nature of most of the biomedical signals, compressed signaling has been employed to sense and compress biomedical signals and thus enable energy efficient communication [2]. In specific, following optimally designed sensing matrices, the reconstruction accuracy of signals can be improved and competitive signal compression ratios can be achieved, which lead to reduced energy consumption.

In addition, the energy saving performance can be enhanced by employing energy efficient modulation techniques. For example, the authors in [3] propose a low power consumption communication technique based on ultra wide band pulse position amplitude modulation which can simplify the communication protocol and thus result in high energy saving performance. Furthermore, the work in [4] demonstrated that using a fixed type of modulation does not provide the highest energy efficiency. Instead, adaptive modulation techniques can lead to a considerable amount of energy savings.

Energy efficient MAC protocols can also result in a high energy saving percentage. For example, the authors in [5] propose an energy efficient MedMAC protocol. Simulation results demonstrate that MedMAC outperforms IEEE 802.15.4 in terms of power efficiency in low and medium data rate medical applications. In addition, the authors in [6] introduce a pulsed-MAC (PMAC) protocol that extends the body area network life time by augmenting the sensor nodes with a charge pumping circuitry which harvests energy from a pulsed signal that is used in order to wake up the nodes. From simulation results, it has been shown that PMAC outperforms the conventional MAC protocols by up to three times and thus enables the body area network to last more that 200 days.

Energy efficient TCP is also examined in [7] for energy saving. In specific, a minimum energy packet forwarding protocol is introduced to transmit the data packet using the minimum transmission power that guarantees a high packet reception rate and postpones packet retransmissions based on the link quality. Simulation results have demonstrated an energy saving of 12% when the proposed TCP protocol is used.

Efficient data routing can lead to energy saving in body area networks. The authors in [8] introduce an energy-balanced rate assignment and routing protocol that selects data routes according to the residual energy of the nodes along that route. Experimental results have shown that the proposed protocol is able to balance energy consumption within the network and thus guarantees a longer network life time. In addition, the work in [9] considers the node temperature, energy level, and received signal power from adjacent nodes as a cost function while determining the optimal route that minimizes the temperature rise and power consumption of the network. Moreover, the work in [10] adopts node clustering for energy saving since communication among clusters enables shorter transmission ranges.

Cooperative relaying is considered to be one of the most effective ways to support energy efficient communications in body area networks since it allows for shorter transmission ranges. On-body relay nodes can be deployed between *in vivo* source nodes and on-body destination nodes. The work in [11] assumes a single source and single relay system and aims to determine the optimal relative location between the relay and destination nodes for minimum energy consumption. The authors in [12] derive closed form expressions for the outage probability and bit error rate as function of the position of multiple relay nodes and the motion of the body. Using these expressions, the authors are able to minimize the required transmission power subject to a minimum QoS requirement. However, the work in [11] and [12] are limited to a single source node system. Furthermore, the authors in [13] deal with a multi-source node system and a single relay node is used to forward data towards the destination. Finally, the authors in [14] consider a multi-source multi-relay system and investigate packet size optimization for energy efficient communications. The existing research in [11] - [14] mainly deal with single-hop relaying; however, higher energy saving can be achieved if multi-hop relaying is enabled.

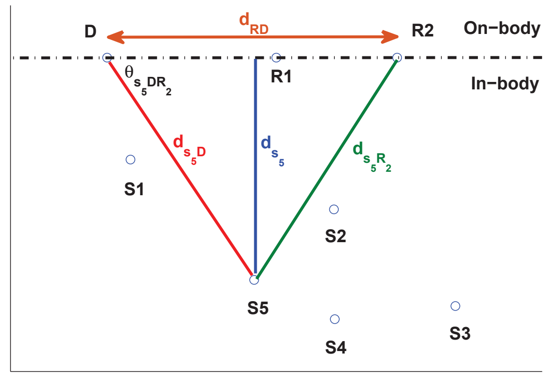

Fig. 1. Illustration of system model with 5 *in vivo* source nodes, 2 on-body relay nodes, and 1 on-body destination node.

