Towards Fast and Energy-Efficient Dissemination via Opportunistic Broadcasting in Wireless Sensor Networks

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Abstract. Broadcasting in wireless sensor networks (WSNs) is a basic operation to control the entire network. However, traditional broadcasting is not appropriate for WSNs with a low-duty-cycle; it is devised for an energy-limited environment, where nodes stay asleep much of the time and wake up only for a short time. Duty-cycled broadcasting methods, such as the opportunistic flooding (OF) scheme, have been studied to reduce the flooding delay. However, OF suffers a problem of energy unbalanced consumption, incurring early network disconnection. In this paper, we modify OF to decrease the broadcast delay and prolong the network lifetime, through acquiring more candidates for senders and considering the remaining energy of nodes. Simulation shows our scheme achieves shorter delay and longer network lifetime than OF (i.e., decrease by up to about 60% and increase by up to about 100%, respectively).

Keywords: Opportunistic, Broadcasting, Energy-efficient, Lifetime, Remaining energy, Fast dissemination.

1 Introduction

Broadcasting facilitates sensor nodes to propagate messages across the entire network, as a fundamental service in wireless sensor networks (WSNs), whilst serving a wide range of high-level operations. This is critical to effectively implement a network-wide broadcast service for the overall optimized performance of WSNs [1]. Therefore, much effort has been made to improve broadcasting efficiency. Several researchers focus on reducing broadcast redundancy [2, 3] or increasing broadcasting reliability [4]. Trickle [5], as a code propagation algorithm, maintains up-to-date information with a low maintenance overhead. DIP [6] extends Trickle to reduce the number of transmissions for a dense network.

However, such research is unsuitable under a duty-cycled environment. The sensor network should have a sufficiently long lifetime to fulfill the application requirements,

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but most sensor nodes use a small battery. A sensor network has operate under a duty-cycle, in which a sensor node schedules itself to be active for only a very brief period of time and then stays dormant for a long time, to bridge the gap between limited energy supplies and application lifetimes. A sender may have to wait for a certain period of time (termed *sleep latency* [7]) until its receivers become active to deliver a packet.

Broadcasting methods under duty-cycles have been recently studied. Wang et al. [1] transformed this problem into a shortest-path problem, and addressed it as a solution via dynamic programming. However, the solution operates only with a centralized method. An opportunistic flooding (OF) scheme for low-duty-cycle networks with unreliable wireless links is proposed [8]. The key idea of OF is to make probabilistic forwarding decisions at a sender based on the delay distribution of next-hop nodes. From a probabilistic viewpoint, the transmission on an energy optimal tree (i.e., composed of links with best quality) could achieve the fastest dissemination. However, senders in OF get a chance to forward a packet using links outside the energy optimal tree when they receive a packet opportunistically early, to reduce flooding delay. Nevertheless, OF has a drawback (i.e., the energy consumption is concentrated on certain nodes on the energy optimal tree) due to the link-quality-based backoff during the sole sender selection phase (discussed in Section 2). Therefore, none of this research has provided good solutions for both small flooding delay and a long network lifetime.

In this paper, we propose an energy-efficient opportunistic broadcasting (EEOB) in a duty-cycled environment. EEOB uses links to the siblings to ensure more sender candidates, and thus increases the probability of energy balancing and fast dissemination. Moreover, EEOB applies a loop prevention scheme to prevent this side effect, by considering the sibling links. EEOB considers not only the link quality but also remaining energy of the nodes, when multiple senders compete for flooding. The nodes in the sender-candidate-set that have greater remaining energy and better link quality than the receiver get a higher chance to be the sole sender. We modify the OF scheme [8] to fit our scheme to provide reliable transmission (i.e., avoid the hidden terminal problem and reduce the collisions).Our contributions follow:

- We develop EEOB to decrease broadcasting delay and prolong network lifetime, through maintaining more candidates for senders and considering the remaining energy of nodes.
- Simulations show the broadcasting delay of EEOB decreases up to 60% and the network lifetime increases up to 100% compared to OF.

