Channel-Aware Repetitive Data Collection in Wireless Sensor Networks

Ryangsoo Kim, Jinho Choi, and Hyuk Lim

Abstract

Wireless sensor networking technology has been applied in practice to a variety of information gathering infrastructures, where sensing data are repetitively delivered to a data collector within a session period. For efficient energy conservation, each sensor node can wait for a higher channel gain before it begins the transmission of sensing data and transmits them with a power that is inversely proportional to the channel gain. However, if the node waits for higher channel gain, switching to the sleeping mode takes a longer time. We formulate this channel-aware data transmission problem using an optimization problem with linear constraints. The numerical simulations indicate that the proposed method significantly reduces the energy consumption compared with other heuristic methods.

Index Terms

Wireless sensor networks, energy efficiency, channel-aware transmission, repetitive data collection.

I. Introduction

With the proliferation of ubiquitous computing environment, wireless sensor networks (WSNs) have received much attention in recent decades owing to its self-organization capability, cost-effective connectivity provisioning, and easy deployment [1]. Nowadays, wireless sensor networking technologies are being actively applied in practice to a variety of information gathering infrastructures such as advanced metering infrastructure (AMI), home and factory automation, smart energy grid control and management, and environment monitoring systems [2], [3]. In such applications, sensing data should be reported periodically or within a certain time period to a

The authors are with the School of Information and Communications, Gwangju Institute of Science and Technology (GIST), Gwangju 500-712, Republic of Korea. E-mail: hlim@gist.ac.kr

data collector. For example, the sensing data reading in an AMI system is repetitively measured and reported to the collector every tens of seconds or few minutes. This repetitive data collection should be carefully taken into account in the design and deployment of WSNs. Another important factor is energy conservation for prolonging the lifetime of WSNs consisting of sensor nodes with a limited power supply [4]. Most of existing work has concentrated their attention on energy-efficient medium access control (MAC) protocols (e.g., [5]–[7]) to prolong the lifetime of WSNs. In [5], a variety of slotted contention-based energy efficient MAC protocols were presented with a comprehensive review and taxonomy of the protocols. In [6], a duty cycling scheme based on the M/G/1 queuing analysis was proposed to alleviate the collision occurrence among sensor nodes. In [7], a sleep/wake state scheduling method which is adaptive to realtime traffic pattern was proposed to reduce energy consumption while minimizing the quality of service (QoS) degradation. In repetitive data collection, sensing data need not be delivered immediately, as there is a sufficient time gap before the deadline for delivery. Therefore, exploiting the channel diversity over time is possible to reduce the transmission power for energy conservation in WSNs.

A variety of energy-efficient data transmission schemes exist in WSNs. In [8], the energy consumption per unit transmit distance was introduced as a new metric for energy-efficient cooperative transmission in WSNs. Then, an algorithm was proposed to minimize the new energy efficiency metric by allowing a subset of sensors to cooperatively transmit. In [9], a scheduling-based data transmission method was proposed for energy optimal data transmission, which was derived based on a finite-state Markov wireless channel model. Then, a finite-horizon dynamic program approach was used to make a sequential decision on whether to transmit the sensing data or to keep it to maximize energy efficiency while satisfying the packet waiting time deadline in a transmission queue. In [10], a collection algorithm for raw sensor data was proposed for a WSN. Because the sensors captured highly correlated data, the spatial correlation could be exploited to reduce the energy consumption in delivering the sensing data to the collector node. In [11], a channel-aware type-based multiple access (TBMA) scheme was proposed. It allowed the sensors to transmit sensing data when their channel gains are higher than a threshold determined by a fusion center. Whereas the channel-aware multiple access scheme was similar to ours, it focused on opportunistic random access without any consideration of timely data delivery and did not consider further energy saving using sleep operations of the sensor nodes.

