GUIDANCE BASED MULTIHOP BROADCAST PROTOCOL FOR ASYNCHRONOUS DUTY-CYCLED WIRELESS SENSOR NETWORKS

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ABSTRACT

In this paper, we propose an efficient guidance based multihop broadcast protocol for asynchronous duty-cycled wireless sensor networks, where each node wakes up according to its own schedule. This adopts two techniques of the forwarder's guidance and the overhearing of broadcast messages and ACKs. A node transmits messages with guidance to neighbor nodes. The guidance presents how the node forwards the broadcast message to neighbor nodes by using unicast transmissions. The proposed technique significantly reduces redundant transmissions and collisions. The overhearing of broadcast messages and ACKs helps to reduce the number of transmissions, thus it minimizes the active time of nodes. The Guidance based broadcast protocol achieves lower message cost than conventional protocols and significantly improves the energy efficiency in terms of both duty cycle and energy consumption.

Keywords: Asynchronous Duty Cycling, Multihop Broadcast,Wireless Sensor Networks,

I. INTRODUCTION

The goal of wireless sensor network is to reliably report sensing data to the sink. A broad class of WSN applications necessitates energy efficiency. Nodes in such WSN applications should operate unattended for a long time on limited battery capacity [1]. Most sleep scheduling protocols today in WSNs utilize duty-cycling which allows a sensor node to alternate between active and sleeping states to reduce energy consumption. The duty-cycled MAC protocols in the previous literature are generally divided into two categories: synchronous and asynchronous. Synchronous sleep scheduling approaches synchronize neighboring nodes before data transmissions to reduce energy consumption. In S-MAC[2] and T-MAC[3] nodes in the vicinity synchronize together and form a virtual cluster with the same schedules. Each node in the cluster communicates with its neighbors only within common active states. Synchronous MAC protocols achieve comparable energy efficiency by reducing idle listening time, but extra complexity and overhead are required for synchronization. In asynchronous approaches, each sensor node wakes up and operates independently according to its own duty cycle schedule. Such protocols use low power listening (LPL) that is one of duty-cycling techniques, where each node periodically samples the channel for a long preamble continuously transmitted by a sender. LPL reduces energy consumption by turning off the radio between samples. A sender, in B-MAC, starts to transmit data after sending a long preamble which lasts at least as long as a sleep period of a receiver. When the receiver wakes up and detects the preamble, it stays awake to receive data following the preamble. However, a node may unnecessarily stay awake to receive data destined to other nodes. To solve this problem, X-MAC replaces a long preamble with a bunch of sequential short preambles. Each preamble contains the target address and it allows nodes not involved in the communication to go to sleep immediately.

1.1 Broadcast in wireless sensor Networks

The common goal of broadcast in WSNs is to deliver data to every node in a network. Broadcast can be divided into two types: single hop broadcast and multihop broadcast. Single hop broadcast involves transmitting messages to all neighbor nodes within 1-hop distance from a sender. Multi-hop broadcast involves forwarding a message to all nodes that compose a network. In multihop broadcast, nodes that received the broadcast message operate as new senders to forward the message to their neighbor nodes.

1.1.1 Single-Hop Broadcast

Single-hop broadcast is quite simple in synchronous MAC protocols. Synchronized nodes easily exchange broadcast messages on their common schedules. More-over, one broadcast message can reach multiple neighbor nodes. However, asynchronous MAC protocols are inherently weak for supporting single-hop broadcast, since nodes wake up independently. In asynchronous WSNs, nodes wake up according to their own duty cycle schedules. Therefore, it is challenging to efficiently support single-hop broadcast for asynchronous WSNs.

