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Minimum Latency Broadcasting with Conflict Awareness in Wireless Sensor Networks

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***Abstract*—In this paper, we will illustrate a practice of pipeline process to maximize the parallelization of all possible interference-free relays in the broadcasting of wireless sensor networks (WSNs), in order to optimize the end-to-end delay performance in both the (synchronous) round-based systems and the (asynchronous) duty cycle systems. Broadcasting is one of the fundamental communications in WSNs. Existing delay-sensitive broadcasting schemes adopt an approximation approach that is based on counting the hop distance to the source. They require all relays in each 1-hop propagation to be synchronized together in order to avoid any interference, but this also incurs the block of the interference-free relays from those 1-hop neighbors that have received the message. In the duty cycle system, such a block can cause the relay to miss the wake-up time of the successor node which incurs the extra delay. In our approach, a heuristic information model enumerating all the possible future sequences in terms of delay time is adopted first to achieve the optimal relay selection, initiating the study of global impact of local interference. Then, a lightweight model estimating the hop distance to the edge of network of the unaccomplished relay work is adopted with the well-known greedy color scheme to achieve the close-to-optimal relay selection. The analytical and experimental results show the substantial improvement by our pipeline practice, compared with the best results known to date.**

***Keywords*-Broadcasting; delay; duty cycle; pipeline; wireless sensor networks (WSNs).**

I. INTRODUCTION

Broadcasting [9] is one of the fundamental communications in wireless sensor networks (WSNs). In many mission-critical applications, it is very important to accomplish the broadcasting quickly. Existing delay-sensitive broadcasting schemes [2], [4], [16] adopt an approximation approach that is based on counting the hop distance. Basically, a breadth-first tree (BFS) is constructed from the source in a greedy manner. Then, each relay in 1-hop propagation is scheduled by a coloring scheme to avoid signal conflict of the interference. The clique of the 1-hop neighbors of a receiver existing in the relay candidates requires a different color for each vertex, forcing each relay with any unselected color to back off. Due to the lack of sufficient analysis of color selections in succeeding rounds, existing methods require all relays in a 1-hop propagation to finish before the next round of neighbor coloring in BFS. This will unnecessarily block the interference-free relays from those 1-hop neighbors that have received the message.

The problem of unnecessary blockage cannot be solved completely by simply considering the node degree in the color scheme to reduce the size of the clique (e.g., [7], [10], [19]). A heuristic evaluation is needed for each color selection in the broadcasting so that the wait can be arranged in a pipelined process with other relays, thus reducing the end-to-end delay to a minimum. The resultant broadcasting is called *minimum latency broadcasting*. This problem is non-trivial, as we will show in the next section, because a change in early color selection can incur different link utilization in the succeeding relays and the corresponding schedules for interference.

Recent systems [18] have adopted the asynchronous sleep-wake scheme to save energy and to extend the lifetime. In this duty cycle system, each node will periodically turn off its message sending channel, while its receiving channel remains on in order to maintain the routine activities. The wake-up schedule at each node uses a predictable pseudo-random sequence, but is independent of those of other nodes. A node can easily forecast any neighbor's next active time by obtaining its pseudo-random seed and the last active slot. The corresponding waiting time is called *cycle waiting time* (CWT). Having different CWTs of 1-hop neighbors increases the diversity of each 1-hop propagation in broadcasting, changing the successor selection in the relays. This increases the complexity of our color schedule.

In this paper, we focus on an accurate color selection scheme in order to arrange the elapsed time of each relay (also including those along the succeeding paths) into a pipelined process. The key is to relabel the unselected relay(s) with those receivers of the selected relay. Thus, the parallelization of all possible relays can be maximized and the total end-to-end delay can be minimized. The contributions are threefold:

1) We clarify the minimum latency problem of broadcasting in both the round-based synchronous system and the asynchronous duty cycle system by a color selection scheme. This is the first attempt to study the impact of the local interference on the global end-to-end delay performance. It helps us to formalize a heuristic solution with the time counter M by given any possible color labeling to identify all interference-free relays. This sets up a more accurate performance target than any existing bound (e.g., [10]) in approximation approaches, for future research to further reduce the overhead cost

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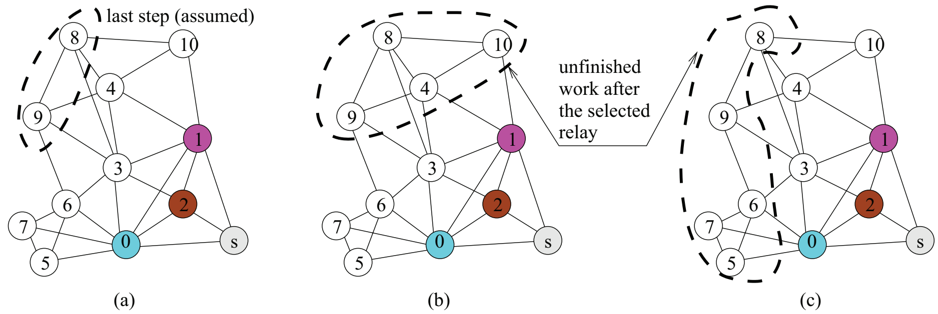

Fig. 1. (a) Approximation solution based on the information of hop distance. (b) Deferred broadcasting due to an inappropriate selection of the cyan relay at s. (c) Minimum latency broadcasting with the appropriate selection of the magenta relay at s.

and to achieve a more practical solution.