In this paper, we propose a channel-aware data transmission scheme for repetitive data collection in WSNs. The proposed data transmission scheme attempts to minimize the energy

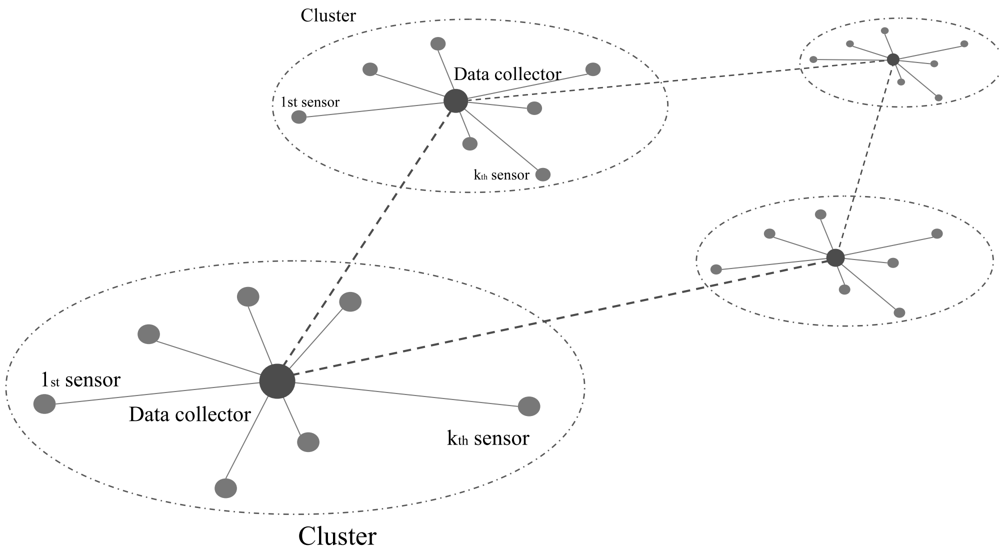

Fig. 1. Topology of a large-scale wireless sensor network.

consumption of the sensor nodes by letting each sensor transmit its sensing data when the channel gain is higher than a certain threshold. If a sensor node waits for a longer time for higher channel gain, it can transmit at a lower transmission power, although it has to remain in the active mode at a longer time before it switches to the sleeping mode. To find the optimal channel gain threshold, an optimization problem with linear constraints is formulated for repetitive data collection in WSNs.

II. System Model

We consider repetitive data transmissions for sensing data collection in large-scale WSNs, where wireless sensor nodes are clustered and are connected to one of cluster heads as shown in Figure 1. Each cluster consists of one data collector (i.e., cluster head) and K wireless sensor nodes with a limited energy supply. We assume that the sensor nodes are located within a communication range of the collector; thus, they can directly communicate with the collector. In addition, each data collector can communicates with its neighbor data collectors through a dedicated wireless channel, and thus the data transmission among the collectors does not interfere with those of the sensor nodes. For timely data collection, all sensor nodes are supposed to transmit their sensing data to the collector at every *collection session*. The reporting time depends on a specific target application. For example, for advanced metering application, it could be once every tens of seconds or few minutes. The transmission of the sensing data from

