33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Power Allocation Strategies to Minimize Energy Consumption in Wireless Body Area Networks

Aravind Kailas
Dept. of Electrical and Computer Engineering
The University of North Carolina at Charlotte
Charlotte, NC 28223-0001, USA
Email: aravindk@ieee.org

***Abstract*—The wide scale deployment of wireless body area networks (WBANs) hinges on designing energy efficient communication protocols to support the reliable communication as well as to prolong the network lifetime. Cooperative communications, a relatively new idea in wireless communications, offers the benefits of multi-antenna systems, thereby improving the link reliability and boosting energy efficiency. In this short paper, the advantages of resorting to cooperative communications for WBANs in terms of minimized energy consumption are investigated. Adopting an energy model that encompasses energy consumptions in the transmitter and receiver circuits, and transmitting energy per bit, it is seen that cooperative transmission can improve energy efficiency of the wireless network. In particular, the problem of optimal power allocation is studied with the constraint of targeted outage probability. Two strategies of power allocation are considered: power allocation with and without posture state information. Using analysis and simulation-based results, two key points are demonstrated: (i) allocating power to the on-body sensors making use of the posture information can reduce the total energy consumption of the WBAN; and (ii) when the channel condition is good, it is better to recruit less relays for cooperation to enhance energy efficiency.**

***Index Terms*—Cooperative communications, healthcare monitoring, m-Health, wireless body area networks**

I. Motivations and Contributions

The development of wireless body area networks (WBANs) brings a number of research challenges such as interoperability, scalability, reliability, QoS, and energy efficiency to the design of communication protocols. As we mentioned, the energy resources are very constrained in WBAN. Utilizing energy efficient communication protocols to maximize the network lifetime is important for WBAN applications. Reducing transmit power can be a potential approach. Note that, to avoid negative impact of electromagnetic radiation on human body, it is critical to keep a low transmit power in WBAN. However, the path loss in WBAN is usually larger than 50 dB [1], causing severe attenuation on wireless signals, and thus, without sufficient transmit power the link quality is very likely to be deteriorated. Recently, it is observed that, with 1 mW transmit power at 2.4 GHz, the on-body (off-body) links of WBAN are intermittently disconnected up to 14.8% (14.9%) of the time when people sleep on bed [2]. As such, the network topology of WBAN could be frequently partitioned [3]. Further, the data packets in WBAN mostly consist of medical information with the demands of high reliability and low delay. As a result, how to design communication protocols to ensure an end-to-end reliable communication with the least energy consumption becomes a key challenge in WBAN. Cooperative communications have the advantage of spatial diversity, thus improving both link reliability and energy efficiency [4]–[5]. The power consumption with cooperation in wireless sensor network is studied in [4]. It is shown that, for a large distance separation between the source and destination, cooperative transmission is more energy efficient than direct transmission. The energy efficiency of cooperative communication is further illustrated in the clustered wireless sensor networks in [5], and similar results are revealed. Keeping this in mind, the use of cooperative communications in WBANs and the associated performance in terms of energy efficiency are explored in this paper.

Contributions: In this paper, the energy efficiency of

Aravind Kailas is an affiliated researcher of the Center for Biomedical Engineering Systems (CBES) at the University of North Carolina at Charlotte and the Charlotte Research Institute (CRI). This work was partially supported by the wachovia Faculty Foundation Grant.

cooperative communications in a WBAN is investigated. To minimize the energy consumption, the problem of optimal power allocation with the constraint of targeted outage probability is studied. Two power allocation strategies are considered: power allocation with and without posture information. To fairly compare the energy consumption between cooperative and noncooperative transmissions, we consider not only transmit energy but also transmitter and receiver circuit energies, which were not considered in the existing literature. Using simulation for the analytical framework, the effects of transmit power allocation, the relay location, the number of relays and the magnitudes of path loss in different posture states on the energy efficiency are shown.