2) To reduce the cost of the heuristic method while still achieving the above optimization target, we provide a non-heuristic solution for the well-known greedy color scheme in both the synchronous and asynchronous systems. It is based on a lightweight estimation E of unfinished work to the edge of the networks, which can be constituted with a cost complexity $O(1)$ in the proactive mode. This new approximation approach fully takes advantage of the pipeline process so that the total latency can be reduced greatly, compared with existing non-heuristic approaches.
3) We develop a custom simulator to testify that the optimization achieved in the greedy color scheme is very close to our ultimate optimization target, in either the synchronous or asynchronous system. The experimental results show the room for improvement on end-to-end delay from the existing approximation approaches. They also illustrate the substantial improvement of our pipeline-based approximation solution in achieving the optimization target of the greedy mode and the ultimate mode as well.

The remainder of the paper is organized as follows. Section 2 briefly introduces our research motivation. Section 3 explains our network models of the round-based system and the duty cycle system. Section 4 introduces our solutions of the minimum latency broadcasting in both synchronous and asynchronous systems. Some analytical results are also provided. Section 5 discusses the experimental results of our custom simulator. The end-to-end delay performance in our approach is compared with the best results known to date. Section 6 summarizes the existing methods and their issues. Section 7 concludes this paper and provides ideas for future research.

II. Motivation

In Figure 1, nodes 0, 1, and 2, as well as their succeeding relays, are colored with cyan, magenta, and brown, respectively, due to a potential interference at node 3. In the hop-distance based schemes, each colored relay will be initiated in the sequence while any other interference-free relay is blocked. The study is limited to the approximation solution and the upper bound of the worst case, whose end-to-end delay is proportional to the product of the network diameter and the maximum size of the color clique, i.e., $4 \times 3 = 12$ steps for the sample in Figure 1.

A pipeline of color selections is constituted in a bottom-up manner in [10]. In Figure 1 (a), this approach assumes that the last relay will reach $\{8, 9\}$ only because they are the farthest (3-hop distance) away from s. Compared with the set $\{5, 6, 7, 8, 9\}$ in the optimal solution (enclosed by the dash line in Figure 1 (c)), the link utilization of this approach is limited, which requires more steps to handle the interference in the same amount of nodes in the networks.

No traditional metric, such as the node degree, can provide accurate information to describe the impact of interferences on the relay latency in the pipeline process. In Figure 1 (b), the relay from node 0 can be scheduled first at s. By this selection, $\{3, 5, 6, 7\}$ will receive the message and leave $\{4, 8, 9, 10\}$ for the rest of the broadcasting (see the area highlighted by the dash line). Then, we cannot find a one-step solution. This is because the relays for nodes 8 and 10 will incur interference at node 4. One of the relays must back off (i.e., extra time is needed).

If the relay from node 1 can be initiated first (see Figure 1 (c)), $\{3, 4, 10\}$ receive the message. The rest of the nodes $\{5, 6, 7, 8, 9\}$, enclosed by the dash line, can be reached immediately by the independent relays initiated from nodes 0 and 4. The wait of the relays from 0 and 2 in the schedule of node s can be pipelined with the relay that is initiated early on. Making a color selection in the pipeline process at s is proven to be difficult by considering a) the potential interference at node 4, b) its schedule solution, c) the difference between the resultant progress in Figure 1 (b) and (c), and d) the potential interference at node 6 by receiving signals from both nodes 0 and 3. Note that the status of each link and its utilization are also relevant to the early color selection. For instance, selecting the relay from node 0 will incur the use of link $0-3$ and an interference at node 4, but selecting the relay from node 1 can avoid both of these matters.

In this paper, we study the mutual impact of different color selections on the link utilization in the succeeding relays and