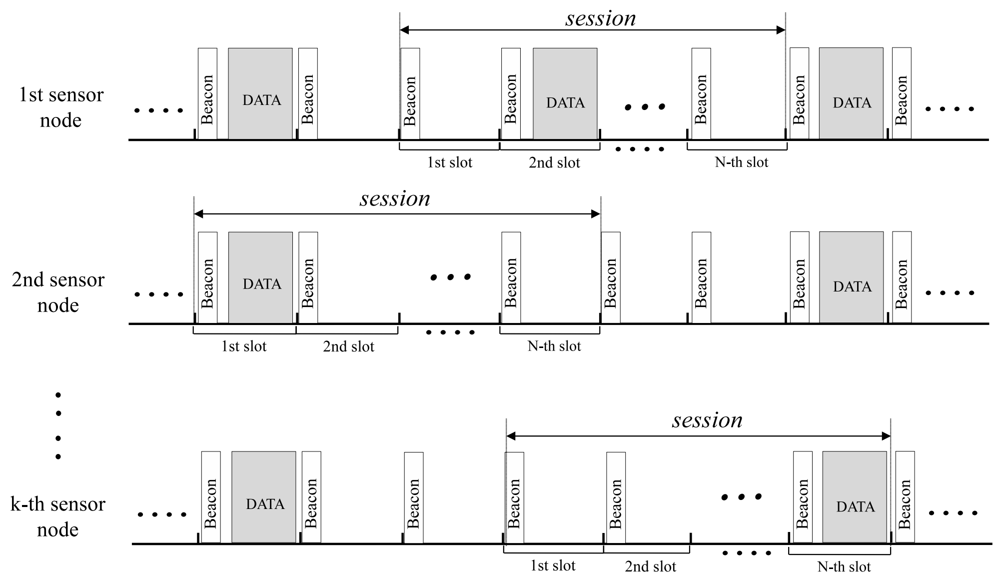

Fig. 2. Example of a repetitive data collection operation in a WSN.

a node is assumed to be successful if the data is successfully delivered to the collector within a single collection session, which is divided into N *time slots*, as shown in Fig. 2. The collection sessions of sensor nodes are asynchronous with each other. Each slot is long enough for the collector to broadcast a beacon packet and the sensor to transmit a data packet to the collector within the slot time; thus data transmissions are performed in a time-division duplex (TDD) manner.

Because the sensor nodes operate with a limited energy supply, energy conservation is one of the most significant factors that determines the lifetime of WSNs. We consider an energy saving mechanism that allows the sensor nodes to alternately stay between the active and sleep modes. Sensor nodes are scheduled to wake up at the first slot of their collection session, which is known in advance. Once a sensor node successfully transmits its data packet to the collector, it goes into the sleep mode to minimize energy consumption. In the sleep mode, the sensor nodes turn off the energy-consuming components such as the radio frequency (RF) front end and sensing modules. On the other hand, in the active mode, the nodes are ready to receive beacon packets broadcast by the data collector. Upon receipt of a beacon packet, they attempt to transmit the data packets according to the channel gain at that time.

In addition to the sleep operation, a channel inversion-based transmit power allocation is adopted to further conserve energy. We assume that the channel gain remains constant during each slot time because of the block fading channel. Then, the measured channel gain of the beacon packets sent by the collector can be used to determine the transmit power of the sensor nodes. Because a sensor node can transmit with a smaller transmit power when the channel gain is high, it may decide to postpone data transmission until the channel gain is sufficiently high. However, this decision may result in more energy consumption because the node has to remain longer in the active mode, which implies that an optimal transmission policy exists that maximizes energy efficiency depending on the channel condition.

III. Proposed Medium Access Control Scheme

We propose a channel-aware data transmission policy for repetitive data collection to minimize energy consumption of the sensor nodes. Let $\gamma_{k,n}$ denote the channel gain of beacon packet broadcast by the data collector at the k-th sensor in the n-th slot of the k-th sensor's collection session. We assume that the uplink channel gain from the sensors to the data collector is identical to that of the downlink from the data collector to the sensors due to the channel reciprocity of the TDD system [11], and the downlink channel gain is measured from the beacon packets broadcast by the data collector. Let $\mathbf{V} = [V_1, \cdots, V_K]$ denote the transmission policy vector, where V_k is the channel gain threshold of the k-th sensor node. If $\gamma_{k,n} \geq V_k$, the k-th sensor node transmits the sensing data at the n-th slot. Since $\gamma_{k,n}$ varies over time because of the time-varying fading and shadowing, we assume that $\gamma_{k,n}$ of the k-th sensor node follows an independent and identically distributed random process over the time slots. Under the assumption of block fading channel, the channel gain does not change within a single slot. Here, we consider the Rayleigh fading channel over the slots for each sensor node; thus, its distribution is given as follows:

$$f(\gamma_{k,n} = k) = \frac{1}{\overline{\gamma}_k}\text{exp}(-\frac{k}{\overline{\gamma}_k}), \tag{1}$$

where $\overline{\gamma}_k$ is the mean channel gain of the k-th sensor. The received signal strength is inversely proportional to the distance between the sensor and data collector; thus, the mean channel gain is given by