II. Related Work

Without considering the extra energy consumed in transmitter and receiver circuits, cooperative communications can consume less transmit power compared to direct and multihop transmission [8]. In an energy-constrained network such as WSN, the extra energy consumption is important [4]. Taking this into consideration, the energy efficiency of cooperative MIMO in WSN is investigated in [4] and further studied in [5] for the clustered wireless sensor networks. Their researches show that, compared to direct transmission, cooperative communication is more energy efficient for a large distance separation between the source and the destination. The similar argument has been also revealed when studying the single-relay and multiple-relay cooperation in [9]. A WBAN is initially assumed as a single-hop star network [10]. However, according to [11]–[12], it is realized that the use of multihop communications could lead to a more energy efficient and reliable network topology. Furthermore, multihop cooperation and relaying schemes are discussed in [13] to prolong the network lifetime of WBAN. In [14], a gossiping data routing protocol is devised to cope with both high node mobility and poor link quality in the network. The data packet scheduling and optimal transmit power are studied in [15] for multihop links among in-body and on-body nodes. Beacon-enabled TDMA MAC with relay transmission is investigated in [16]. For a beacon-free network, a cooperative preamble-sampling protocol (PS-MAC) is developed by the authors of [17]. However, no cooperation diversity is exploited in these communication protocols. The gains of cooperative diversity in WBAN was first introduced in [18], and then in [19], where the spatial diversity gain is analyzed in a two-relay assisted transmission link. In [20], cooperative transmission is employed for communications between the on-body nodes and the off-body gateway. Compared to non-cooperative transmission, cooperative transmission (single-relay) can significantly reduce the bit error rate (BER) and prolong the system lifetime. Further, for a specific BER, cooperative transmission saves transmit energy consumption up to 20%. The packet error probability (PEP) for direct, two-hop, and single-relay cooperative transmission are investigated respectively in [21]. Although these studies demonstrate that cooperative communication can be effectively implemented in the WBANs, the performance analysis of its energy efficiency is still an open issue.

III. System Model

The propagation of wireless signals in body area communications experiences fading due to diffraction, reflection, energy absorption, and shadowing by body and clothes [1]. Generally, the fading (i.e., the large-scale and small-scale fading) depends on the location of the transceiver on/in human body, the posture/movement of human body, and the working frequency. Research on on body channel model shows that the large-scale fading referred to as the path loss can be approximated by the Friis formula [22]. The path loss for a fixed transmission pair varies significantly depending on the body posture, and its variation can be as large as 22.2 dB [1]. On the other hand, compared to other distributions such as Rayleigh, Rice, Weibull, and Nakagami-m, the Lognormal distribution provides the best fit for the small-scale fading in the WBANs [22]. Therefore, provided a posture state i, when the source node sends a signal s to its destination node d, the received SNR (in dB) at the destination is given by $\gamma_{sd|i} = P_{s,i} - PL_i^{sd} - X_{\sigma_i^{sd}} - N_0$, where $i = 1, 2, \ldots, N$, N is the total posture state number, the N_0 is the power of the additive white Gaussian noise (AWGN) at the receiver, $P_{s,i}$ is the transmit power of the source node, PL_i^{sd} is the path loss between the source and the destination, and $X_{\sigma_i^{sd}} \sim \mathcal{N}(0, \sigma_i^{sd})$ is the channel attenuation due to the small-scale fading. Notice that the posture states can be modeled as a Markov chain process and each state has a steady state probability π_i [23].