1.1.2 Multi-Hop Broadcast

Multi-hop broadcast is a crucial service for higher-level operations in WSNs. The goal of multi-hop broadcast is to deliver a broadcast message to all nodes in a network. For data collection, nodes propagate queries across the whole network. Multi-hop broadcast is also used for network maintenance services such as network configuration and network reprogramming. Broadcast is comparatively simple in single-channel communication protocols, because only one channel is employed for data transmission

II. RELATED WORKS

DW-MAC which is one of synchronous sleep scheduling protocols supports multihop broadcast by using multihop forwarding. An operational cycle in DW-MAC is divided into three parts: Sync, Data, and Sleep. Each node synchronizes its clock with its neighbor nodes during the Sync period. During the Data period, a sender that wants to broadcast transmits a scheduling frame (SCH) which indicates the starting point for the broadcast transmission that will be performed within a following Sleep period. The sender starts broadcasting a message at that point. Every node receiving the broadcast message becomes a new sender to forward it to other nodes.

DW-MAC simply extends multihop forwarding without substantially increasing overhead in order to support multihop broadcast. Multihop broadcast in asynchronous approaches is substantially complicated due to independent sleep schedules of nodes. However, both schemes are very inefficient because a node receives multiple copies of the same message. These redundant transmissions cause frequent collisions, followed by unnecessary energy consumption. Therefore, multihop broadcast for asynchronous approaches should minimize redundant transmissions and collisions. ADB is recently proposed to support multihop broadcast for asynchronous duty-cycled sensor networks. ADB is designed based on RI-MAC. ADB adopts unicast and updates the receiver information on the broadcast progress, which enables each node to avoid redundant transmissions by allowing transmission delegating.

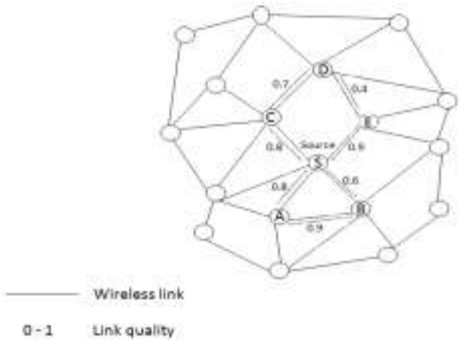

Fig.1. WSN with heterogeneous topologies.

In Figure 1, node S is a source node and node A wakes up earlier than node B. Upon receiving node A's beacon, node S sends A a broadcast message including an ADB footer that indicates the broadcast progress and the link quality information of S. Looking into the footer, node A recognizes that the quality of the link between nodes S and B is poorer than that of link between itself and B. Node A decides to forward the broadcast message to node B and inform node S of this fact by sending ACK with a new footer. Upon receiving this ACK, node S delegates handling of node B to node A. However, ADB does not efficiently support multihop broadcast in polygonal topologies except triangle shapes. For example, in Figure 1, nodes S, C, E, and D compose a quadrangular topology where node C and node E are located out of each other's communication range. Node S sends a broadcast message including a footer to node C. However, the link quality between nodes S and E in the footer is useless to node C since C and E cannot communicate with each other.

Similarly, node E also ignores the link quality between nodes S and C after receiving the broadcast message from S. Both nodes C and E stay active to forward the broadcast message to node D. After node D wakes up, they simultaneously forward the broadcast message to D and a collision occurs at D. Each of nodes C and E retransmits the collided message by using backoff. As a result, node D will receive the two identical broadcast messages after the collision. This problem will lead to the unnecessary energy dissipation and the reduced lifetime of the network. The frequency of triangles decreases as the network is getting sparser. In sparse networks, the ADB therefore would show the degraded performance in multihop broadcast.

The proposed Guidance based multihop broadcast protocol efficiently supports the multihop broadcast in sparse networks by using (i) the forwarder's guidance. In addition, the proposed protocol makes good use of (ii) the overhearing of broadcast messages and ACKs to minimize redundant transmissions. As a result, this shows good performance even in dense networks.