$$\overline{\gamma}_k = \frac{C}{d_k^{\eta}}, \tag{2}$$

where d_k is the Euclidean distance between the k-th sensor and data collector, η is the path loss exponent, and C is a constant. Given a Rayleigh fading distribution for each sensor, the probability that the k-th sensor decides to transmit a sensing data within N slots can be expressed as

$$\text{Pr}(\max_{n} \gamma_{k,n} > V_k) = 1 - F^N_{\gamma_{k,n}}(V_k) = 1 - (1 - e^{-\frac{V_k}{\overline{\gamma}_k}})^N, \tag{3}$$

where $F_{\gamma_{k,n}}(V_k) = 1 - e^{-\frac{V_k}{\overline{\gamma}_k}}$ is the cumulative distribution function of $\gamma_{k,n}$. We note that the data transmission probability of each sensor depends on the corresponding channel gain threshold V_k.

For repetitive data collection, each sensor has sensing data with a size of D bits in every collection session. Let T denote the one slot time in seconds, B denote the channel bandwidth in hertz, σ denote the noise power, and P_k denote the transmission power of the k-th sensor. Then, the minimum transmission power required to achieve the rate of D bits per slot for the k-th sensor node is derived as follows:

$$\begin{aligned} TB \log_2(1 + \frac{P_k V_k}{\sigma}) &\geq D \\ \log_2(1 + \frac{P_k V_k}{\sigma}) &\geq \frac{D}{TB} =: A \\ P_k &\geq \sigma \frac{2^A - 1}{V_k} = \frac{\bar{A}}{V_k}. \end{aligned} \tag{4}$$

From (3), the average number of slots until the first data transmission of the k-th sensor node, i.e., the mean of $T_k(V_k) = \min\{n : \gamma_{k,n} \geq V_k, n = 1, \cdots, N\}$ can be derived as follows:

$$\begin{aligned} \mathbb{E}[T_k(V_k)] &= \sum_{n=1}^{N} n \cdot \text{Pr}(T_k(V_k) = n) \\ &= \sum_{n=1}^{N} n \cdot \{\text{Pr}(T_k(V_k) \leq n) - \text{Pr}(T_k(V_k) \leq n-1)\} \\ &= \sum_{n=1}^{N} n \cdot e^{-\frac{V_k}{\overline{\gamma}_k}} (1 - e^{-\frac{V_k}{\overline{\gamma}_k}})^{n-1} \\ &= e^{\frac{V_k}{\overline{\gamma}_k}} - (1 - e^{-\frac{V_k}{\overline{\gamma}_k}})^N (e^{\frac{V_k}{\overline{\gamma}_k}} + N). \end{aligned} \tag{5}$$

From the above equations, the energy consumption of the k-th sensor is given by

$$\begin{aligned} E_k(V_k) &= (P_k + P_a \cdot \mathbb{E}[T_k(V_k)]) \cdot T \\ &= \frac{\bar{A}}{V_k} \cdot T + P_a \cdot (e^{\frac{V_k}{\overline{\gamma}_k}} - (1 - e^{-\frac{V_k}{\overline{\gamma}_k}})^N (e^{\frac{V_k}{\overline{\gamma}_k}} + N) \cdot T, \end{aligned} \tag{6}$$

where P_a is the power consumption in the active mode. Based on (6), we formulate the data transmission policy as an optimization problem over $\mathbf{V}$ as follows:

$$\underset{\mathbf{V}=[V_1,\cdots,V_K]}{\arg\min} \sum_{k=1}^{K} E_k(V_k) = \sum_{k=1}^{K} \left(\frac{\bar{A}}{V_k} \cdot T + P_a \cdot (e^{\frac{V_k}{\overline{\gamma}_k}} - (1-e^{-\frac{V_k}{\overline{\gamma}_k}})^N (e^{\frac{V_k}{\overline{\gamma}_k}} + N)) \cdot T \right) \tag{7}$$
$$\text{s.t.} \quad \Pr(\max_n \gamma_{k,n} > V_k) \cdot p_s \geq \bar{p}, \quad \forall k \in \mathcal{K},$$