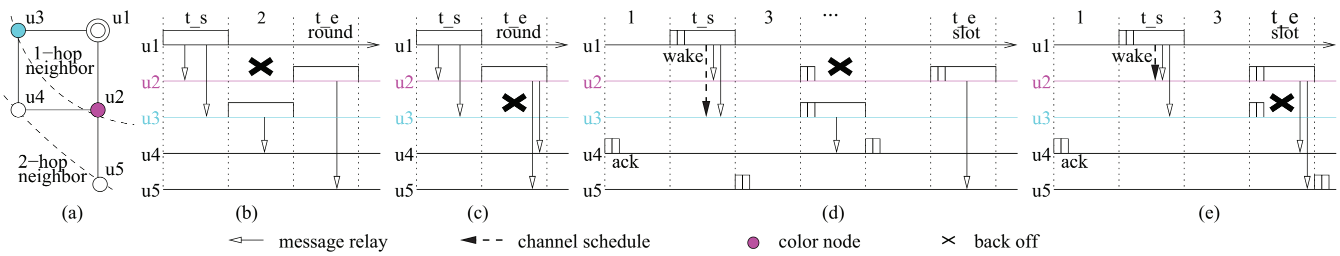

Fig. 2. (a) Broadcasting (from u_1) with a conflict at u_4. (b) Deferred broadcasting and (c) the minimum latency broadcasting under the network model of the round-based system. (d) Deferred broadcasting and (e) the optimal solution under the duty cycle model.

re-clarify the minimum latency problem with the right metric. Our goal is to determine a balance of relay processes in terms of the overall delay. The link utilization and its wake-up schedule must be reconsidered. For instance, in Figure 1, if node 1 wakes up before node 3 receives the message from either node 0 or 2, its relay to $\{4, 10\}$ does not need to wait and can be initiated immediately. In the other case, when the propagation along $0 \to 6 \to 9 \to 4$ can be conducted without any delay before node 1 wakes up, the entire broadcasting tree will change. Instead of propagating along the direction of $1 \to 4$, the optimal solution must use this link in the opposite direction of $4 \to 1$. The adoption of each link and the use of its direction in the broadcasting tree can affect the overall delay and may require a new balance in color decisions of the latency. This makes each color decision challenging.

III. Network Model

A WSN under the duty cycle model can be represented by a simple directed graph $G = (N, E)$, where N is a set of vertices (nodes) and E is a set of directed edges. $N(u)$ denotes the set of neighbors within the radius of node u under the unit disc graph (UDG) model. Supported by the MAC protocol, each node will periodically turn off its message sending channel (i.e., inactive to send any message out) in order to save energy and extend system lifetime. Its schedule is determined by a pseudo-random sequence in the uniform distribution with a preset seed [18]. Each time it wakes up, a beaconing process is initiated to connect nodes within its communication range. The data receiving process consumes a lot less energy than data sending. The receiving channel is always on in order to maintain the routine information exchange among neighbors. It will fall into an idle status when no data signal can be detected. When a node receives the beacon message from its neighbor, it will respond with its own status information, including the location, last wake-up time, metric values, etc. Therefore, each node can predict the active time of its neighbors. When a node is scheduled to turn on its sending channel, it will send the stored message to all of its 1-hop neighbors (also called neighborcasting), regardless of whether or not its neighbors are also in active mode.

The entire network simply synchronizes all node actions into each round $\in T = \{1, 2, 3, \cdots\}$ until the end of the lifetime, but not necessarily requiring each node to use a global clock. In the duty cycle system, the schedule of the data sending channel is denoted by $T(u) = \{u(1), u(2), \cdots\} \subset T$, with respect to its 1^{st}, 2^{nd}, $\cdots$ wake-up time. Let $r = \frac{|T|}{|T(u)|}$ denote the cycle rate. On average, each node can become active after every r slots, but there is not necessarily a fixed interval r between any two consecutive wake-ups.

We let s be the source that initiates the broadcasting at its active slot t_s. To avoid the storm problem of flooding [17], each relay node can only send once per round/slot. Without being interfered with by other signals of concurrent relays, all of its neighbors will receive such a message. By using a simple broadcasting sample, Figure 2 demonstrates all possible relay selections under our network models; optimal vs. non-optimal, and synchronous vs. asynchronous.

IV. Minimum Latency Broadcasting with Conflict Awareness

To achieve the minimum latency, our approach is to avoid initiating any relay that will incur unnecessary conflicts and the corresponding delay in the succeeding paths. Such a selection of interference-free relays is described in the color scheme. After a color is selected, all the relays labeled by it will be launched and such a propagation activity is called the *advance* of the broadcasting. Our work is to identify each color set and its initialization time in the optimal sequence to minimize the end-to-end delay. As a result, each advance of the broadcasting can be determined.

In this section, we formalize the minimum latency problem first. Then, we present our optimal target. After that, adopting the greedy color scheme that we introduce as the preliminary work, we propose a feasible target which is shown, by our experimental results, to be very close to our ultimate goal. Inspired by this effectiveness, we present our practical broadcasting protocol in the greedy color mode. It is based on an estimation of the unfinished work in terms of the hop distance, saving the cost in the heuristic mode. All the work is developed in the synchronous system first and then extended to the asynchronous system.

A. Preliminary

Existing methods adopt the color scheme in each 1-hop propagation to avoid any signal conflict. All relays of the same color are interference-free and can be initiated concurrently.

Algorithm 1 (Extended greedy color scheme): Determine the color label C_i for each node u, with respect to W in the round-based synchronous system (or $W(t)$ in the duty cycle system).