III. MOTIVATION AND NETWORK MODEL

3.1 Motivation

In WSNs, a topology generated by randomly deployed nodes includes various types of polygons (n-gons) such as triangles(3-gons), quadrangles (4-gons). The frequency of each n-gon is mainly affected by the network density which is the average number of 1-hop neighbors per node. Dense networks have higher frequency of triangles than sparse networks. In other words, the occurrence of n-gons where n is equal to or greater than 4 (referred to as n(≥ 4)-gons) becomes more frequent as the network is getting sparser. If walls or obstacles are located in a deployment area, the occurrence of n (≥ 4)- gons is more frequent because the number of wireless links between nodes is reduced. In addition, controlling transmission power is also one of reasons for an increase in the number of n (≥ 4)-gons.

3.2 Network Model

We consider a WSN consisting of fixed nodes that do not have an ability to move. Topology changes (e.g., the addition of a new node, or the elimination of a node from the network due to node fault or exhausted battery power) are infrequent and link quality information are valid for a relatively long time (approximately a few minutes). In our network model, a transmission of a message is very likely to be unsuccessful when a node sends the message over a poor link. If this happens, the retransmission is required and therefore results in additional energy consumption. To avoid retransmissions, a node should send messages over links with as good quality as possible. Guidance based broadcasting uses knowledge of wireless link quality which can be provided from existing link estimation mechanisms such as four-bit link estimation [5]. This link estimator uses various signal and decoding statistics such as RSSI (Received Signal Strength Indicator), SNR (Signal to Noise Ratio), LQI (Link Quality Indicator). The Guidance Based Broadcasting operates based on RI-MAC and uses a beacon message generated by a receiver for the start and acknowledgement of a data transmission. RI-MAC achieves higher throughput, higher energy efficiency, and lower end-to-end delay compared to the prior asynchronous approaches.

We consider that a MB procedure is to propagate one broadcast message to all nodes in a network. A node may receive identical broadcast messages from multiple neighbors. In addition, collisions may occur when multiple senders attempt to transmit broadcast messages to a common node. Both redundant transmissions and collisions result in longer idle listening and more energy consumption because a node which has a broadcast message should stay awake and listen the channel until all of its neighbor nodes are covered. A covered node represents that it already received the broadcast message. Each node maintains a 1-hop neighbor table that consists of a 1-hop neighbor list and quality information of links between itself and each of its neighbor nodes. We denote the neighbor list of node s as N(s) and we denote the link quality between s and a neighbor node r as LQ(s, r). Node s generates an advertisement message including the sequenced pairs of N(s) and LQ(s, r). The node s then exchanges this advertisement message with its neighbor nodes to share the link quality information. We refer to this as the advertisement procedure.

Advertised information helps for a node to decide either to take responsibility for covering of an uncovered neighbor node or to delegate this transmission to another node that has a better link. The advertisement procedure is periodically conducted and the advertising period is configurable by a network administrator. Each node maintains another table, 2-hop neighbor table which is composed of 2-hop neighbor list and link quality information obtained through the advertisement procedure. Supporting n(≥ 5)-gon makes the protocol much more complicated. For example, 3-hop neighbor information is required in case of a 5-gon shape. However, supporting n(≥ 5)-gon yields very little performance improvement due to the very low frequency of n(≥ 5)-gon. Therefore, in guidance based broadcasting, it would be enough to maintain 2-hop neighbor information.

IV GUIDANCE BASED BROADCAST PROTOCOL

In this section, we describe the details of guidance based broadcast protocol. We propose two techniques of the forwarder's guidance and the overhearing of broadcast messages and ACKs[6]

4.1 Overview of the Forwarder's Guidance

In broadcast, there are two types of senders: a source node of broadcast and a node that forwards a broadcast message generated by a source node. We refer to both of them as forwarders. In multihop broadcast, a forwarder s transmits a broadcast message i, BPKTi, to each neighbor node r. Node r prepares to work as a new forwarder after receiving BPKTi. If there is a node v which is a common uncovered neighbor of nodes s and r, v will receive two identical BPKT is from both s and r. In addition, a collision will occur if nodes s and r simultaneously transmit BPKTi to node v. guidance based broadcasting can significantly reduce redundant transmissions and collisions by using the forwarder's guidance.