where $\mathcal{K}$ is the set of sensors, p_s is the transmission success probability when a sensor attempts to transmit its data packet, and $\bar{p}$ is a lower bound of the session delivery probability required for reliable data transmission. Under the assumption that the collection sessions are asynchronous with each other and are uniformly distributed over time, p_s is given by

$$p_s = (1 - \frac{1}{N})^{K-1}. \tag{8}$$

Here, the constraint in (7) can be simply rewritten as

$$\Pr(\max_n \gamma_{k,n} > V_k) = 1 - (1 - e^{-\frac{V_k}{\overline{\gamma}_k}})^N \geq \frac{\bar{p}}{p_s}$$
$$V_k \leq -\overline{\gamma}_k \ln(1 - (1 - \frac{\bar{p}}{p_s})^{\frac{1}{N}}) =: \mu_k. \tag{9}$$

The constraint in (9) shows that the channel gain threshold V_k for the k-th sensor is bounded by μ_k, which depends on N, K, $\overline{\gamma}_k$, and the lower bound $\bar{p}$. If the lower bound $\bar{p}$ increases for more reliable data transmission, the upper bound of channel gain threshold V_k decreases, and the waiting time for data transmission becomes smaller. In this case, the sensor node may have less opportunity to exploit the channel diversity for energy conservation.

Under the assumption that N is sufficiently large (i.e., $N \to \infty$), the energy consumption of the k-th sensor in (6) can be simply rewritten as

$$\lim_{N\to\infty} E_k(V_k) = \frac{\bar{A}}{V_k} T + P_a e^{\frac{V_k}{\overline{\gamma}_k}} T. \tag{10}$$

The above equation indicates that the energy consumption of the k-th sensor heavily depends on the channel gain threshold V_k. In (10), the first term corresponds to the amount of energy consumption for data transmission, and it decreases with respect to V_k. The second term corresponds to the amount of energy consumption in active mode, and it increases with respect to V_k. Note that as V_k increases, the sensors have to wait longer before they transmit data packets in an average sense, resulting in more energy consumption. This implies that a tradeoff relationship exists between them. Therefore, the channel gain threshold should be carefully determined in order to minimize the overall energy consumption of sensor nodes. Obviously, the problem in (7) is a convex optimization problem with linear constraints. Furthermore, it can be decomposed into K subproblems with linear constraint V_k in (9). The optimal threshold V_k^* for each subproblem can be easily obtained from either μ_k or the root of the first derivative of the function in (6).

IV. Performance Evaluations

To evaluate the performance of the proposed method, we carried out numerical simulations using MATLAB. In the simulations, we considered a smart metering scenario, where K metering sensors are uniformly distributed around the data collector. Each sensor transmits 12 kbits of sensing data to the data collector every 15 minutes [12]. For our repetitive data collection, the bandwidth B is 10 kHz, one slot time T is 100 ms, and the session delivery probability $\bar{p}$ is 0.99. The amount of sensing data D is 12 kbits, and the number of slots in one data session N is 9000. The path loss exponent η is 3.2, and the noise power σ is 10 μW. The power consumption in the active mode P_a is 1 mW, and that in the sleep mode is assumed to be negligible. For comparison purpose, two heuristic data collection methods are considered as follows:

- Random method: Each sensor attempts to transmit a data packet with a certain probability until it transmits it within the session. The probability is set to $\frac{1}{K}$, which is the optimal channel access probability for slotted ALOHA networks with K nodes.
- Sequential method: In each session, the sensor nodes are scheduled to transmit their packet at the first slot. The time duration when the sensors are in the active mode is minimized.

For both heuristic methods, the sensor nodes use transmission power that is inversely proportional to the channel gain, as performed in the proposed method. In addition, the TBMA scheme in [11] is also considered for comparison. The TBMA scheme allows sensor nodes to transmit the data packets when their channel gains are higher than a threshold determined by the data collector. In the simulations, the threshold of TBMA is set to make exactly one sensor node transmit a data packet at each slot in an average sense.

