Optimal Transmission Power Level Sets for Lifetime Maximization in Wireless Sensor Networks

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***Abstract*—In Wireless Sensor Networks (WSNs) data transmission by using the highest available power level leads to energy wastage on certain links. Therefore, assigning the optimal transmission power for each link in a WSN is necessary to prolong the network lifetime. Transceivers of WSN nodes perform transmission power control by selecting one of the available discrete transmission power levels. As such, the power level set of a WSN transceiver is an important tool for achieving energy efficiency, yet, the power level sets are determined without considering their effects on WSN lifetime. In this study, we investigate the characteristics of the optimal transmission power level sets from WSN lifetime maximization perspective.**

***Index Terms*—wireless sensor networks, transmission power control, network lifetime, mixed integer programming, optimal power levels set.**

I. Introduction

Wireless Sensor Networks (WSNs) are composed of a multitude of sensor nodes and at least one base station. Network lifetime is, arguably, the most important performance metric for WSNs. Communication energy dissipation is the dominant energy dissipation terms for sensor nodes. Optimization of transmission power levels on the links connecting the sensor nodes for reducing energy waste in communication is an effective way of prolonging WSN lifetime [1]. Transceivers utilized by sensor node platforms can adjust their transmission power level from a predetermined set of transmission power levels. Utilizing the highest power level available for all links in the network is shown to result in significant lifetime losses when compared to optimal utilization of all available power levels. Hence, utilizing multilpe power levels is better than utilizing a single power level. However, do we need all the power levels available to achieve the maximum power level?

In literature there are a few studies on the determination of optimal power levels set in wireless communications. In [2], throughput improvement in a communication network is analyzed for a given power levels set and optimal probability distribution for power levels is determined. In [3], a discrete transmission power control scheme to determine the optimal power levels set is proposed for capacity optimization. In this study, we investigate the characteristics of optimal transmission power level sets with minimal cardinality that does not compromise the WSN lifetime, significantly. To the best of our knowledge this is problem has never been investigated in the literature. To analyze the tradeoff between the network lifetime maximization and cardinality of the transmission power level set we built a Mixed Integer Programming (MIP) framework.

II. Energy Model

For the constructed energy model, Mica2 motes' energy dissipation characteristics are used. Transmission power consumption ($P_{tx}^{crc}(l)$ in mW) and corresponding output power on antenna ($P_{tx}^{ant}(l)$ in mW) for Mica2 motes are reported in [1] for 26 power levels (l). The reception power consumption is denoted as $P_{rx}^{crc} = 35.4$ mW.

Time is organized in rounds, where round duration, T_{rnd}, is 60 seconds and in each round s_i number of data packets is generated by all sensor nodes. Data exchange between node pairs is achieved by two-way handshake mechanism (data and ACK packet transmissions). Each sensor node has a battery power of $\varrho = 25$ kJ. Power consumption in the sleep mode is $P_{slp} = 3$ μW. In a single round, data acquisition energy is $E_{DA} = 600$ μJ and each node produces 240 Bytes raw data. We assume each node to transmit $s_i = 1$ data packet at each round with 240 Bytes of payload and 16 Bytes header (*i.e.*, M_P = 240 + 16 = 256 Bytes). The size of an ACK packet is $M_A = 20$ Bytes. Total data processing and acquisition time is $T_{DA} = 20$ ms.

Duration of data exchange between any two node pair is expressed as the slot time ($T_{slot} = 116$ ms). Durations of data and ACK packet transmissions are allowed in slot times and calculated by the division of the packet size to data rate of the wireless channel ($\xi = 19.2$ Kbps).

The received signal power for the transmission with power level-l over the link-(i,j) is [4]

$$P_{rx,ij}^{ant}(l)[\text{dBm}] = P_{tx}^{ant}(l)[\text{dBm}] - \Upsilon_{ij}[\text{dB}], \qquad (1)$$

where the calculated path loss value for the log-normal shadowing path loss model over the link-(i,j) is denoted as Υ_{ij}. The noise power (P_n) is taken -115 dBm at 300 Kelvin temperature [5]. Signal-to-noise ratio (SNR) is formulated as $\psi_{ij}(l) = \frac{P_{rx,ij}^{ant}(l)}{P_n}$.