In this paper, we investigate multi-hop cooperative relaying in an attempt to improve energy efficiency in body area networks, unlike [11] - [14]. We consider a multi-source multi-relay system and aim at selecting the optimal transmission mode (i.e., direct transmission, single-hop, or multi-hop relaying) for multiple source nodes and perform optimal relay assignment for the source nodes that are adopting cooperative relaying.

III. System Model

Consider a wireless body area network, as shown in Figure 1, with a set $\mathcal{S} = \{1, 2, \ldots, S\}$ of *in vivo* source nodes and an on-body destination node D. The *in vivo* source nodes in $\mathcal{S}$ measure different physiological signals (e.g., pulse rate, blood pressure, toxins levels, etc. [13]) and transmit information bits towards the destination node D. The on-body destination node is a coordinator (hub) which receives the physiological information bits and forwards them to the hospital server for further processing and monitoring [11], [14]. Let the depth of the source node $s \in \mathcal{S}$ inside the body be d_s (milli-meter) and the distance between the source node s and destination node D be d_{sD} (milli-meter).

Three transmission modes can be distinguished. The first is a direct transmission mode where the *in vivo* source node $s \in \mathcal{S}$ directly transmits its information bits to the on-body destination node D. The second is a single-hop relaying mode where an on-body relay node r forwards the information bits received from the *in vivo* source node s to the on-body destination node D. The last mode adopts multi(two)-hop relaying where the *in vivo* source node $s \in \mathcal{S}$ forwards its data to an on-body relay node r which in turn forwards the data to another on-body relay node $r^{\hat{\prime}}$ (closer to the destination node) which eventually forwards the data to the destination node D. In this paper, only two-hop relaying is considered. Amplify-and-forward (AF) relaying is adopted in cooperative transmission since it exhibits a lower implementation complexity than the decode-and-forward (DF) scheme [11].

This paper deals with two on-body relay nodes. We define a set of relay nodes $\mathcal{R} = \{R_1, R_2\}$. The distance between the last relay node $R_2 \in \mathcal{R}$ and the destination node D is denoted by d_{RD} (milli-meter). The two relay nodes in $\mathcal{R}$ are uniformly distributed within d_{RD}, which defines the distance d_{rD} between relay node r and destination node D. Multi-hop relaying is implemented only in the direction from relay node R_2 to relay node R_1 then to destination node D. Let x_s^{m} be a binary decision variable that indicates whether or not a source node s is adopting multi-hop relaying. Also, let x_{sr} represent an association decision variable that indicates if source node $s \in \mathcal{S}$ is using relay node $r \in \mathcal{R}$, otherwise direct transmission is adopted. The distance between the source node s and the relay node r is denoted by d_{sr}. Let θ_{sDr} be the angle between d_{sD} and d_{sr}, $\theta_{sDr} = \arcsin(d_s/d_{sD})$. Hence, $d_{sr}^2 = d_{rD}^2 + d_{sD}^2 - 2d_{rD}d_{sD}\cos\theta_{sDr}$.

Each source node implements the cooperative relaying protocol based on a TDMA scheme (which uses time slots with equal duration) on a given frequency carrier [11]. For single-hop relaying, in the first time slot, the source node $s \in \mathcal{S}$ broadcasts its information to the destination node D and the assigned relay node r (with $x_{sr} = 1$). In the second time slot, the relay node forwards the received information to the destination node D when a feedback is not available from D to r. For multi-hop relaying, in the second time slot the relay node R_2 forwards the received information to the relay node R_1, and a third time slot is defined in which the information received by R_1 is forwarded to the destination node D. Furthermore, multiple source nodes in $\mathcal{S}$ can use the same relay node $r \in \mathcal{R}$ for cooperative transmission. Specifically, an FDMA scheme is assumed to be in place to coordinate the source nodes' utilization of the same relay node $r \in \mathcal{R}$. In this case, relay node r splits its transmission power, p_t to forward the data of each source node towards the destination node. Specifically, for relay node R_1, the transmission power allocated to relay the information bits of each source node that is using relay node R_1 is given by