The remainder of the paper is organized as follows. Section 2 gives background information and related work. Section 3 details EEOB operations. Section 4 demonstrates the performances of the network lifetime and broadcasting delay through simulation. Section 5 concludes this paper.

2 Related Work

Much research into broadcasting has progressed in WSNs. The traditional flooding method and many improved schemes [3,4] have proven that they had good performance on delivery ratio, delay and energy cost in an always-awake network. However, the performance of such flooding schemes under a duty-cycled environment will be seriously declined [8]. Moreover, if unreliable links and collisions in the wireless are considered, their delivery ratios worsen; simulations show a network with 2% duty-cycle delivers less than 5% of packets [8].

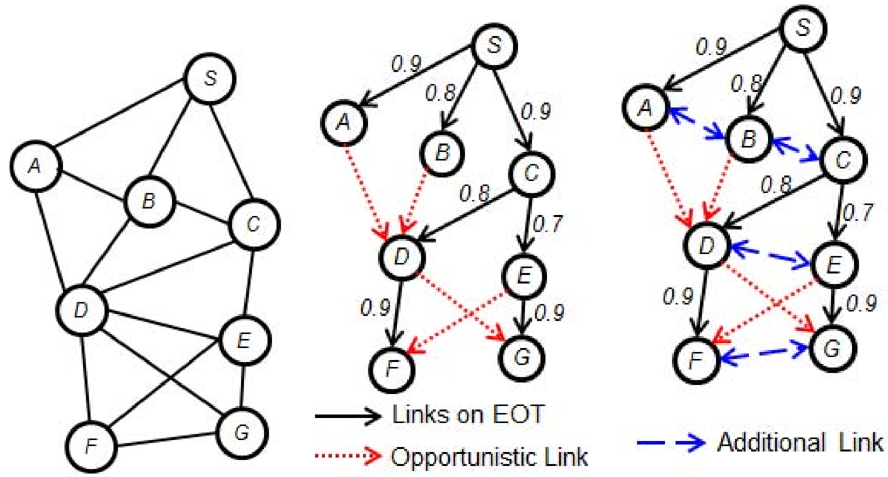
Guo et al. [8] proposed an opportunistic flooding (OF) that improves the reliability of traditional flooding for duty-cycled environments. The key point is the forwarding decision making, in which nodes forward a packet with a higher probability, if the packet arrives opportunistically earlier. This is achieved by comparing the delay of individual packets to the statistic packet delay distribution, i.e., *probability mass function (pmf)* at next-hop nodes. OF includes three steps:

- **Computing the *pmf*:** Each node in the networks computes the probability of receiving from its parents on the energy optimal tree (EOT) over time t, makes the *pmf* table using this information and shares it with its neighbors.
- **Composing the sender-candidate-set:** When the intermediate node receives a packet from its parents, it checks the *pmf* of receivers and checks if the expected receiving time is earlier than a threshold of *pmf*. If yes, the node is added to the sender-candidate-set.
- **Computing the *pmf*:** When there are multiple sender candidates, they compete to be the sole sender, and thus collision is avoided.

However, energy consumption in OF may be concentrated on certain links, as shown in Fig. 1. Note that node E has sole parent (node C). Node C has two children, both are on the EOT. When node C competes with A or B to be the sole sender of D, it backoffs based on the link quality to D, and thus C always gets the highest probability of transmitting the packet. Finally, node C may "die earlier" than other nodes. If node C is exhausted, node E will be isolated. Node E can no longer receive packets, even if it has sufficient energy to receive. Note that neighbor node D could deliver to node E, but there are no logical links. We can find out that the opportunistic links are only connected between the parents and the children in Fig. 1(b). In [8], the authors assume a link only between the parents and the children for loop prevention. This constraint decreases the chance of fast dissemination and energy balancing, since the size of the sender-candidate-set is limited. Thus, our scheme maintains more opportunistic links to the siblings, as shown in Fig. 1(c). These additional links also contribute to reduce the isolation problem. Our scheme uses additional information, such as a node ID in the packet header, for loop prevention.