IV. Energy Consumption Minimization

We adopt the energy model from [5], where for a single-link transmission the overall consumed energy per bit includes three parts: the transmitter circuit energy consumption per bit, the receiver circuit energy consumption per bit, and the transmitting energy consumption per bit, denoted respectively by E_{ct}, E_{cr}, and E_t. Without loss of generality, it is assumed that all nodes in WBAN consume the same E_{ct} and E_{cr}, and the targeted transmission rate is R_b bits/s. Then, the transmitting energy consumption per bit can be derived using $\mathrm{E}_t = \frac{10^{P_t/10}}{R_b}$, where P_t is the transmit power of a sending node in dB. Given posture state i, the overall energy consumption per bit for each of the three transmission schemes can be found. For the direct transmission, $\mathrm{E}^D_{tot|i} = \mathrm{E}^D_{s,i} + \mathrm{E}_{ct} + \mathrm{E}_{cr}$, where $\mathrm{E}^D_{s,i} = \frac{10^{P^D_{s,i}/10}}{R_b}$. For a single-relay cooperation, the energy consumption can be calculated by considering three possible events, namely a successful delivery from the source to the destination in the first timeslot, and a failed data delivering from the source to the relay and destination in the first timeslot, and a failed data delivering from the source to the destination but a successful data delivering from the source to the relay. Mathematically, $\mathrm{E}^S_{tot|i} = (\mathrm{E}^S_{s,i} + \mathrm{E}_{ct} + 2\mathrm{E}_{cr})[1 - F(P^S_{s,i}, \mathrm{PL}^{sd}_i, \sigma^{sd}_i) + (\mathrm{E}^S_{s,i} + \mathrm{E}_{ct} + 2\mathrm{E}_{cr})F(P^S_{s,i}, \mathrm{PL}^{sd}_i, \sigma^{sd}_i)F(P^S_{s,i}, \mathrm{PL}^{sr}_i, \sigma^{sr}_i) + (\mathrm{E}^S_{s,i} + \mathrm{E}^S_{r,i} + 2\mathrm{E}_{ct} + 3\mathrm{E}_{cr})F(P^S_{s,i}, \mathrm{PL}^{sd}_i, \sigma^{sd}_i)[1 - F(P^S_{s,i}, \mathrm{PL}^{sr}_i, \sigma^{sr}_i)]$, where $\mathrm{E}^S_{s,i} = \frac{10^{P^S_{s,i}/10}}{R_b}$ and $\mathrm{E}^S_{r,i} = \frac{10^{P^S_{r,i}/10}}{R_b}$. Since the energy consumption for a NACK is usually much smaller than that for a data-packet transmission, for analysis simplicity, we omit the energy consumption for the NACK. Similarly, the analysis for the energy consumption can be calculated by considering models for multiple-relay cooperation strategies, but has not been shown here in the interest of space.

V. Results and Discussion

In this section, the energy efficiency among different transmission schemes with the two power allocation strategies are compared. In the simulation, the average noise power and the required SNR threshold are set as $N_0 = -100$ dB and $= 10$ dB, respectively. The values of the transmitter circuit energy consumption per bit and the receiver circuit energy consumption per bit are obtained from [11], where $\mathrm{E}_{ct} = 16.7$ nJ/bit and $\mathrm{E}_{cr} = 36.1$ nJ/bit. The transmission rate is set as $R_b = 200$ kbit/s, and the outage threshold is set as $P^*_{out} = 10^{-4}$. The steady state probability of the postures are calculated based on the data in [23], where the transition probability among six postures (i.e., sit, sit-reclining, lying-down, standing, walking, and running) are measured. For simplicity, only two posture states are considered in the simulation: sit for posture state one and standing for posture state two; and their steady state probabilities in the simulation are $\pi_1 = 0.49$ and $\pi_2 = 0.51$, respectively. We assume the variances of the small-scale fading for any links in the two posture states are $\sigma_1 = 0.6$ and $\sigma_2 = 2.5$ [1], respectively. To compare the energy consumption between non-cooperation and cooperation, we define energy efficiency as the reduced energy consumption (in percentage) due to cooperative transmission. Data was obtained by performing 100 simulation runs and averaging all the simulation results.

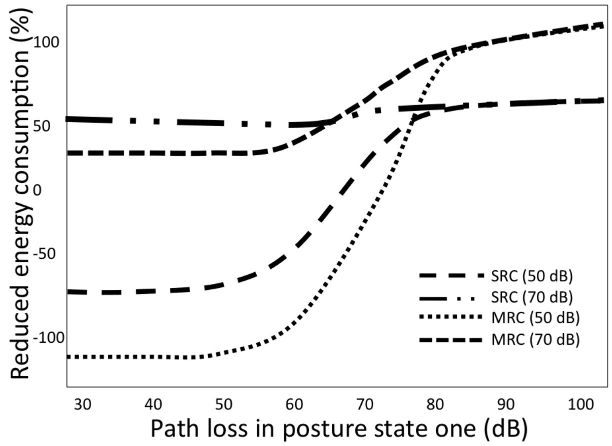

Fig. 1. *Energy efficiency for single relay cooperation (SRC) and multiple relay cooperation (MRC).*