When a forwarder s sends BPKTi, it constructs sets as shown in Table I. Each set is one of subsets of N(s) and should satisfy following two conditions:

$$N(s) = N^i_{cv}(s) \cup N^i_{ucv}(s), \qquad (1)$$

$$N^i_{oblg}(s) = N^i_{ucv}(s) - N^i_{dg}(s) \qquad (2)$$

TABLE 1

Sets for a forwarder with broadcast message BPKT^i

Set	Element	Initial set
$N^i_{cv}(s)$	Covered neighbor nodes by BPKT^i	ϕ
$N^i_{ucv}(s)$	Uncovered neighbor nodes	N(s)
$N^i_{oblg}(s)$	Neighbor nodes which forwarder s is obligated to cover	$N^i_{ucv}(s)$
$N^i_{dg}(s)$	Neighbor nodes of which covering is deligated to another node with better link quality	ϕ

The forwarder s is obligated to send BPKTi to every node in $N^i_{oblg}(s)$ by using unicast. We refer to $N^i_{oblg}(s)$ as the obligation set of the forwarder s. Before the forwarder s transmits BPKTi to a neighbor node r ∈ $N^i_{oblg}(s)$, it generates a guidance list (GL) for r, which is piggybacked in BPKTi. Through the advertisement procedure, node s has obtained the neighbor list of node r (v1, . . . , v|N(r)| ∈ N(r)) and the link quality information of r (LQ(r, v1), . . . , LQ(r, v|N(r)|)).

Node s as a forwarder provides the guidance about how node r covers each of neighbor nodes of r. We denote the guidance from node s to node r as GLsr and it is composed of GLsr [v1], . . . , GLsr[v|N(r)|]. The forwarder s assigns one of the following guidance states to GLsr [v] for each node v ∈ N(r):

- GLsr[v] = COVERED if nodes v and s are the same node or v is already covered.

- GLsr[v]= DELEGATED if covering of node v is delegated to another node that can be either the forwarder s or any other 1-hop neighbor of node v except node r.
- GLsr[v] = OBLIGATED if node r is obligated to cover node v. Since node r has the best link quality to node v among the neighbors of node s, r has responsibility for forwarding BPKTi to v.

GLsr is delivered to node r with BPKTi. Before working as a new forwarder, node r eliminates the IDs of nodes assigned by COVERED or DELEGATED state from its obligation set. The new forwarder r will cover the reduced set of its neighbor nodes by the aid of the forwarder's guidance from node s.

4.2 The Forwarder's Guidance Details

Algorithm 1 Procedure CONSTRUCT GL()

1: // s: forwarder, r: receiver, i: broadcast message i
2: **for** each node $v \in N(r)$ **do**
3: **if** $v \in N^i_{cv}(s)$ or $v = s$ **then**
4: GLsr[v] ←COVERED
5: **else if** $v \in N^i_{ucv}(s)$ **then**
6: **if** $LQ(s, v) \geq LQ(r, v)$ **then**
7: GLsr[v] ←DELEGATED
8: **else**
9: GLsr[v] ←OBLIGATED
10: $N^i_{dg}(s) \leftarrow N^i_{dg}(s) \cup \{v\}$
11: $N^i_{oblg}(s) \leftarrow N^i_{oblg}(s) - \{v\}$
12: **end if**
13: **else** // if $v \notin N(s)$
14: find the node t which has the best quality link to v among s's neighbor nodes
15: **if** r = t **then**
16: GLsr[v] ←OBLIGATED
17: $N^i_{dg}(s) \leftarrow N^i_{dg}(s) \cup \{v\}$
18: $N^i_{oblg}(s) \leftarrow N^i_{oblg}(s)) - \{v\}$
19: **else**
20: GLsr[v] ←DELEGATED
21: **end if**
22: **end if**
23: **end for**

Before a forwarder s transmits a broadcast message to a receiver $r \in N^i_{oblg}(s)$, it executes Algorithm 1 to make GLsr. The procedure of constructing the GL consists of three parts. First, if node v which is a neighbor node of the receiver r is already covered, GLsr[v] is simply set to COVERED (lines 3 –4). If node r receives GLsr [v] = COVERED from the forwarder s, r will never do anything for node v because v is already covered.