3 Energy-Efficient Opportunistic Broadcasting

In EEOB, we consider not only the link quality but also remaining energy of nodes. The consideration for link quality is related to both fast broadcasting and the reduction of the total energy consumption in the network, since links with better quality can reduce retransmission. However, the frequent use of such links makes nodes of the links suffer extreme load, and finally die earlier. Consideration of remaining energy can prolong network lifetime by energy balancing. We also consider additional opportunistic links



(a) Network Topology (b) EOT (c) Modified EOT

Fig. 1. An Example of Opportunistic Flooding

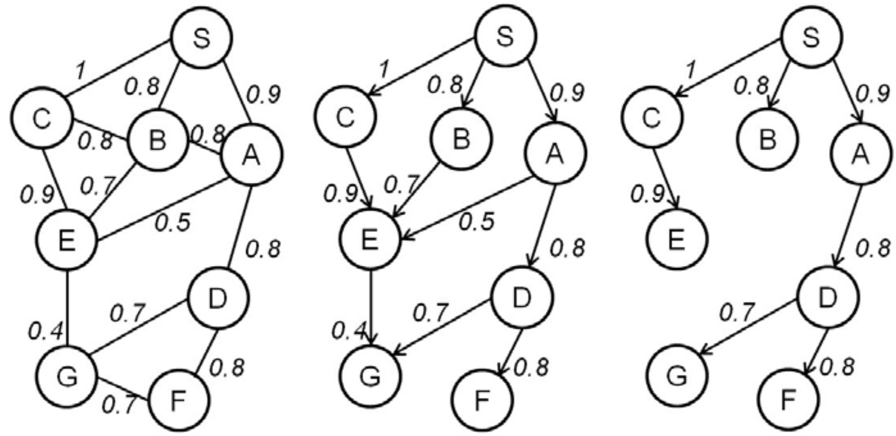
from each node to its siblings with the loop prevention scheme. Such additional opportunistic links may raise the possibility of both energy balancing and fast dissemination. In addition, we modify the OF to avoid the hidden terminal problem and reduce the collision for reliable transmission.

The assumptions in this paper are as follows. Each node sets up its working schedule and shares it with all its neighbors, as soon as it joins the network. This process is usually called low-duty-cycle rendezvous [9]. Each node knows its neighbors' working schedules after rendezvous. A node changes its working schedule, if its neighbors update schedules. We assume that unreliable links and collisions may occur in the network. In one communication range, if two or more ongoing transmissions occur simultaneously, none of them succeed. The measurement for link quality can be updated at a very low cost or by conventional low-cost piggybacking of data traffic. The network is locally synchronized and it can be achieved using the MAC-layer time stamping technique, as described by the flooding time synchronization protocol (FTSP) [10]. A node knows when it can send packets to the neighbors, given their working schedules.

3.1 Opportunistic Transmission

A node outside energy optimal tree (EOT) decides transmission to its neighbors by judging if the transmission is opportunistically early. This is the same as OF.

1) Constructing EOT and Computing pmf: Fig. 2 shows how to construct EOT. When an original network topology is constructed, as shown in Fig. 2(a), EEOB first reduces the sibling links and then specifies the flooding direction making a directed acyclic graph (DAG), as shown in Fig. 2(b). EEOB then selects a link that has the highest link quality from a parent to a child, as shown in Fig. 2(c).



(a) Network Topology (b) DAG for Flooding (c) Energy Optimal Structure

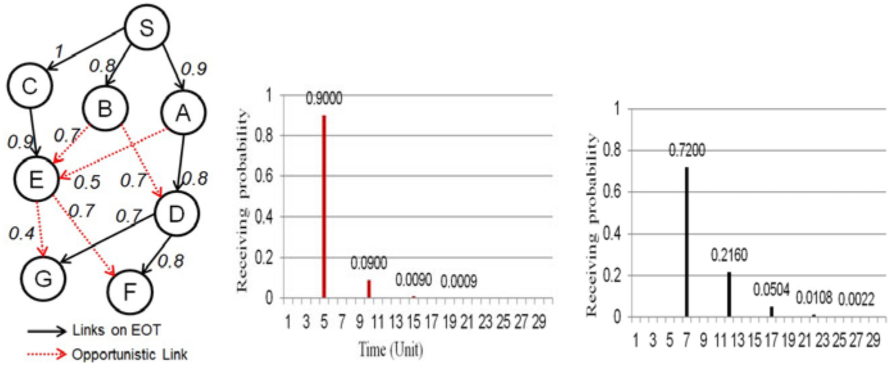
Fig. 2. Constructing Energy Optimal Tree