$$p_{R_1D} = \frac{p_t}{\sum_{s\in\mathcal{S}} x_{sR_1}}. \tag{1}$$

On the other hand, for relay node R_2, the transmission power allocated to transmit the information bits of each source node depends on the selected transmission mode. The transmission power allocated to transmit the information bits of a source node that is adopting multi-hop relaying via R_2 is half the transmission power allocated to transmit the information bits of a source node that is adopting single-hop relaying via R_2. Hence, for $s \in \mathcal{S}$ with $x_s^{\mathrm{m}} = 1$, we have

$$p_{R_2R_1-s} = \frac{p_t}{2\sum_{s\in\mathcal{S}} x_{sR_2}(1-x_s^{\mathrm{m}}) + \sum_{s\in\mathcal{S}} x_{sR_2}x_s^{\mathrm{m}}}, \tag{2}$$

and for $s \in \mathcal{S}$ with $x_s^{\mathrm{m}} = 0$, we have

$$p_{R_2D-s} = \frac{2p_t}{2\sum_{s\in\mathcal{S}} x_{sR_2}(1-x_s^{\mathrm{m}}) + \sum_{s\in\mathcal{S}} x_{sR_2}x_s^{\mathrm{m}}}. \tag{3}$$

Each source node $s \in \mathcal{S}$ employs transmission power p_t for direct transmission.

For the on-body channel, the path loss in dB as a function of distance d (milli-meter) is given by [15], [16]

$$H_{\text{on}}(d) = \alpha_1 \log_{10}(d) + \beta_1 + \kappa_1, \tag{4}$$

and for the *in vivo* channel is given in dB by

$$H_{\text{in}}(d) = \alpha_2(\frac{d}{d_0})^n + \beta_2 + \kappa_2, \tag{5}$$

where $\alpha_1 = 19.2$, $\alpha_2 = 0.987$, $n = 0.85$, $d_0 = 1$ milli-meter, $\beta_1 = 3.38$ dB, $\beta_2 = 10$ dB, and κ_1 and κ_2 are normally distributed random variables in dB with zero mean and standard deviation values $\sigma_1 = 4.4$ and $\sigma_2 = 7.84$. Hence, for transmission power p_t (dB), the received signal-to-noise ration (SNR) at distance d (milli-meter) is given in dB by

$$\gamma = p_t - H_{\text{on/in}}(d) - p_n, \tag{6}$$

where p_n denotes the additive white Gaussian noise power in dB.

Define the outage probability as the probability that the received SNR falls below a certain threshold Γ.

IV. Problem Formulation

This section formulates the problem of optimal transmission mode selection and relay assignment for minimum energy consumption in body area networks.

For the direct transmission link between *in vivo* source node s and on-body destination node D, the per bit energy consumption is expressed by [17]

$$\begin{aligned} E_{sD}^{\text{direct}} &= E_t + E_{c1} + E_{c2}, \\ &= \tfrac{p_t}{R_o} + E_{c1} + E_{c2}, \end{aligned} \tag{7}$$

where E_t is the transmission energy, R_o is the transmission bit rate (bits/sec), and E_{c1} and E_{c2} are the transmitter and receiver circuit energy consumption per bit. For this link, the outage probability P_{sD}^{direct} is given by [11]

$$\begin{aligned} P_{sD}^{\text{direct}} &= P(\gamma_{sD} < \Gamma) \\ &= P(p_t[\text{dB}] - H_{\text{in}}(d_{sD}) - p_n < \Gamma) \\ &= Q(\frac{p_t[\text{dB}] - \alpha_2 d_{sD}^n - \beta_2 - p_n - \Gamma}{\sigma_2}), \end{aligned} \tag{8}$$

where $Q(\cdot)$ is the Q-function. Hence, the per bit average energy consumption for direct transmission is given by [11]

$$\begin{aligned} \bar{E}_{sD}^{\text{direct}} &= E_{sD}^{\text{direct}} \sum_{m=0}^{\infty} (m+1) P_{sD}^{m\ \text{direct}} (1 - P_{sD}^{\text{direct}}) \\ &= \frac{E_{sD}^{\text{direct}}}{1 - P_{sD}^{\text{direct}}}. \end{aligned} \tag{9}$$