1) Check whether u has received the message ($\in W$ or $W(t)$), but at least one neighbor $v \in N(u)$ does not ($v \in \overline{W}$ or $\overline{W(t)}$) so that v can gain benefits from the 1-hop neighborcast of u (see constraints 1 and 2 in Eq. (1)).
2) Set color label $i = 1$.
3) Sort all qualified candidates by the order of the utilization of its relay, i.e., the number of possible receivers in its 1-hop neighborhood (see the extra constraint in Eq. (2)).
4) From the top in this list to its bottom, a candidate u is labeled by C_i when it does not have any signal conflict with other C_i nodes (see constraint 3 in Eq. (1)).
5) For any node that has not been labeled, it must conflict with any of the labeled nodes (see constraint 4 in Eq. (1)). Set color label $i = i + 1$ and repeat the above process in step 4 until all candidates are labeled.

After one color is selected, all other colors must back off. In the well-known greedy color scheme [2], a relay with the most receivers will be labeled first, in order to maximize the utilization of data sending channels and to avoid too many concurrent relays. However, existing color schemes ignore the ability of nodes that received the message from the selected color relay to initiate their own relays with those lagged relays concurrently, due to the synchronization in each 1-hop propagation. To maximize the parallelization of all possible relays and to further reduce the broadcasting task and its elapsed time, we extend the color scheme. The key is to apply the color scheme immediately once the selected interference-free relays are accomplished so that the unselected relays will be re-labeled with those receivers of this selected relay, even if they have different hop distances to the source. Their original color(s) will thus be superseded.

In the synchronous round-based system, assume that the broadcasting ends at round t_e. During the broadcasting process at t ($t_s \leq t < t_e$), the set of the nodes that have already received the message is denoted by $W(t)$, and $N - W(t)$ is denoted by $\overline{W(t)}$. We have $W(t_s) = \{s\}$ and $W(t_e) = N$. A color of W, say $C_i(W)$, is defined as follows:

$$\begin{cases} u \in W & \forall u \in C_i(W) \\ \exists v \in N(u), v \in \overline{W} & \forall u \in C_i(W) \\ N(u) \cap N(v) \cap \overline{W} = \phi & \forall u, v \in C_i(W) \\ \exists v \in C_j, 1 \leq i \neq j \leq \lambda(W), & \forall u \in C_i \\ \overline{W} \cap N(u) \cap N(v) \neq \phi & \end{cases} \quad (1)$$

where $1 \leq i \leq \lambda(W)$ denotes the number of colors needed. The first two constraints indicate that the color is labeled on each node carrying the message $\in W$ for a neighbor $\in \overline{W}$ that is requesting it. The third constraint confirms the interference-freedom among all nodes of the same color (i.e., no common neighbor under the UDG model). The fourth constraint reveals the fact that we can always find an interference node that is neighboring with different colors.

$$\begin{cases} \textit{the same in Eq. } (1) & \\ \max_{u \in C_i(W)}\{\mid N(u) \cap \overline{W} \mid\} \geq & \forall i, j \\ \max_{v \in C_j(W)}\{\mid N(v) \cap \overline{W} \mid\} & 1 \leq i < j \leq \lambda(W) \end{cases} \quad (2)$$

The well-known greedy color scheme (e.g., [2]) can be described in Eq. (2). The extra constraint helps to label the node with more receivers ($\in N \cap \overline{W}$) first. The more receivers, the more efficient the single neighbor-cast channel of this color relay will be. This constraint also provides a construction that can label each color gradually. That is, from color 1 to λ, one node is labeled by color i if and only if it conflicts with any color that is labeled previously.

Eq. (2) is easy to extend into the duty cycle system. By simply identifying those nodes available to send a message at time slot t, a color $C_i(w, t)$ can be decided as follows. Let $\lambda(W, t)$ denote the number of colors needed for W at slot t:

$$\begin{cases} u \in W, t \in T(u) & \forall u \in C_i(W, t) \\ \textit{the same in Eq. } (2), & \\ \textit{with respect to } t & \end{cases} \quad (3)$$

The details of our color scheme can be seen in Algorithm 1.

B. Target problem described by time counter M

Given the current progress of message propagation W at round/slot t, we focus on the selection of a color C_i for the broadcasting advance

$$A(W, t) = N(u) \mid_{\forall u \in C_i(W), 1 \leq i \leq \lambda(W)}$$

in the round-based system, or

$$A(W, t) = N(u) \mid_{\forall u \in C_i(W,t), 1 \leq i \leq \lambda(W,t)}$$

in the duty cycle system.

In the round-based synchronous system, starting from the source s and its start time (round t_s), our task of the minimum latency broadcasting is to minimize t_e. Such a problem can be formatted as follows, in terms of the number of rounds:

$$\begin{aligned} P(A) &= \min\{t_e\} \\ s.t. & \\ t_e &= M(\{s\}, t_s) \\ M(N, t) &= t - 1, \textit{ activity ends} \\ M(W, t) &= M(W + A(W, t), t + 1) \end{aligned} \quad (4)$$

The delay problem in the duty cycle system is formatted by rewriting Eq. (4) to a slot-based system, with respect to different time unit t and the corresponding counter M. Table I summarizes all of the notions used in this paper.