Computing the packet delay distribution via an EOT and comparing the delay along the EOT, a node can decide whether opportunistic forwarding via links outside of the EOT needs or not. This packet delay distribution is represented to *probability mass function (pmf)* and the computation process of *pmf* starts from a source node (level-0) and spreads throughout the network level by level. Initially, the source node always awakes and the probability that it receives the packet with delay 0 is 100%. In other words, the *pmf* of the source is (0,100%). Then, a level-1 node calculates its *pmf* based on its level-0 parent node's *pmf*. Similarly, a level-(*l*+1) node calculates its *pmf* based on its level-*l* parent's *pmf*. Given the *pmf* of level-*l* nodes (i.e., active time units t_l (*i*) and the probability of reception p_l (*i*) for any *i*) and t_{l+1} (*j*) for any j, each level-(*l*+1) node calculates the probability that it receives the flooding packet at its j^{th} active time unit as follows:

$$p_{l+1}(j) = \sum_{i:t_i(i)<t_{l+1}(j)} p_l(i)q(1-q)^{n_{ij}} \tag{1}$$

where q is the corresponding link quality satisfying q $\in (0, 1]$, n_{ij} is the number of the level-(*l*+1) nodes' active time units between $t_l(i)$ and $t_{l+1}(j)$. The term $p_l(i)q(1-q)^{n_{ij}}$ is the probability that the packet that arrives at the level-*j* node at its i_{th} active time unit is first delivered to the level-(*i*+1) node at its j_{th} time unit. Clearly, the *pmf* of a node can be derived from its parent's *pmf* with initial *pmf* (0,100%) at the source.

Fig. 3 shows an example of the *pmf* computation process. Assume that the nodes wake up periodically every 5 time units (20% duty-cycle) and node A and D first wake up at time 5 and at time 2, respectively. Node A computes its *pmf* first based on the link quality 0.9 and its own work schedule. The probability that node A receives the packet for the first time, at time 5, is 0.9. At time 10, the probability becomes $(1 - 0.9) \times 0.9 = 0.09$ and so on. Node D then computes its *pmf* based on the *pmf* of A. For node D at time 7, the probability is the multiplication of the link quality and the probability that node A receives the packet at time 5, $0.9 \times 0.8 = 0.72$. For node D, at time 12, the probability is the sum of the probability that (i) node A receives the packet at time 5 and succeeds at the second transmission, and (ii) the probability that node A receives the packet at time 10 and succeeds in the first transmission, $0.9 \times (1 - 0.8) \times 0.8 + 0.09 \times 0.8 = 0.216$. Similarly, all the nodes within the network compute their *pmf*, as long as their parents' *pmf* becomes available.



(a) Network Topology (b) *pmf* of Node A (c) *pmf* of Node D

Fig. 3. Computing *pmf*

From the computed delay distribution, a node finds its p-quantile delay (denoted as D_p), as a threshold for delay, and shares this threshold with its previous-hop nodes. D_p is a threshold, such that if a flooding packet arrives at this node later than D_p, the probability that the node has already received this packet from its parent is greater than p. Then, for each new flooding packet and each next-hop node, a node computes the expected packet delay (EPD) and makes a forwarding decision based on the comparison between EPD and D_p. If EPD $\leq D_p$, the probability that the next-hop node has already received this flooding packet via the EOT is no greater than p. Thus, this packet is considered forwarded. If EPD$>D_p$, the next-hop node has more than p percentile of chance that it has already received this packet. Thus, this packet is considered redundant and will not be forwarded to the next-hop.