For single-hop relaying, the per bit energy consumption is expressed by [11]

$$\begin{aligned} E_{srD}^{\text{1-hop}} &= \frac{\rho p_t}{R_o} + E_{c1} + E_{c2} + \frac{(1-\rho)p_t}{R_o} + E_{c1} + 2E_{c2}, \\ &= \frac{p_t}{R_o} + 2E_{c1} + 3E_{c2}, \end{aligned} \tag{10}$$

where ρp_t and $(1-\rho)p_t$ are the transmission powers of the $s-r$ link and the $r-D$ link, respectively. Without loss of generality, it is assumed that $\rho = 0.5$ [11]. The outage probability for the cooperative relaying scheme is given by [18]

$$\begin{aligned} P_{srD}^{\text{1-hop}} &= P_{sD}P_{sr} + P_{sD}(1-P_{sr})P_{rD}, \\ &= P(\gamma_{sD} < \Gamma)P(\gamma_{sr} < \Gamma) + \\ &\quad P(\gamma_{sD} < \Gamma)P(\gamma_{sr} \geq \Gamma)P(\gamma_{rD} < \Gamma), \end{aligned} \tag{11}$$

where P_{sD}, P_{sr}, and P_{rD} are the outage probabilities of the $s-D$, $s-r$, and $r-D$ links, respectively, which following the same approach in (8) are given by [11]

$$\begin{aligned} P_{sD} &= Q(\frac{p_t[\text{dB}] - 3 - \alpha_2 d_{sD}^n - \beta_2 - p_n - \Gamma}{\sigma_2}), \\ P_{sr} &= Q(\frac{p_t[\text{dB}] - 3 - \alpha_2 d_{sr}^n - \beta_2 - p_n - \Gamma}{\sigma_2}), \\ P_{rD} &= Q(\frac{p_{rD-s}[\text{dB}] - \alpha_1 \log_{10}(d_{rD}) - \beta_1 - p_n - \Gamma}{\sigma_1}), \end{aligned} \tag{12}$$

where p_{rD-s} denotes the transmission power allocated by relay node $r \in \mathcal{R}$ to relay the information bits of source node s, and is given by (1) for R_1 and (3) for R_2 and replacing p_t in (1) and (3) by $p_t/2$. Hence, the per bit average energy consumption for the single-hop relaying transmission scheme is given by [11]

$$\bar{E}_{srD}^{\text{1-hop}} = \frac{E_{srD}^{\text{1-hop}}}{1 - P_{srD}^{\text{1-hop}}}. \tag{13}$$

For multi-hop relaying, the per bit energy consumption is expressed by

$$\begin{aligned} E_{sD}^{\text{2-hop}} &= \frac{\rho_1 p_t}{R_o} + E_{c1} + E_{c2} + \frac{\rho_2 p_t}{R_o} + E_{c1} + E_{c2} + \\ &\quad \frac{\rho_3 p_t}{R_o} + E_{c1} + E_{c2}, \\ &= \frac{p_t}{R_o} + 3E_{c1} + 3E_{c2}, \end{aligned} \tag{14}$$

where $\rho_1 p_t$, $\rho_2 p_t$, and $\rho_3 p_t$ are the transmission powers of the $s-R_2$, R_2-R_1, and the R_1-D links, respectively. Without loss of generality, it is assumed that $\rho_1 = \rho_2 = \rho_3 = 1/3$. The outage probability for the multi-hop relaying scheme is given by

$$\begin{aligned} P_{sD}^{\text{2-hop}} &= P_{sD}P_{sR_2} + P_{sD}(1-P_{sR_2})P_{R_2R_1} + \\ &\quad P_{sD}(1-P_{sR_2})(1-P_{R_1R_2})P_{R_1D}, \\ &= P(\gamma_{sD} < \Gamma)P(\gamma_{sR_2} < \Gamma) + \\ &\quad P(\gamma_{sD} < \Gamma)P(\gamma_{sR_2} \geq \Gamma)P(\gamma_{R_2R_1} < \Gamma) + \\ &\quad P(\gamma_{sD} < \Gamma)P(\gamma_{sR_2} \geq \Gamma)P(\gamma_{R_2R_1} \geq \Gamma) \times \\ &\quad P(\gamma_{R_1D} < \Gamma), \end{aligned} \tag{15}$$