C. Target solution with any possible scheme

After a comprehensive study of relay parallelization in the broadcasting with conflict awareness, we make the following observations.

1) The traditional color scheme applies to nodes with the same hop distance to the source s, and enables their

s/u	source / current node
$N/N(u)$	nodes in the network / 1-hop neighbors of u
T	lifetime (in terms of the number of rounds)
$T(u)$	wake-up time of u in asynchronous systems
r	cycle rate, i.e., $avg(\frac{\lvert T\rvert}{\lvert T(u)\rvert})$, $u \in N$
$t(u,v)$	CWT that u waits for v, i.e., $\min\{t_i - t\}\mid_{t_i \in T(v) > t \in T(u)}$
t_s/t_e	start / end time
W (/$W(t)$)	nodes that received the packet (/at slot t)
$\overline{W}$ (/$\overline{W(t)}$)	$N - W$ (/$N - W(t)$)
$\lambda(W)$ (/$\lambda(W,t)$)	number of colors needed of W (/at slot t)
$C_k(W)$ (/$C_k(W,t)$)	k^{th} color relay from W (/at slot t), $1 \le k \le \lambda$
$A(W)$ (/$A(W,t)$)	broadcasting advance from W (/at slot t)
M	time counter, with respect to W, t, and S
$Q_i(u)$	i^{th} quadrant with u as the origin, $1 \le i \le 4$
$E_i(u)$	time estimation for the relay from u in $Q_i(u)$
$P(A)$	solution for the broadcasting from s, with respect to S and its resultant A

TABLE I
LIST OF NOTIONS USED.

relays only. The label of a color node remains stable until all color relays finish. It ignores the ability of those nodes that received the message earlier to initiate their relay concurrently with the lagged color relays.

2) To initiate all possible relays and to maximize their parallelization in the minimum latency broadcasting, each node in an unselected relay must be relabeled. The corresponding selection in the succeeding paths can be changed. One single color decision can change the link utilization anywhere in the entire network.
3) The existing color pipeline process (e.g., [10]) assumes that the farthest nodes are the receivers in the last step, i.e., $\overline{W(t_e - 1)}$. Such an assumption ignores the fact that these nodes can be reached at different time in the minimum latency broadcasting. This setting will mislead the evaluation in early color selection, missing the opportunity to achieve the optimal schedule.

Based on our study, we format the schedule problem in the (round-based) synchronous systems here:

$$\begin{array}{c} A(W,t) = N(u)\mid_{\forall u \in C_i(W)} \\ \forall 1 \le j \le \lambda(W), \\ M(W + C_i(W), t+1) \le M(W + C_j(W), t+1) \end{array} \quad (5)$$

where $C_i(W)$ and $C_j(W)$ are any color set $\in W$ that meets the constraints in Eq. (1). Similarly, the extension to the asynchronous duty cycle system is described as follows:

$$\begin{array}{c} A(W,t) = N(u)\mid_{\forall u \in C_i(W,t)} \\ \forall 1 \le j \le \lambda(W,t), \\ M(W + C_i(W,t), t+1) \le M(W + C_j(W,t), t+1) \end{array} \quad (6)$$

Note that $C(W)$ in the synchronized system is applied on all 1-hop neighbors in the topology structure, but $C(W,t)$ in the duty cycle system is applied on those awake 1-hop neighbors only (i.e., $t \in T(u)$ in Eq. (3)).

The optimization in the above solutions is obvious: Each local decision will select the color only when such a selection has the best performance in the overall view. The following theorems prove the aim of the minimum latency broadcasting.

Theorem 1 *$P(A) - t_s < d + 2$ (rounds) for the round-based synchronous system and $P(A) - t_s < 2r(d+2)$ (slots) for the duty cycle system, where d is the hop distance from s to the farthest node to reach in the network.*

Proof: In the round-based synchronous system, according to the calculation of M, our schedule A always selects the direction without deferring the entire broadcasting. That is, the farthest node to reach is always preferred, unless such a relay is delayed by interference. In such a delay, another relay must be selected, with no less than d hops. Because of the unit-disc-graph model, there is no other relay between these two. But, such a 1-round-lagged relay can meet another similar one, causing one of them to have another delay. Now, one 2-round-lagged relay and one 1-round-lagged relay are surrounded by two d-hop relays in both sides. No other relay path can supersede this 2-round-lagged relay. Therefore, the elapsed time has

$$P(A) - t_s + 1 \le d + 2.$$

The worst case of a 1-hop relay in the duty cycle system is that both end nodes wake up according to the same schedule, so that the successor node must wait for the entire cycle to synchronize the receiving and sending process, causing an extra delay with a maximum of $2r$ slots. The worst case is that all $(d+2)$ rounds require such a synchronization. Thus, in the duty cycle system, the elapsed time has

$$P(A) - t_s + 1 \le 2r(d+2).$$

■

Theorem 2 *Each calculation of M converges.*

Proof: In the recursive procedure, the set W expands greedily as well as the broadcasting progress under our network model. Due to the limit of λ and the size of N, the calculation converges. ■

Theorem 1 provides the performance bound of a broadcasting as it is claimed as a solution of the minimum latency broadcasting. It is also the closest target that we can achieve in our optimization. Theorem 2 proves the effectiveness of M in the above heuristic calculation.