The analytical and simulation results of energy efficiency with the strategy of power allocation with posture state information is shown in Fig. 1. Here, we fix the path loss of posture state two, and vary the path loss of posture state one in a typical potential range from 30 to 120 dB [23]. In the simulation, we find that the simulated outage probabilities always satisfy the targeted outage probability. This is because that the energy consumption is minimized with the constraint of the target outage probability in the power allocation strategy for each transmission scheme. From Fig. 1, it can be seen that whether the cooperative transmission can improve energy efficiency or not depends on the path loss between a source and a destination. When $PL^{sd}_2 = 70$ dB, cooperation is always more energy efficient than non-cooperation; however, when $PL^{sd}_2 = 50$ dB, cooperation is more energy efficient only if the path loss of posture state one (PL^{sd}_1) is larger than a threshold. Further, we can see that multi-relay cooperation can consume more energy than single relay cooperation if the path loss is small. This is because that, the more the number of the relays, the larger the amount of energy consumed in receiver circuit. Therefore, when the channel condition is good, it is better to utilize less relays for energy efficiency.

In Fig. 2, the performances of the two power allocation strategies are compared by fixing $PL^{sd}_2 = 70$ dB. From the figure, it can be seen that the strategy of power allocation with posture state information is better than the strategy of power allocation without posture state information. However, the performance gap decreases

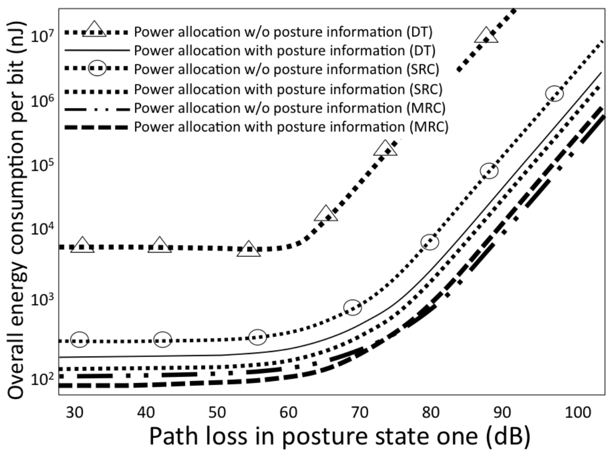

Fig. 2. *The comparison of average energy consumption per bit between the two power allocation strategies for direct transmission (DT), SRC, and MRC.*

as the number of the relay nodes increases. In addition, direct transmission with the strategy of power allocation with posture state information outperforms single-relay cooperation with the strategy of power allocation without posture state information. Therefore, it is important to utilize posture state information when designing a power allocation scheme in WBAN.

VI. Conclusions

This paper explores the issue of improving energy efficiency for WBAN. Three transmission schemes are compared, and for each one of them, the optimal power allocation with the constraint of target outage probability was studied. Simulation results demonstrate that cooperative communication can improve energy efficiency for WBAN. Further, the posture state information is important when designing a power allocation scheme for WBAN. Using our analysis and simulation-based results, it was shown that: (i) by allocating power to the on-body sensors using posture information, the energy consumption in the WBAN can be decreased compared to direct transmission; and (ii) when the channel conditions are good, it is energy-efficient to recruit fewer nodes for cooperative relaying.