Figure 3 shows the energy consumption per successfully collected sensing data in one data session in terms of the number of sensor nodes, when their transmission range is 20 m. The figure shows the proposed data collection method uses much lower energy than the other methods. Whereas the proposed method makes the sensors wait for more slots until the data transmission than the other methods, it consumes less power on average because the sensor nodes have higher probability to transmit their sensing data when the channel gain is high. As the number of sensors

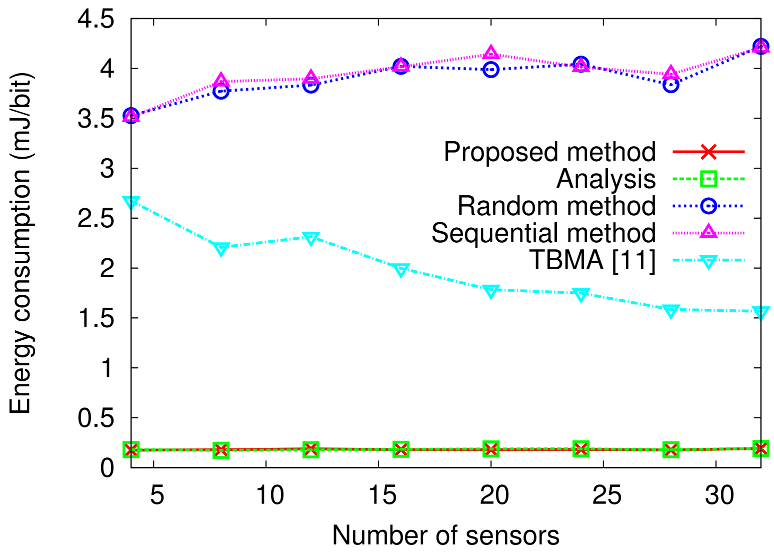

Fig. 3. Energy consumption of all sensors in one data session in terms of the number of sensors.

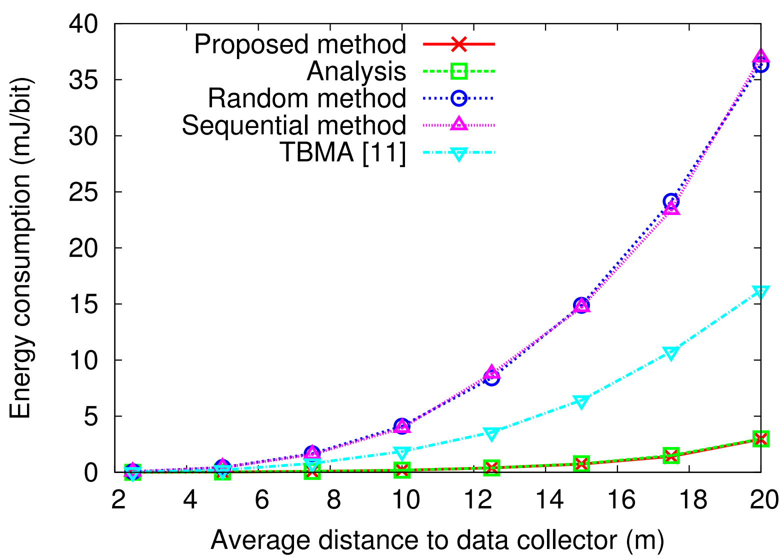

Fig. 4. Energy consumption of all sensors in one data session in terms of the average distance between the sensors and data collector.

increases, the energy consumption of TBMA decreases. This is because the threshold of TBMA increases with respect to the number of sensors, and the sensors can use smaller transmission power for energy conservation.