The probability of successful packet reception of a φ-Byte packet transmitted at power level-l over the link-(i,j) is

$$p_{ij}^{s}(l,\varphi) = \left(1 - \frac{1}{2}\exp\left(\frac{-\psi_{ij}(l)}{2}\frac{1}{0.64}\right)\right)^{8\varphi}, \qquad (2)$$

which is given for non-coherent FSK (Frequency Shift Keying) modulation and NRZ (Non-Return-to-Zero) encoding that are used in Mica2 motes. For the successful communication, each data packet should be transmitted $\lambda_{ij}^{l} = \frac{1}{p_{ij}^{HS,s}(l)}$ times on the average, where $p_{ij}^{HS,s}(l)$ is the probability of a successful handshake when the data and ACK packet is transmitted at power level-l over the link-(i,j). The probability of a successful handshake is calculated by the multiplication of the probabilities of a successful data packet reception and ACK packet reception.

Energy consumption of the transmitter for completing a handshake including retransmissions is

$$E_{tx,ij}^{D}(l) = E_{PP} + \lambda_{ij}(l) E_{tx}^{HS}(l, M_P), \tag{3}$$

where the packet processing energy is, $E_{PP} = 120$ μJ. $E_{tx}^{HS}(l, M_P)$ denotes the total energy dissipation of a transmitter during a single handshake in a slot, which is the summation of energy dissipation for transmitting M_P Bytes of data at power level-l and energy consumption in receiving mode during reception.

Energy consumption of the receiver for completing a handshake including retransmissions is

$$\begin{aligned} E_{rx,ji}^{D}(l) &= E_{PP} + \lambda_{ij}(l) \Big[p_{ij}^{HS,s}(l) E_{rx}^{HS,s}(l, M_A) + \\ & p_{ij}^{s}(l, M_P) p_{ji}^{f}(l, M_A) E_{rx}^{HS,s}(l, M_A) + p_{ij}^{f}(l, M_P) E_{rx}^{HS,f} \Big], \end{aligned} \tag{4}$$

where $E_{rx}^{HS,s}(l, M_A)$ is the energy dissipation of a receiver for a successful handshake and it is obtained by summing the energy dissipation for transmitting M_A Bytes of data at power level-l and the energy consumption for receiving data packet. $E_{rx}^{HS,f}$ denotes the energy cost of reception with handshake failure which is formulated as the multiplication of power consumption for reception, P_{rx}^{crc}, by slot time, T_{slot}. Finally, $p_{ij}^{s}(l, M_P)$, $p_{ij}^{f}(l, M_P)$, and $p_{ji}^{f}(l, M_A)$ represents the probability of the successful data packet reception, failure data packet reception and failure ACK packet reception, respectively.

Maximize t
Subject to:

$$\sum_{l \in S_L} \sum_{(i,j) \in A} f_{ij}^{l} - \sum_{l \in S_L} \sum_{(j,i) \in A} f_{ji}^{l} = t \times s_i, \ \forall i \in W \tag{5}$$

$$\begin{aligned} T_{bsy,i} = T_{slot} \sum_{l \in S_L} \left[\sum_{(i,j) \in A} \lambda_{ij}^{l} f_{ij}^{l} + \sum_{(j,i) \in A} \lambda_{ji}^{l} f_{ji}^{l} \right] \\ + t \times T_{DA}, \ \forall i \in W \end{aligned} \tag{6}$$

$$\begin{aligned} &\sum_{l \in S_L} \sum_{(i,j) \in A} E_{ij}^{tx,l} f_{ij}^{l} + P_{slp}(t \times T_{rnd} - T_{bsy,i}) \\ &+ \sum_{l \in S_L} \sum_{(j,i) \in A} E_{ji}^{rx,l} f_{ji}^{l} + t \times E_{DA} \leq \varrho, \ \forall i \in W \end{aligned} \tag{7}$$

$$\begin{aligned} &T_{slot} \sum_{l \in S_L} \Bigg[\sum_{(i,j) \in A} \lambda_{ij}^{l} f_{ij}^{l} + \sum_{(j,i) \in A} \lambda_{ji}^{l} f_{ji}^{l} \\ &+ \sum_{(j,n) \in A} \lambda_{jn}^{l} f_{jn}^{l} I_{jn}^{i,l} \Bigg] \leq t \times T_{rnd}, \ \forall i \in V \end{aligned} \tag{8}$$

$$I_{jn}^{i,l} = \begin{cases} 1 \text{ if } P_{rx,ji}^{ant,l} \geq P_{sns} \\ 0 \text{ o.w.} \end{cases} \tag{9}$$

$$\sum_{(i,j) \in A} f_{ij}^{l} \leq \mathcal{M} \times b_l, \ \forall l \in S_L \tag{10}$$

$$\sum_{l \in S_L} b_l \leq \zeta \tag{11}$$

$$f_{ij}^{l} \geq 0, \ \forall l \in S_L, \forall (i,j) \in A \tag{12}$$

$$b_l \in \{0, 1\}, \ \forall l \in S_L \tag{13}$$

Fig. 1: MIP model for the lifetime maximization.