References

[1] K. Y. Yazdandoost, "Channel models for body area network (ban)," IEEE P802.15-08-0780-08-0006, Tech. Rep., Apr. 2009.
[2] D. Miniutti, "Sleeping channel measurements for body area networks," IEEE 802.15-09-0778-01-0006, Tech. Rep., Jan. 2010.
[3] M. Quwaider and S. Biswas, "Probabilistic routing in on-body sensor networks with postural disconnections," *Proc. 7th ACM Int. Symp. Mobility Management and Wireless Access*, 2009, pp. 149–158.
[4] S. Cui, A. J. Goldsmith, and A. Bahai, "Energy-efficiency of mimo and cooperative mimo techniques in sensor networks," *IEEE J. Sel. Areas Commun.*, vol. 22, no. 6, pp. 1089–1098, Aug. 2004.
[5] Z. Zhou, S. Zhou, S. Cui, and J. Cui, "Energy-efficient cooperative communication in a clustered wireless sensor network," *IEEE Trans. Veh. Tech.*, vol. 57, no. 6, pp. 3618–3628, Nov. 2008.
[6] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation – Part I: System description, Part II: Implmentation aspects and performance analysis," *IEEE Trans. Commun.*, vol. 51, no. 11, pp. 1927–1948, Nov. 2003.
[7] J. N. Laneman, D. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior,"*IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3063–3080, Dec. 2004.
[8] D. Gunduz and E. Erkip, "Opportunistic cooperation by dynamic resource allocation," *IEEE Trans. Wireless Commun.*, vol. 6, no. 4, pp. 1446–1454, Apr. 2007.
[9] A. K. Sadek, W. Yu, and K. J. R. Liu, "On the energy efficiency of cooperative communications in wireless sensor networks," *ACM Trans. Sensor Netw.*, vol. 6, no. 1, Dec. 2009.
[10] C. Otto, A. Milenkovic, C. Sanders, and E. Jovanov, "Sytem architecture of a wireless body area network for ubiquitous health monitoring," *J. Mobile Multimedia*, vol. 1, no. 4, pp. 307–326, 2006.
[11] B. Braem, B. Latre, I. Moerman, C. Blondia, and P. Demeester, "The need for cooperation and relaying in short-range high path loss sensor networks," Proc. SENSORCOMM, 2007, pp. 566–571.
[12] A. Natarajan, B. Silva, K. Yap, and M. Motani, "Link layer behavior of body area networks at 2.4 ghz," *Proc. 15th Annual Int. Conf. Mobile Computing and Networking*, 2009, pp. 241–252.
[13] E. Reusens, W. Joseph, B. Latre, B. Braem, G. Vermeeren, E. Tanghe, L. Martens, I. Moerman, and C. Blondia, "Characterization of on-body communication channel and energy efficient topology design for wireless body area networks," *IEEE Trans. Inf. Tech. Biomed.*, vol. 13, no. 6, pp. 933–944, 2009.
[14] M. Nabi, T. Basten, M. Geilen, M. Blagojevic, and T. Hendriks, "A robust protocol stack for multi-hop wireless body area networks with transmit power adaptation," *Proc. BODYNETS*, Sep. 2010.
[15] K. D. Lee, S. G. Kim, and B. K. Yi, "Low power u-healthcare sevices using mdc packet-level scheduling for in/on-body wireless multi-hop links in a medical body area networks," *Proc. Fifth International Conference on Body Area Networks*, Sep. 2010.
[16] M. Maman, F. Dehmas, R. D'Errico, and L. Ouvry, "Evaluating relaying scheme for ban tdma mac using a space-time dependent channel model," *Proc. IEEE PIMRC*, Sep. 2009, pp. 2101–2105.
[17] B. Miscopein, J. Schwoerer, and J. M. Gorce, "Cooperative beacon-free mac layer for body area networks," *Proc. IEEE PIMRC*, Sep. 2009, pp. 2157–2161.
[18] A. Kailas and M. A. Ingram, "A cooperative transmission technique for telehealth," *Proc. WPMC*, Jaipur, India, Dec. 3–6, 2007.
[19] Y. Chen, *et al.*, "Cooperative communications in ultra-wideband wireless body area networks: channel modeling and system diversity analysis," *IEEE J. Sel. Areas Commun.*, vol. 27, no. 1, pp. 5–16, Jan. 2009.
[20] R. Yu, Y. Zhang, and R. Gao, "Mobile device aided cooperative transmission for body area networks," *Proc. BODYNETS*, Sep. 2010.
[21] J. Gorce, C. Goursaud, G. Villemaud, R. D'Errico, and L. Ouvry, "Opportunistic relaying protocols for human monitoring in ban," *Proc. IEEE PIMRC*, Sep. 2009, pp. 732–736.
[22] Q. Wang, T. Taymachi, I. Kimura, and J. Wang, "An on-body channel model for uwb body area communications for various postures," *IEEE Trans. Ant. Prop.*, vol. 57, no. 4, pp. 991–998, Apr. 2009.
[23] M. Quwaider and S. Biswas, "Physical context detection using wearable wireless sensor networks," *J. Commun. Softw. Sys.*, vol. 4, no. 3, pp. 191–201, Sep. 2008.