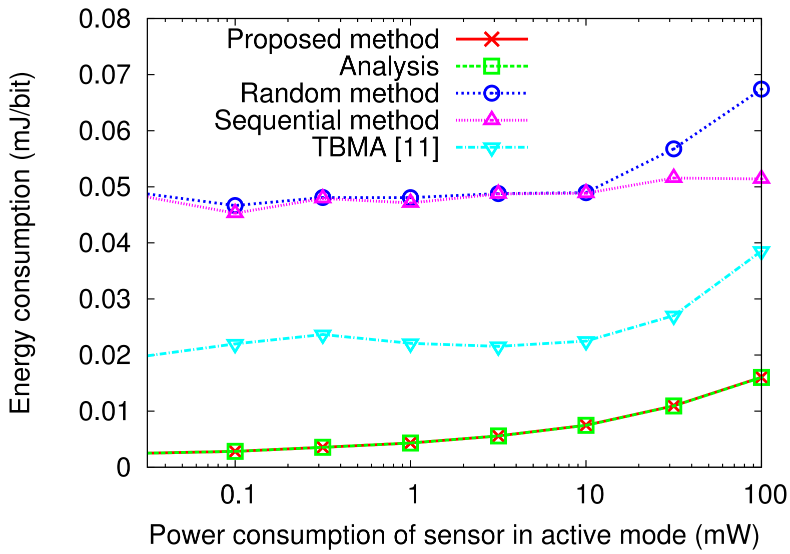

Fig. 5. Energy consumption of all sensors in one data session in terms of the power consumption in the active mode.

Figure 4 shows the energy consumption for every successfully collected data in terms of the average distance between the sensor and data collector when the number of sensor K is 20. As the distance increases, the energy consumption of all the methods rapidly increases because the channel gain between the collector and sensors decreases. Figure 4 shows that the proposed data collection method significantly outperforms the other methods in terms of energy conservation in the entire distance range.

Figure 5 shows the energy consumption for every successfully collected data in terms of the power consumption of the sensor nodes in the active mode when the number of sensor K is 20 and their transmission range is 5 m. As the power consumption of the sensor nodes in the active mode increases, the energy consumption per bit of all the methods increases; however, that of the sequential method does not change because the duration of the active mode of the sequential method is short, and thus, the transmission power is more dominant.

Figure 6 shows the average waiting time for data transmission of the sensors after the beginning of each collection session when the number of sensors K is 20. As the power consumption in the active mode increases, the waiting time for data transmission becomes smaller because the sensor nodes wait a less time for data transmissions in order to reduce energy consumption in the active mode. As the path loss exponent and the distance between the sensors and data collector increase, the waiting time also increases because the sensor nodes wait a longer time

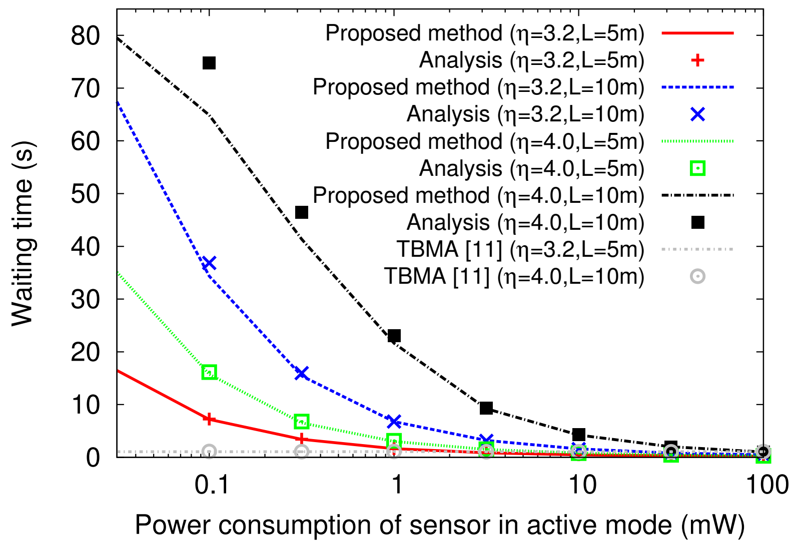

Fig. 6. Waiting time of data transmissions for different values of the path loss exponent (η) and the average distance between the data collector and sensors (L).

for a higher channel gain in order to transmit their sensing data with a lower transmission power. If the sensor nodes have to use higher transmission power, the sensor nodes wait for a longer time to minimize the energy consumption for data transmissions by exploiting channel diversity over time. On the other hand, the waiting time of TBMA does not change for different values of the path loss exponent and the distance; this is because TBMA makes only one sensor node transmit at each slot, and the waiting time is solely dependant on the number of sensors rather than the channel conditions.