For example, in Fig. 3 we assume that node B wants to make an opportunistic link to node D. The expected number of transmissions for successful packet delivery is ceiling of 1/q, where q is the link quality between two nodes. Thus, the expected number from node B to node D is 2, since q is 0.7. Assume that p is 0.8, D_p is 12, because at time 12, node D will receive a packet successfully via an EOT with probability 0.936 (=0.72+0.216) more than p (=0.8). When node B receives a packet from S, if it can try to send at least twice before D_p (=12), then it decides to send a packet to D, else it gives up.

2) Using Sibling-links as Additional Opportunistic Links: We introduced the link limitation of OF in Section 2. We consider additional links to the siblings to prevent an isolation problem and maintain the larger sender-candidate-set. We can achieve both load balancing and fast dissemination through the additional links. When a node receives a packet, it checks the possibility of making the opportunistic links to its children and siblings using the *pmf* of receivers. If EPD is less than D_p, this opportunistic link is included in the sender-candidate-set. We propose the loop prevention scheme by using sequence number (SEN) to prevent a broadcasting-loop in which each node floods a duplicated packet repeatedly. SEN indicates the packet sequence whose packet is newer. When a node receives a packet, it first checks the SEN in the packet header. If the packet has an older SEN than that received before, then the node discards it. Otherwise the node updates current SEN and it floods this packet. Using this scheme, each node does not send a duplicated packet that is has already received.

3) Considering the Residual Energy of Nodes: We know the energy balancing is still a major issue in WSNs. Thus, the remaining energy should be considered as a factor when choosing the sender. Our EEOB, via the factor, can improve energy balancing and enable the nodes to work longer. In EEOB, the node that has more energy and a better link quality has a higher probability to be the sole sender. When multiple senders are in the competing phase to send a packet to *j*, the weight of node *i* is computed using the following equation:

$$p_i = e_i^r \times q_{ij} \tag{2}$$

where e_i^r denotes the percentage of remaining energy of node *i*, and q_{ij} denotes link quality between *i* and *j*, p_i is the weight that node *i* is selected as the sole sender of *j*. The bigger P_i means node *i* has the high probability to be selected as the sender. In the early stage of the network, the nodes with higher link quality are selected as a sender more frequently, and thus their remaining energy decreases. As times go on, nodes with higher link quality are assigned a smaller weight to be senders, and thus energy consumption is balanced. Thus, energy balancing and fast dissemination can be achieved. In [11], Zhao et al. designed a residual energy scan that approximately depicts the remaining energy distribution within a sensor network. Their approach has good scalability to continuously extract the residual energy level individually from each node. We can use this approach to know the remaining energy of nodes in the network. After combining it with link quality, EEOB selects the optimal link to broadcast the packets.

3.2 Reliable Transmission

1) Preventing Hidden Terminal Problem: In wireless communication, a certain percentage of collisions are caused by the hidden terminal problem (HTP), where two nodes forward a packet to the same node without knowing each other. If this occurs, both keep sending but neither of them succeeds. OF scheme alleviated the HTP, using a link quality threshold l_{th} [8]. We apply the scheme with some modifications to fit our method. At Eq.2, we showed an equation for the sole sender selection. When there are multiple opportunistic links to a receiver, the links are added in the sender-candidate-set. The nodes in the sender-candidate-set must have higher link quality than l_{th} with all other nodes in the set. If there are some mutual links with bad quality in the sender set, some nodes may not overhear others' transmission, even if the packet has already arrived at the receiver.

2) Reducing the Collision: We should resolve the collisions problem after the sender set is constructed. Ideally, a node with the highest value P (in Eq.2) has the highest priority to use the channel and start a transmission with no collision. Selecting the best link always means the least number of transmissions is expected, so that both the expected next-hop delay and energy cost are minimized. When nodes intend to start a transmission, they first do backoff for random times. The duration of the backoff depends on the *P* value of the node. A node that has a higher P gets a higher probability to get a shorter backoff duration. When multiple nodes within communication range make their decisions to send towards the same node, they backoff first before transmission, and the one with the shortest backoff time starts first.