D. Optimization achieved with the greedy color scheme

The adoption of the greedy color scheme will reduce the cost in determining all possible color sets from the current propagation progress W. Then, the optimization achieved in the synchronous system with the greedy color scheme (see Algorithm 1) can be written as:

$$\begin{array}{c} A(W,t) = N(u)\mid_{\forall u \in C_i(W)} \\ \forall 1 \le j \le \lambda(W), \\ M(W + C_i(W), t+1) \le M(W + C_j(W), t+1) \end{array} \quad (7)$$

Algorithm 2: Estimate the delay cost for the broadcasting from u in Q_i: $E_i(u)$.

1) Apply the hull algorithm [3] and the boundary construction algorithm [6] to constitute the edge of the networks.
2) Set $E_i(u)$ of any edge node to 0 when $N(u) \cap Q_i(u) = \phi$, $1 \leq i \leq 4$.
3) For any other node $u \in N$, set $E_i(u) = \infty$, $1 \leq i \leq 4$.
4) Update $E_i(u)$ from ∞, by applying Eq. (9) in the synchronous system (or Eq. (11) in the asynchronous system).
5) Set $E_i(u)$ to 0 for node u when $N(u) \cap Q_i(u) = \phi$, $1 \leq i \leq 4$.
6) Update $E_i(u)$ from ∞ by applying Eq. (9) in the synchronous system (or Eq. (11) in the asynchronous system).

Its extension to the asynchronous duty cycle system is described as follows:

$$\begin{array}{c} A(W,t) = N(u) \mid_{\forall u \in C_i(W,t)} \\ \forall 1 \leq \ j \leq \lambda(W,t), \\ M(W + C_i(W,t), t+1) \leq M(W + C_j(W,t), t+1) \end{array} \quad (8)$$

Note that C_i and C_j are any color set $\in W$ that meets the constraints in Eq. (2).

Table II illustrates the detailed process to determine the selected color for A in the round-based synchronous system in order to achieve the minimum latency broadcasting with our extended greedy color scheme. Table III shows the effectiveness of our schedule when the link utilization in the multiple-hop succeeding relays must be considered. Table IV displays the application of our schedule in the duty cycle system.

E. The solution with a lightweight estimation 4-tuple E

To save the cost of the heuristic search for each intermediate status in the above constitution of M, we provide the practical implementations that balance the performance with the overhead cost. Inspired by the analysis of the critical paths of interfered relays in Theorem 1, the new schedules are based on the estimation of the unfinished work in terms of the hop distance to the edge of the networks, unlike many existing methods that only consider the finished work in terms of the hop distance to the source. The idea is straightforward: the longer the path in expectation, the earlier the relay must be selected and initiated in the pipeline process.

[11] adopts a proactive method to collect the delay information for the unicasting toward the edge of the network. The information constituted in a 4-tuple at each node can efficiently guide any routing that is passing through, saving the cost and delay in the reactive (on-demand) information mode. We extend the method here to help the color schedule when the broadcasting propagates toward the edge of the network. Instead of selecting a node with a short delay to the network edge along the forwarding direction, we select a color with the node that has the longest delay to the network edge as the performance bottleneck of the entire broadcasting process.

The edge of the network can be identified by applying the boundary construction in [6] from any node that is located on the hull [3] of the entire network. Each edge node u sets its metric value $E_i(u)$ ($1 \leq i \leq 4$) to 0 when it does not have any neighbor in quadrant-i (i.e., $N(u) \cap Q_i(u) = \phi$); otherwise, $E_i(u) = \infty$ for any node $u \in N$, and $1 \leq i \leq 4$.

In the synchronous system, after the above initialization, each node $u \in N$ will update its ∞ value in $E_i(u)$ by:

$$E_i(u) = 1 + \min\{E_i(v)\}, \quad 1 \leq i \leq 4 \quad (9)$$

where $v \in Q_i(u) \cap N(u)$. Starting from the edge nodes of the networks with a fixed status, the whole phase converges.

There exists a local minimum node [1] with ∞ still in its E value. After the above process converges, any node u with ∞ in its E_i will change the value to 0 when it does not have any neighbor in quadrant-i. Then, each node $u \in N$ will update its ∞ value and only ∞ value in $E_i(u)$ by Eq. (9).