III. OPTIMIZATION MODEL

In this section, we present an MIP model for WSN network lifetime maximization under transmission power level set cardinality constraints. The topology of the WSN is represented by a directed graph, $G = (V, A)$. In this notation, V is defined as the set of all nodes including the base station (node-1). W set includes all nodes except node-1. (*i.e.*, $W = V \setminus \{1\}$). $A = \{(i,j) : i \in W, j \in V - i\}$ denotes the set of links. The set of all available power levels is expressed as S_L. The number of data packets flowing from node-i to node-j transmitted at power level-l is represented with the non-negative integer variable, f_{ij}^{l}. The MIP model is presented in Figure 1. The objective function of the MIP model is the network lifetime (t) which is represented in terms of rounds. The lifetime in terms of seconds can be calculated by $t \times T_{rnd}$.

Flow balancing constraint is given in (5) which states that data flowing into node-i plus data generated by node-i is equal to the data flowing out of node-i, for all nodes with exception of base station. Calculation for the total amount of time that node-i stays busy is expressed in (6) (*i.e.*, whether a node is transmitting, receiving, or acquiring data). *Energy balancing constraint* which states that the total energy dissipation at each sensor node is limited by the amount of initial energy of batteries (ϱ), is given in (7). *Bandwidth constraint* is given in (8) which guarantees that the channel bandwidth at all of the sensor nodes and base station is bounded from above by the available bandwidth. Interference indicator function ($I_{jn}^{i,l}$) at node-i is formulated in (9). Determination of optimal power levels sets are governed by (10)–(13). If power level-l is used in flow between any node-i and node-j, then the value of binary variable b_l is unity; if it is not used then value of b_l is zero. In (10), no flow is allowed if $b_l = 0$. In this constraint $\mathcal{M}$ represents a large positive number. In (11), the size of the optimal power levels set is bounded by ζ. By scanning a range of ζ values in Section IV, the MIP model is used to characterize the optimal power level sets. Finally, (12) and 13 represent the bound of the variables.

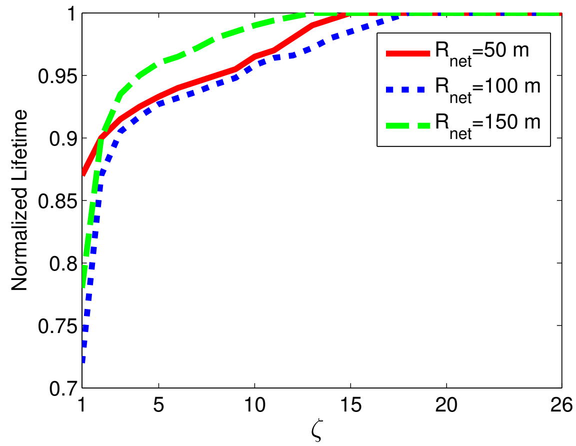

Fig. 2: Normalized network lifetimes as a function of ζ for three R_{net} values.

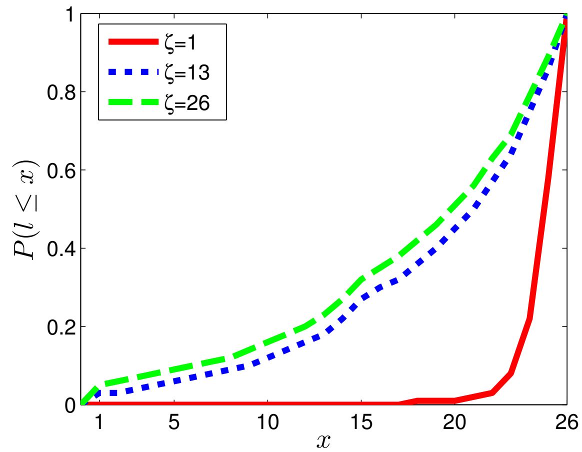

Fig. 3: Cumulative occurrence probability, $P(l \leq x)$, for three ζ values when $R_{net} = 100$ m.