where P_{sD}, P_{sR_2}, $P_{R_2R_1}$, and P_{R_1D} are the outage probabilities of the $s-D$, $s-R_2$, R_2-R_1, and R_1-D links, respectively, which following the same approach in (8) are given by

$$\begin{aligned} P_{sD} &= Q(\frac{p_t[\text{dB}] - 4.8 - \alpha_2 d_{sD}^n - \beta_2 - p_n - \Gamma}{\sigma_2}), \\ P_{sR_2} &= Q(\frac{p_t[\text{dB}] - 4.8 - \alpha_2 d_{sR_2}^n - \beta_2 - p_n - \Gamma}{\sigma_2}), \\ P_{R_2R_1} &= Q(\frac{p_{R_2R_1-s}[\text{dB}] - \alpha_1 \log_{10}(d_{R_2R_1}) - \beta_1 - p_n - \Gamma}{\sigma_1}), \\ P_{R_1D} &= Q(\frac{p_{R_1D}[\text{dB}] - \alpha_1 \log_{10}(d_{R_1D}) - \beta_1 - p_n - \Gamma}{\sigma_1}) \end{aligned} \tag{16}$$

where p_{R_1D} and $p_{R_2R_1-s}$ denote the transmission power allocated by relay node $r \in \mathcal{R}$ to relay the information bits from relay node r, and is given by (1) for R_1 and (2) for R_2 and replacing p_t in (1) and (2) by $p_t/3$. Hence, the per bit average energy consumption for the single-hop relaying transmission scheme is given by

$$\bar{E}_{sD}^{\text{2-hop}} = \frac{E_{sD}^{\text{2-hop}}}{1 - P_{sD}^{\text{2-hop}}}. \tag{17}$$

Each source node $s \in \mathcal{S}$ can be assigned to one and only one relay node for single-hop relaying, i.e.,

$$\sum_{r \in \mathcal{R}} x_{sr} \leq 1, \quad \forall s \in \mathcal{S}. \tag{18}$$

In addition, if source node s adopts multi-hop relaying, it cannot be assigned to relay node R_1 and instead it is assigned to relay node R_2 (which in turn will forward the data towards the destination), i.e.,

$$\sum_{r \in \mathcal{R}} x_{sR_1} \leq 1 - x_s^{\text{m}}, \quad \forall s \in \mathcal{S} \tag{19}$$

and

$$\sum_{r \in \mathcal{R}} x_{sR_2} \geq x_s^{\text{m}}, \quad \forall s \in \mathcal{S} \tag{20}$$

The per bit average energy consumption for the body area network is given by

$$\begin{aligned} E_{\text{total}} = \sum_{s \in \mathcal{S}} \{ &(1 - x_s^{\text{m}})(1 - \sum_{r \in \mathcal{R}} x_{sr}) \bar{E}_{sD}^{\text{direct}} + \\ &(1 - x_s^{\text{m}}) \sum_{r \in \mathcal{R}} x_{sr} \bar{E}_{srD}^{\text{1-hop}} + x_s^{\text{m}} \bar{E}_{sD}^{\text{2-hop}} \}. \end{aligned} \tag{21}$$

The problem in hand is to specify the transmission mode selection and relay assignment in order to minimize the per bit average energy consumption for the body area network while satisfying the problem constraints, i.e.,

$$\begin{aligned} \min_{x_s^{\text{m}}, x_{sr}} \quad & E_{\text{total}} \\ s.t. \quad & (18) - (20), \end{aligned} \tag{22}$$

The transmission mode selection and relay assignment problem (22) is a binary program that is solved once in a set up phase and hence can be efficiently solved using the CPLEX