At each W, we apply the color scheme in Algorithm 1 first. Then, a color with the node u that has the largest value, say $E_i(u)$, will be selected for the broadcasting advance in quadrant-i (i.e., $N(u) \cap Q_i(u) \cap \overline{W} \neq \phi$).

$$\begin{array}{ll} & A(W,t) = N(u) \mid_{\forall u \in C_i(W)} \\ s.t. & \\ & E_k(u) \geq E_k(v) \\ & \mid_{\exists u \in C_i(W) \wedge N(u) \cap Q_k(u) \neq \phi,\ \forall v \in C_j(W) \wedge N(v) \cap Q_k(v) \neq \phi} \end{array} \quad (10)$$

For example, in Figure 1, $E_2(7) = E_2(8) = E_2(9) = 0$, and $E_2(0) = E_2(4) = E_2(5) = E_2(6) = E_2(10) = 1$. We have $E_2(1)$=2 as the maximum. Color magenta with node 1 will be selected to achieve the optimization in Figure 1 (c).

Then, the E-model is extended to the asynchronous duty cycle system by revising Eq. (9) as follows:

$$E_i(u) = \min\{t(u,v) + E_i(v)\}, \quad 1 \leq i \leq 4 \quad (11)$$

At each slot t, Algorithm 1 will be applied on W to decide the broadcasting advance. Among total $\lambda(W,t)$ colors, a color will be selected by applying Eq. (10) with respect to $C(W,t)$.

Algorithm 2 shows the details of the construction of E in both synchronous and asynchronous systems. The following theorem proves such construction to be cost-effective. Note that there is no delay cost in the proactive mode.

Theorem 3 *The E-model has a cost complexity of $O(1)$ in terms of the number of information exchanges and updates.*

Proof: In both synchronous and asynchronous systems, each node updates its E value once from ∞ and becomes stable. If not, such a node u must have a neighbor v with a smaller value after stabilization. Due to the initial status and the update procedure, v must be stable before $E(u)$ is updated, which leads to a contradiction.

For all possible broadcasts ($O(N)$) in the network, the total cost of updates is less than $4 \times N$. Therefore, the cost complexity is $O(1)$. ■

F. Summary

In this section, we first discuss an overall optimization, denoted by OPT, as our target. A new time counter M is used to measure the delay for each color selection. This ultimate goal can be achieved with an off-line calculation, as we did in the simulator. Then, we study the difference

Task $M(W,t)$, # of rounds	$C_1 \cdots C_\lambda$	M in consideration	selected color C_i	$A(W,t)$
$M(\{1\},1)$	$C_1:\{1\}$	$M(\{1,2,3\},2)$	C_1	$\{2,3\}$
$M(\{1,2,3\},2)$	$C_1:\{2\}$ $C_2:\{3\}$	$M(N,3)$, $M(\{1,2,3,4\},3)$	C_1	$\{4,5\}$
$M(N,3)=2$				
$M(\{1,2,3,4\},3)$	$C_1:\{2\}$	$M(N,4)$,		
$M(N,4)=3$				

TABLE II

SCHEDULE FOR THE SAMPLE IN FIGURE 2 (A), WITH $N=\{1,2,3,4,5\}$, $t_s=1$, AND $P(A)=2$.

Task $M(W,t)$, # of rounds	$C_1 \cdots C_\lambda$	M in consideration	selected color C_i	$A(W,t)$
$M(\{s\},1)$	$C_1:\{s\}$	$M(\{s,0-2\},2)$	C_1	$\{0-2\}$
$M(\{s,0-2\},2)$	$C_1:\{0\}$ $C_2:\{1\}$ $C_3:\{2\}$	$M(\{s,0-3,5-7\},3)$, $M(\{s,0-4,10\},3)$, $M(\{s,0-3\},3)$	C_2	$\{3,4,10\}$
$M(\{s,0-3,5-7\},3)$	$C_1:\{3\}$ $C_2:\{1,6\}$	$M(\{s,0-9\},4)$, $M(\{s,0-7,9-10\},4)$		
$M(\{s,0-9\},4)$	$C_1:\{1\}$ $C_2:\{4\}$ $C_3:\{8\}$	$M(N,5)=4$, $M(N,5)=4$, $M(N,5)=4$		
$M(\{s,0-7,9-10\},4)$	$C_1:\{4\}$ $C_2:\{9\}$ $C_3:\{10\}$	$M(N,5)=4$, $M(N,5)=4$, $M(N,5)=4$		
$M(\{s,0-4,10\},3)$	$C_1:\{0,4\}$ $C_2:\{3\}$ $C_3:\{10\}$	$M(N,4)=3$, $M(\{s,0-4,6,9-10\},4)$, $M(\{s,0-4,8,10\},4)$	C_1	$\{5-9\}$
$M(\{s,0-4,6,9-10\},4)$	$C_1:\{0,4\}$ $C_2:\{6,10\}$	$M(N,5)=4$, $M(N,5)=4$,		
$M(\{s,0-4,8,10\},4)$	$C_1:\{0,4\}$ $C_2:\{3\}$ $C_3:\{8\}$	$M(N,5)=4$, $M(\{s,0-4,6,8-10\},5)$, $M(\{s,0-4,8-10\},5)$		
$M(\{s,0-4,6,8-10\},5)$	$C_1:\{0\}$ $C_2:\{6\}$	$M(N,6)=5$, $M(N,6)=5$,		
$M(\{s,0-4,8-10\},5)$	$C_1:\{0\}$ $C_2:\{3\}$ $C_2:\{9\}$	$M(N,6)=5$, $M(\{s,0-4,6,8-10\},6)=6$, $M(\{s,0-4,6,8-10\},6)=6$,		
$M(\{s,0-3\},4)$	$C_1:\{3\}$ $C_2:\{0,1\}$	$M(\{s,0-4,6,8-9\},5)$, $M(\{s,0-7,10\},5)$,		
$M(\{s,0-4,6,8-9\},5)$	$C_1:\{0,1\}$ $C_2:\{4,6\}$ $C_3:\{8\}$	$M(N,6)=5$, $M(N,6)=5$, $M(\{s,0-4,6,8-10\},6)=6$,		
$M(\{s,0-7,10\},5)$	$C_1:\{3\}$ $C_2:\{4\}$ $C_3:\{6,10\}$	$M(N,6)=5$, $M(N,6)=5$, $M(N,6)=5$,		