IV. Analysis

In this section, we present the results of analysis on the determination of the optimal transmission power levels set for maximization of network lifetime. We consider random disk shaped network topologies (with radius R_{net}). Networks consist of 20 sensor nodes that are uniformly distributed within the disk and the base station is located at the center of the disk. Throughout the analysis section, R_{net} is chosen as 50, 100 and 150 meters. Simulations are done by using MATLAB and General Algebraic Modeling System (GAMS). Results presented in Figures 2 and 3 are the averages of the results obtained for 100 randomly generated topologies.

In Figure 2, we present normalized lifetimes with respect to size of the optimal power levels set (*i.e.*, ζ). Normalization is done by dividing each absolute lifetime value by the maximum lifetime value obtained for a given R_{net}. Since we aim to observe the relative effect of limiting the number of available power levels for each R_{net} value we opt not report the absolute lifetime values. Note that maximum network lifetime is obtained when there is no limitation on the power levels set (*i.e.*, $\zeta = 26$). As we limit ζ from its highest value to its 50% value (*i.e.*, $\zeta = 26$ to $\zeta = 13$) the drop in maximum network lifetime is lesser than 5%. When $\zeta = 1$, maximum network lifetime decreases at most 30% (when $R_{net} = 100$ m). The reason of such behaviour is the diversity of power levels which has great impact on lifetime maximization for networks that are neither dense nor sparse. In denser networks, nodes choose lower powers to minimize the energy consumed for communications while in sparser networks, nodes prefer higher power levels to minimize the packet loss for reliable communications. Nonetheless, in both scenarios, the number of power levels that are utilized are much lower than moderately dense networks.

In Figure 3, we present cumulative occurrence probability of power levels, $P(l \leq x)$, for three ζ values (*i.e.*, $\zeta = 1$, 13, and 26) for a moderately dense network (*i.e.*, $R_{net} = 100$ m). If a single power level is allowed in the optimal power levels set (*i.e.*, $\zeta = 1$) around 92% of the links ($P(l < 24) = 0.08$) utilize high power levels ($l = 24$, 25, and 26). The reason behind such trend is the trade-off between network lifetime and packet loss. In this configuration, nodes aim to minimize the packet loss by compromising network lifetime (up to 30% decrement in maximum network lifetime is observed when $\zeta = 1$). As we increase ζ, this trade-off vanishes such that utilization of high power levels drops to 36% ($P(l < 24) = 0.64$) and 30% ($P(l < 24) = 0.70$) for $\zeta = 13$ and $\zeta = 26$, respectively.

V. Conclusion

In this study the impact of optimal power levels set size on WSN lifetime is investigated. We propose an MIP model built on top of a realistic link layer model adopted from Mica2 motes' characteristics. We perform extensive analysis and observe that by adjusting the size of optimal power levels set half of all power levels available for Mica2 motes', at least 95% of the maximum lifetime that can be achieved when considering all available power levels. Furthermore, our results show a non-monotonic behaviour. If the network is too dense (or sparse), the assignment of low (or high) power levels increase. However, for moderate density networks, diversity of power levels has a great impact on lifetime maximization as compared to dense and sparse networks.

References

[1] H. Yildiz, B. Tavli, and H. Yanikomeroglu, "Transmission power control for link level handshaking in wireless sensor networks," *IEEE Sensors Journal*, vol. 16, no. 2, pp. 561–576, 2016.

[2] M. Zou, S. Chan, H. L. Vu, and L. Ping, "Throughput improvement of 802.11 networks via randomization of transmission power levels," *IEEE Trans. Vehicular Tech.*, vol. 65, no. 4, pp. 2703–2714, 2016.

[3] C.-H. Liu, B. Rong, and S. Cui, "Optimal discrete power control in poisson-clustered ad hoc networks," *IEEE Trans. Wireless Commun.*, vol. 14, no. 1, pp. 138–151, 2015.

[4] S. Kurt and B. Tavli, "Propagation model alternatives for outdoor wireless sensor networks," in *Proc. of the IFIP Wireless Days (WD)*, 2013, pp. 1–3.

[5] M. Zuniga and B. Krishnamachari, "Analyzing the transitional region in low power wireless links," in *Proc. IEEE Communications Society Conf. Sensor, Mesh and Ad Hoc Communications and Networks (SECON)*, 2004, pp. 517–526.