The probability that more than two nodes get the same backoff duration is very low. Nevertheless, if more than two nodes get the same backoff duration, they backoff again with a longer duration than before. After starting backoff, the nodes listen to the channel, and they can catch the ongoing transmission. The nodes that overhear other transmissions abort their transmissions. Using this random backoff method, EEOB can reduce collisions and decrease the chance that a packet is forwarded via a very weak link, since the winner must have a relatively good link quality and more energy to start early.

4 Performance Evaluation

We proposed two main ideas to achieve fast dissemination and prolong network lifetime. First, use additional links to the siblings for broadcasting. Second, consider the remaining energy of nodes when there are multiple senders. In this section, we compare three schemes, OF, OF+AL (i.e., OF using additional links), and EEOB (i.e., using additional links and considering the remaining energy of each node) in the aspects and *network lifetime* and *broadcasting delay*.

4.1 Simulation Setup

We implement a simulator with C# based on real topology with 54 sensors, as shown in Fig. 4 [12], to evaluate our design. We select only the links with quality higher than 0.3, based on measured link information and quality on the topology, since the links with quality below 0.1 or 0.3 may not be considered as valid links in a real environment [13]. We follow the energy consumption model of CC2420 for a more sophisticated simulation. ChipCon CC2420 radio [14] draws 19.7 mA when receiving or idle listening, larger than the 17.4 mA used in transmitting. We convert the unit from mA to energy unit, and assume that each node has 100,000 energy units initially to apply the energy model to the simulation.

We measure the network lifetime, until the first node in the network dies. When a source node broadcasts a packet, all nodes alive have to receive it. However, when the first node is dead, the network could be partitioned, and thus some nodes may not receive the packet, even if they are alive. Thus, we measure the network lifetime until the first node dies. We measure the lifetime and delay with time units. A time unit is a period to complete 1-hop transmission. We assume that node #1 is a unique source node, and broadcasting delay is measured until all nodes receive a packet successfully. Nodes periodically wake up with duty-cycle, and the initial wake up time is randomly set. For example, when a network has 10% duty-cycle, the nodes in the network first wake up from 0 to 9 time units randomly, and they wake up every 10 time units after their first wake up time.