The second part (lines 7 – 12) is a case that node v is a common neighbor of nodes s and r (v ∈ N(r) ∩ N(s)). To avoid sending the broadcast message over a poor link, Guidance based broadcasting makes the following guidance to choose the forwarder which covers node v:

- If $v \in N^{i}_{ucv}(s)$ and $LQ(s, v) \geq LQ(r, v)$, GLsr [v] is set to DELEGATED.
- If $v \in N^{i}_{ucv}(s)$ and $LQ(s, v) < LQ(r, v)$, node s assigns GLsr[v] OBLIGATED and updates $N^{i}_{dg}(s) \leftarrow N^{i}d_{g}(s) \cup \{v\}$ And $N^{i}_{oblg}(s) \leftarrow N^{i}_{oblg}(s) - \{v\}$.

Node r will work as a new forwarder after receiving GLsr piggybacked in BPKTi from node s. If node r receives GLsr [v] = DELEGATED, r will not do anything for node v because v will be covered by another node which has better link quality to v than r. Node r will cover node v only if GLsr [v] is OBLIGATED.

The last part (lines 13 – 21) is a case that node v is not a neighbor of a forwarder s (v ∈ N(r) − N(s)). This part is executed when a forwarder is one of nodes forming a quadrangular topology. The forwarder s does not have any knowledge of whether node v is already covered (because nodes s and v cannot communicate with each other). Assume that there are two or more neighbors of node s can communicate with node v. We denote them as r1, . . . , rn. If forwarder s assigns OBLIGATED to all of GLsr1 [v], . . . ,GLsr n[v], redundant transmissions and collisions will occur because all nodes r1, . . . , rn will attempt to cover node v. To prevent this problem, a forwarder s gives the guidance (OBLIGATED or DELEGATED) to each node of r1, . . . , rn. Node s gives OBLIGATED only to a node rt which has the best link. Node s, then, gives DELEGATED to other nodes r1, . . . , rt−1, rt+1, . . . , rn. The node rt receiving GLsr t [v]= OBLIGATED will only attempt to cover node v.

A forwarder s transmits BPKTi with the GL to each neighbor node $r \in N^{i}_{oblg}(s)$. Upon receiving BPKTi, each node r sends an acknowledgement message to node s. Let ACKi be an acknowledgement message to signify receipt of BPKTi. After receiving ACKi from node r, node s updates the sets as follows:

$$Ni\ cv(s) = Ni\ cv(s) \cup \{r\} \quad (3)$$

$$Ni\ ucv(s) = Ni\ ucv(s) - \{r\} \quad (4)$$

$$Ni\ oblg(s) = Ni\ oblg(s) - \{r\} \quad (5)$$

If Ni oblg(s) becomes empty, the forwarder finishes broadcast and goes to sleep. A receiver node r executes the ANALYZE GL procedure after receiving BPKTi. The purpose of this procedure is to analyze a guidance list delivered from a forwarder s and to follow the guidance. As shown in Algorithm 2, node r decodes the GLsr piggybacked in BPKTi to decide how to handle each neighbor node v ∈ N(r). First, if GLsr [v] is COVERED, node r adds the ID of node v into $N^{i}_{cv}(r)$ and removes it from both $N^{i}_{ucv}(r)$ and $N^{i}_{oblg}(r)$ (lines 7 – 10). Second, if GLsr[v] is DELEGATED, node r inserts the ID of node v into Ni dg(r) and eliminates it from $N^{i}_{oblg}(r)$ (lines 11 – 13). Node r examines whether $N^{i}_{oblg}(r)$ is empty after analyzing the GLsr . If Ni oblg(r) is empty, node r goes to sleep immediately. Otherwise, node r serves as a new forwarder and performs the same procedures as explained above.