V. Conclusion

We have investigated an energy efficient repetitive sensing data collection that exploits the channel gains between the data collector and sensor nodes in WSNs. We proposed a channel gain threshold-based transmission policy, which makes each sensor transmit the data packet to the data collector only when its channel gain is larger than the threshold to minimize energy consumption within a data session. The numerical simulations indicated that the proposed method significantly reduces the energy consumption compared with other methods.

REFERENCES

[1] G. P. Hancke and V. C. Gungor, "Guest editorial: Special section on industrial wireless sensor networks," *IEEE Transactions on Industrial Informatics*, vol. 10, no. 1, pp. 762–765, 2014.

[2] X. Xu, J. Luo, and Q. Zhang, "Delay tolerant event collection in sensor networks with mobile sink," *IEEE International Conference on Computer Communications (INFOCOM), San Diego, CA, USA, March 15-19*, 2010.

[3] L. Xue, X. Guan, Z. Liu, and B. Yang, "TREE: Routing strategy with guarantee of QoS for industrial wireless sensor networks," *International Journal of Communication Systems*, vol. 27, no. 3, pp. 459–481, 2014.

[4] N. Xiong, M. Cao, A. V. Vasilakos, L. T. Yang, and F. Yang, "An energy-efficient scheme in next-generation sensor networks," *International Journal of Communication Systems*, vol. 23, no. 9-10, pp. 1189–1200, 2010.

[5] M. Doudou, D. Djenouri, N. Badache, and A. Bouabdallah, "Slotted contention-based energy-efficient MAC protoocls in delay-sensitive wireless sensor networks," *IEEE Symposium on Computer and Communications (ISCC), Cappadocia, Turkey, July 1-4*, pp. 419–422, 2012.

[6] F. C. Jiang, D. C. Huang, C. T. Yang, C. H. Lin, and K. H. Wang, "Design strategy for optimizing power consumption of sensor node with min(N,T) policy M/G/1 queuing models," *International Journal of Communication Systems*, vol. 25, no. 5, pp. 652–671, 2012.

[7] Y. Song, B. Ciubotaru, and G. M. Muntean, "Application-aware adaptive duty cycle-based medium access control for energy efficient wireless data transmissions," *IEEE Conference on Local Computer Networks (LCN), Clearwater, Florida, USA, October 22-25*, pp. 172–175, 2012.

[8] B. Li, Q. W. Yin, R. Yang, Y. Li, and C. Wang, "A new cooperative transmission metric in wireless sensor networks to minimize energy consumption per unit transmit distance," *IEEE Communication Letters*, vol. 16, no. 5, pp. 626–629, 2012.

[9] R. Srivastava and C. M. Koksal, "Energy optimal transmission scheduling in wireless sensor networks," *IEEE Transactions on Wireless Communications*, vol. 9, no. 5, pp. 1650–1660, 2010.

[10] S. Sharafkandi, D. H. Du, and A. Razavi, "A distributed and energy efficient algorithm for data collection in sensor networks," *International Conference on Parallel Processing (ICPP), San Diego, CA, USA, September 13-16*, pp. 571–580, 2010.

[11] H. Jeon, J. Choi, H. Lee, and J. Ha, "Channel-aware energy efficient transmission strategies for large wireless sensor networks," *IEEE Signal Processing Letters*, vol. 17, no. 7, pp. 643–646, 2010.

[12] J. Zhou, R. Q. Hu, and Y. Qian, "Scalable distributed communication architectures to support advanced metering infrastructure in smart grid," *IEEE Transactions on Parallel and Distributed Systems*, vol. 23, no. 9, pp. 1632–1642, 2012.