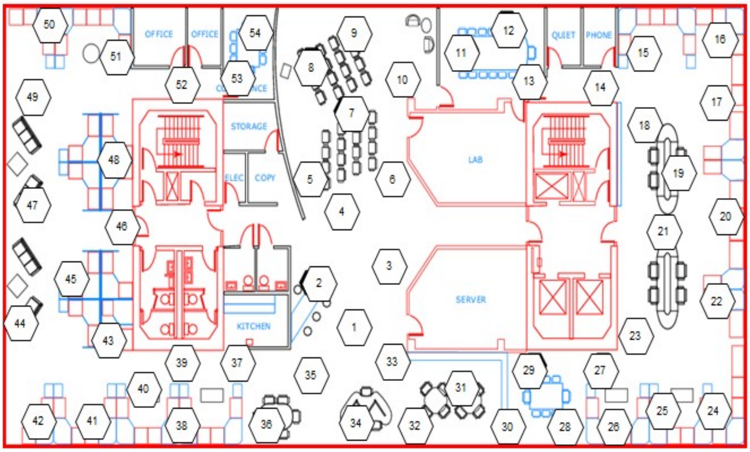


Fig. 4. Real-topology in the Intel Berkeley Research Lab

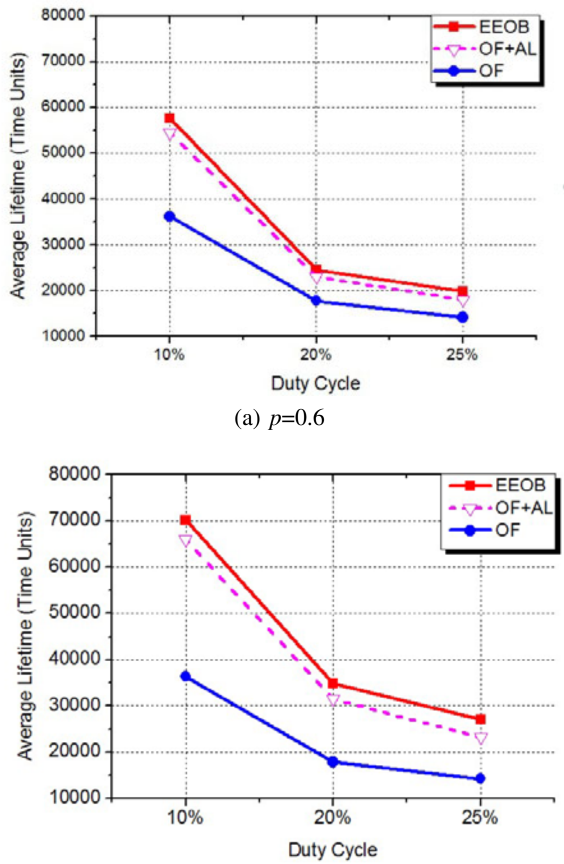
4.2 Simulation Results

In OF, energy consumption is concentrated in some nodes on the EOT due to lack of sender candidates and link-quality based backoff. OF+AL considers additional sibling links to acquire more sender candidates. Thus, it can have a greater chance to achieve faster dissemination and prolong network lifetime. EEOB considers both using sibling links and residual energy of nodes for more sophisticated energy balancing.

The results show the average lifetime and broadcasting delay when a quantile probability p is 0.6 and 0.8. We study the impact of p, the threshold to decide if a packet is opportunistically early. As p increases, more opportunistic links are considered, and thus energy balancing can be more sophisticated. In this simulation, a link quality threshold l_{th} is fixed to 0.5, while the duty-cycle is set with 10%, 20%, and 25%, respectively. The higher duty-cycle can achieve faster dissemination, but it reduces network lifetime.

Fig. 5 shows the average network lifetime when p is 0.6 and 0.8, and l_{th} is fixed to 0.5. The results show that the network lifetime is increased when a duty-cycle is lower and p is higher, as per our expectation. EEOB considers the remaining energy of nodes, and thus the network is maintained for longer.

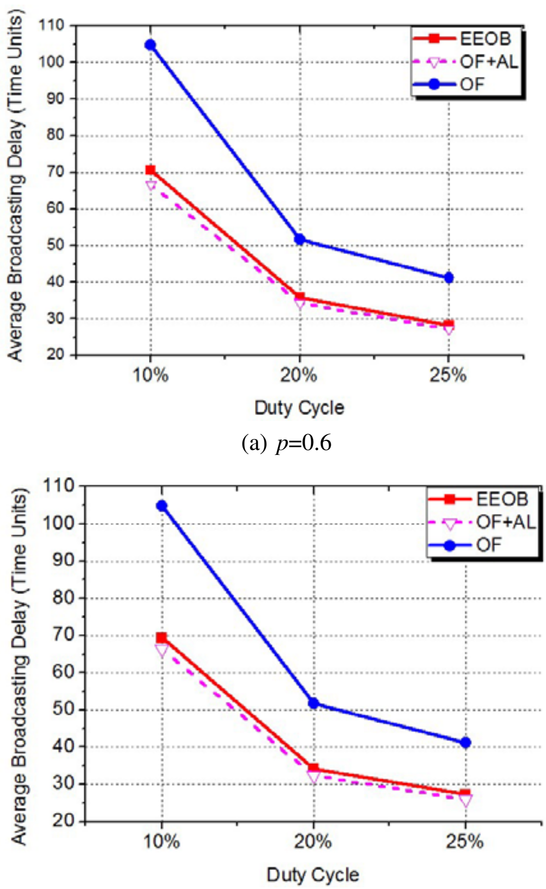
Fig. 6 shows the average broadcasting delay with the same parameter values as in Fig. 5. OF+AL achieve a slightly better performance from the viewpoint of delay than EEOB, because it only considers the link quality in the competing phase of multiple senders, and thus it could minimize retransmissions. Despite increasing *p*, the results of delay are similar. Commonsensically, as *p* increases, the waiting delay to obtain more candidates increases. However, as *p* increases, more links can be considered, and thus a better link could be chosen. Therefore, the delay is not increased against expectations. In conclusion, EEOB outperforms other schemes in synthesizing the results of two performance metrics.