Algorithm 2: Procedure ANALYZE GL(s,i)

1: // s: forwarder, r: receiver, i: broadcast message i

2: Nicv(r) ← φ

3: Niucv(r) ← N(r)

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Nioblg(r) ← Niucv(r)
Nidg(r) ← φ
for each node v ∈ N(r) do
    if GLsr[v] =COVERED then
        Nicv(r) ← Nicv(r) ∪ {v}
        Niucv(r) ← Niucv(r) − {v}
        Nioblg(r) ← Nioblg(r) − {v}
    else if GLsr[v] =DELEGATED then
        Nidg(r) ← Nidg(r) ∪ {v}
        Nioblg(r) ← Nioblg(r) − {v}
    end if
end for
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We give simple examples to describe the overall process of the forwarder's guidance.

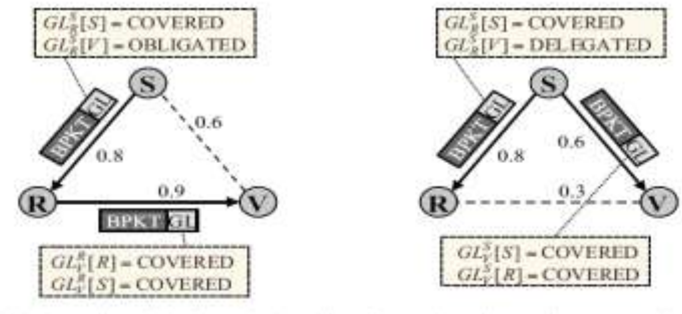

Figure 3(a) Operation of the forwarder's guidance in a triangular topology.

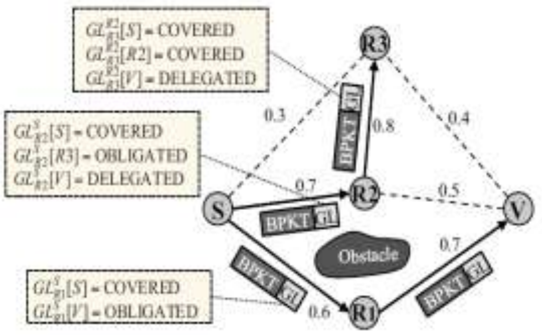

Figure 3(b) Operation of the forwarder's guidance in a complex topology including a quadrangle

Figure 3(a) shows the operation of the forwarder's guidance of EMBA in a triangular topology formed by S, R, and V . The source node S initiates to broadcast with BPKTi. In the triangle, node S transmits a broadcast message with GLsr[v] = OBLIGATED to node R if the link quality between nodes R and V is better than that between nodes S and V . Node V , therefore, will be covered by node R without any redundant transmissions or collisions. If the link quality from S to V is better than that from R to V, node S informs node R that covering of node V is delegated to the original forwarder S. Therefore, node R does not attempt to cover node V and it goes to sleep immediately upon receiving GLsr[v]= DELEGATED.

Figure 3(b) gives an example of the operation of EMBA in a complex topology which includes a quadrangle formed by four nodes: S, R1, R2, and V . Node S transmits BPKTi to only nodes R1 and R2, but not R3. If forwarder S sends BPKTi to node R3, the probability of message loss will be increased due to the poor link between S and R3. Therefore, covering of node R3 is delegated to node R2 which has the better link to R3. If without the forwarder's guidance, node V will receive the same broadcast messages from nodes R1, R2, and R3. In EMBA, node V will be covered only by node R1 since forwarder S gives GLS R1[V] = OBLIGATED only to R1 that has the best link quality to V . As a result, nodes R1, R2, and R3 can avoid redundant transmissions and collisions.