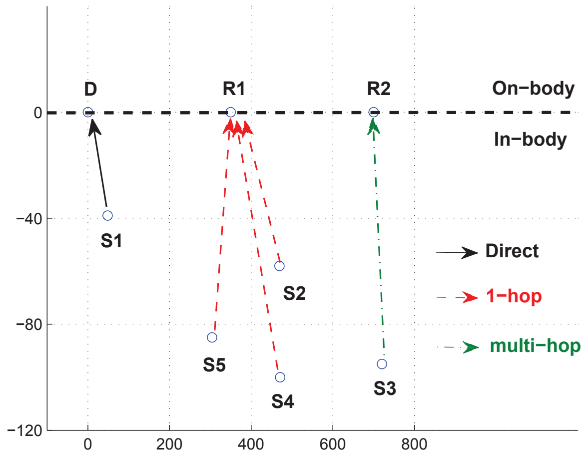

Fig. 2. Optimal transmission mode selection and relay assignment for minimum energy consumption with $d_{RD} = 700$ milli-meter and $\Gamma = 30$ dB.

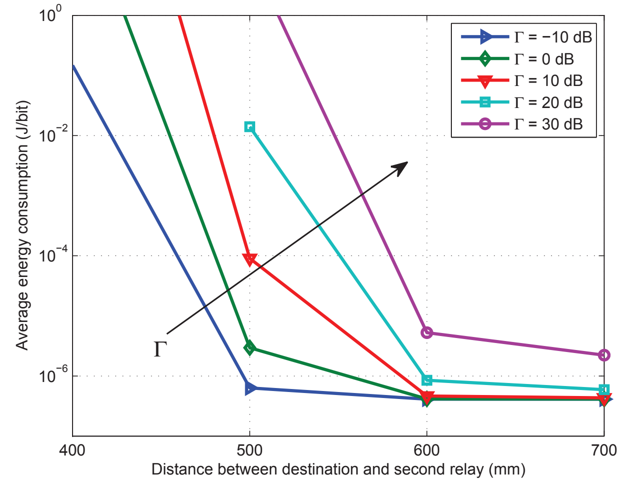

Fig. 3. Average energy consumption performance versus d_{RD} for variable Γ.

solver of the general algebraic modeling system (GAMS) [19].

V. Numerical Results and Discussion

This section presents numerical results for the transmission mode selection and relay assignment problem in (22). Five *in vivo* source nodes are assumed to be in place at a depth $d_s = 39, 58, 95, 100,$ and 85 milli-meter, respectively and an angle of $\theta_{sDr} = 0.6792, 0.123, 0.1311, 0.2092,$ 0.2724 radians. The following parameters are adopted $p_n = -100$ dBm, $p_t = 0$ dBm, $E_{c1} = 18.75$ nJ/bit, $E_{c2} = 18.75$ nJ/bit, and $R_o = 100$ Kbps [11]. In all numerical results, direct transmission always suffers from outage and hence requires infinite energy consumption.

Figure 2 shows the optimal transmission mode selection and relay assignment for $d_{RD} = 700$ milli-meter and $\Gamma = 30$ dB. As shown in figure, since the first source node (S_1 in Figure 2) is close to the destination node, it relies on direct transmission and does not employ cooperative relaying. On the other hand, each source node S_2, S_4, and S_5 employs a single-hop relay transmission via R_1. As source node S_3 is far away from the destination node, it relies on multi-hop relaying via R_2 and R_1 for data transmission. Such optimal placement results in a total average energy consumption of 2.23 micro-Joule per bit for the body area network.

Figure 3 shows the per bit average energy consumption for a variable SNR threshold, Γ versus d_{RD}. As the distance between the destination and the last relay node increases, relay nodes can be placed at better locations to serve more number of source nodes and hence reduces the per bit average energy consumption of the body area network. Furthermore, as a more strict QoS is required (i.e., larger values of Γ), higher energy consumption is expected in order to satisfy such a requirement.

VI. Conclusions

This paper investigates optimal transmission mode selection and relay assignment for energy efficient body area networks. The problem is formulated as a binary program that can be efficiently solved using CPLEX solver of GAMS. Two parameters govern the total average energy consumption per bit for the network, namely, the distance between the destination node and the last relay node and the SNR threshold for QoS requirement. Numerical results demonstrate the improved performance of the cooperative relaying with optimal transmission mode selection and relay assignment.

VII. Acknowledgment

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