(a) *p*=0.6

(b) *p*=0.8

Fig. 5. Average Network Lifetime



(a) p=0.6

(b) p=0.8

Fig. 6. Average Broadcasting Delay

5 Conclusion

One of the important issues in WSN is to extend the lifetime of the sensor nodes. Thus, the design of an energy-efficient flooding scheme with balanced consumption is essential, because flooding schemes have significant impact on the overall energy consumption of sensor networks. The existing opportunistic flooding scheme gives a chance to become the opportunistic link to only the link towards the children nodes, but energy consumption tends to be concentrated in certain nodes on the EOT. In our design, each node makes probabilistic forwarding decisions based on the delay distribution of next-hop nodes and its own remaining energy. The node that has higher energy and better link quality has a greater probability to be the sender. We built a qualified sender set to alleviate the hidden terminal problem, and in the same sender set, we use the random backoff method based on a link quality and remaining energy to resolve simultaneous forwarding operations. We used the sibling links for broadcasting and considered the remaining energy of the nodes at the candidate selection for forwarding. We also prevented the loop occurrence by using node ID. Simulations showed our scheme significantly contributed to prolong network lifetime and reduce broadcasting delay.

Acknowledgment

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References

1. Wang, F., Liu, J.: Duty-cycle-aware Broadcast in Wireless Sensor Networks. In: IEEE INFOCOM (2009)
2. Lou, W., Wu, J.: On Reducing Broadcast Redundancy in Mobile Ad Hoc Networks. IEEE Transactions on Mobile Computing 1(2), 111–123 (2002)
3. Kyasanur, P., Choudhury, R.R., Gupta, I.: Smart Gossip: An Adaptive Gossip-based Broadcasting Service for Sensor Networks. In: IEEE MASS (2006)
4. Stann, F., Heidemann, J., Shroff, R., Murtaza, M.Z.: RBP: Robust Broadcast Propagation in Wireless Networks. In: ACM SenSys. (2006)
5. Levis, P., Patel, N., Culler, D., Shenker, S.: Trickle: A self-regulating algorithm for code propagation and maintenance in wireless sensor networks. In: ACM NSDI (2004)
6. Lin, K., Philip, L.: Data Discovery and Dissemination with DIP. In: ACM IPSN, pp. 433–444 (2008)
7. Gu, Y., He, T.: Data Forwarding in Extremely Low Duty-Cycle Sensor Networks with Unreliable Communication Links. In: ACM SenSys. (2007)
8. Guo, S., Gu, Y., Jiang, B., He, T.: Opportunistic Flooding in Low-Duty-Cycle Wireless Sensor Networks with Unreliable Links. In: ACM MobiCom. (2009)
9. Dutta, P., Culler, D.: Practical Asynchronous Neighbor Discovery and Rendezvous for Mobile Sensing Applications. In: ACM SenSys. (2008)
10. Maroti, M., Kusy, B., Ledeczi, A.: The Flooding Time Synchronization Protocol. In: ACM SenSys. (2004)
11. Zhao, Y.J., Govindan, R., Estrin, D.: Residual Energy Scan for Monitoring Sensor Networks. In: IEEE WCNC (2002)
12. Real-topology in the Intel Berkeley Research Lab, http://db.lcs.mit.edu/labdata/labdata.html
13. Zamalloa, M., Seada, K., Krishnamachari, B., Helmy, A.: Efficient Geographic Routing over Lossy Links in Wireless Sensor Networks. In: ACM TOSN, vol. 4(3) (2008)
14. Texas Intruments. 2.4 GHz IEEE 802.15.4 / ZigBee-Ready RF Transceiver (Rev.B), http://focus.ti.com/docs/prod/folders/print/cc2420.html