4.3 The Overhearing of Broadcast Messages and ACKs

EMBA adopts another technique of the overhearing of broadcast messages and ACKs (BPKTi and ACKi). If a forwarder overhears BPKTi or ACKi destined to a certain node during an active state, it can eliminate the ID(s) of the node(s) specified in the message from its obligation set. Therefore, the number of transmissions required for covering of neighbor nodes will be reduced. This technique significantly increases energy efficiency by reducing the active time of each forwarder and the number of transmissions. This proposed technique is more efficient in dense networks since the number of overhearable messages increases.

If forwarder x overhears BPKTi transmitted from node u to node v during an active state, it updates the sets as follows:

$$Nicv(x) \leftarrow Nicv(x) \cup \{u\} \quad (6)$$

$$Niucv(x) \leftarrow Niucv(x) - \{u\} \quad (7)$$

$$Nioblg(x) \leftarrow Nioblg(x) - \{u\} \quad (8)$$

$$Nidg(x) \leftarrow Nidg(x) - \{u\} \quad (9)$$

A transmission of ACKi message indicates that both a forwarder and a receiver are already covered. Overhearing ACKi can reduce the size of the obligation set of a forwarder more quickly than overhearing BPKTi. If forwarder x overhears ACKi destined from node u to node v, it updates the sets as follows:

$$Nicv(x) \leftarrow Nicv(x) \cup \{u, v\} \quad (10)$$

$$Niucv(x) \leftarrow Niucv(x) - \{u, v\} \quad (11)$$

$$Nioblg(x) \leftarrow Nioblg(x) - \{u, v\} \quad (12)$$

$$Nidg(x) \leftarrow Nidg(x) - \{u, v\} \quad (13)$$

The number of transmissions required to complete broadcast is very closely related to the size of the obligation set. This simple technique significantly improves the performance of EMBA in terms of both the message cost and energy efficiency.

4.4 Handling of Network Failure

Guidance based broadcasting makes the best effort to avoid transmissions over poor links. Nevertheless, a message can be lost in the air either due to a collision or a link error. To support reliable multihop broadcast, guidance based broadcasting technique follows the network failure resolving mechanism of the MAC protocol cooperated with itself. If BPKTi or ACKi is lost, a forwarder will retransmit the BPKTi after a retransmit timeout. The retransmission can easily compensate for the loss of BPKTi or ACKi. However, the loss of BPKTi or ACKi in the overhearing is an important problem. If a forwarder x overhears an ACKi destined from node u to node v and it is lost, x will eliminate the IDs of u and v from Nioblg(x) but v actually does not receive the ACKi yet. Since the ACKi is not delivered to node v within a retransmit timeout, v will retransmit the BPKTi to node u. guidance based broadcast protocol solves this problem in a best effort manner. Each node maintains the forwarder address, the receiver address, and the broadcast number i of the most recently received BPKTi or ACKi for a period of n duty cycles. After this duration, it updates its sets.

V. CONCLUSIONS

In this paper, we have proposed an efficient Guidance Based Multihop Broadcast Protocol for asynchronous duty-cycled WSNs. Guidance based protocol can support multihop broadcast efficiently by using two techniques of the forwarder's guidance and the overhearing of broadcast messages and ACKs. The forwarder's guidance significantly reduces redundant transmissions and collisions in polygonal topologies such as triangle (3-gon) and quadrangle (4-gon). This technique greatly improves the energy efficiency in sparse networks by reducing duty cycle. The overhearing of broadcast messages and ACKs helps to reduce the number of transmissions. This simple technique minimizes the active time of forwarders, which is more efficient in dense networks. Guidance based broadcast shows much higher energy efficiency in both sparse and dense networks compared to the conventional protocols such as ADB and RI-MAC broadcast. This significantly improves the energy compared to ADB and RI-MAC broadcast. It also shows better performance of the message cost than the conventional protocols in terms of the message cost ratio (MCR) and the average number of bytes transmitted. Therefore, we have concluded that guidance based broadcast protocol achieves much higher energy efficiency and message cost.

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