TABLE III

SCHEDULE FOR THE SAMPLE IN FIGURE 1 (C) IN THE ROUND-BASED SYNCHRONOUS SYSTEM, WITH $N=\{s,1-10\}$, $t_s=1$, AND $P(A)=3$.

Task $M(W,t)$, # of rounds	$C_1 \cdots C_\lambda$	M in consideration	selected color C_i	$A(W,t)$
$M(\{1\},2)$	$C_1:\{1\}$	$M(\{1,2,3\},3)$	C_1	$\{2,3\}$
$M(\{1,2,3\},3)$	N/A	$M(\{1,2,3\},4)$	N/A	ϕ
$M(\{1,2,3\},4)$	$C_1:\{2\}$ $C_2:\{3\}$	$M(N,5)=4$, $M(\{1,2,3,4\},5)$	C_1	$\{4,5\}$
$M(\{1,2,3,4\},5)$	N/A	$M(\{1,2,3,4\},6)$	N/A	ϕ
$\cdots$		$\cdots$		
$M(\{1,2,3,4\},r+3)$	$C_1:\{2\}$	$M(N,r+4)>>4$		

TABLE IV

SCHEDULE FOR THE SAMPLE IN FIGURE 2 (E) IN THE DUTY CYCLE SYSTEM, WITH $N=\{1,2,3,4,5\}$, $t_s=2$, AND $P(A)=4$.

Algorithm 3: Color selection to decide the broadcasting advance A at the current progress W.

1) OPT: Define each possible color by Eq. (1) and select the one with the best end-to-end performance (determined in a heuristic manner by Eq. (5) in the synchronous system and by Eq. (6) in the asynchronous system).
2) G-OPT: Determine the greedy colors (by Eq. (2) in the synchronous system and by Eq. (3) in the asynchronous system) and select the one with the best end-to-end performance (determined in a heuristic manner by Eq. (7) in the synchronous system and by Eq. (8) in the asynchronous system).
3) E-model: Determine the greedy colors (see the above) and select the one with the largest E value (by Eq. (10)).

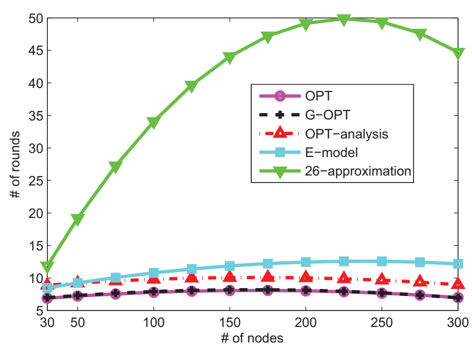

Fig. 3. $P(A)$ in the round-based synchronous system.

between the greedy color scheme and the optimal color scheme in achieving the minimum end-to-end delay. A more feasible optimization with such a greedy scheme, denoted by G-OPT, is described in this section. At last, based on some prior work and the results of our study on the effectiveness of the greedy color scheme, we present a practical solution, denoted by E-model, which is derived from a delay estimation E that is constituted in a lightweight process under the proactive mode. All the solutions have two versions, one for the synchronous round-based system and the other for the asynchronous duty cycle system. Algorithm 3 summarizes the color selection schemes that we are proposed in this paper.

V. Simulation

In this section, we verify the effectiveness of our approach in achieving the ultimate performance goal $P(A)$ of end-to-end latency by using a custom simulator built from real Mica mote testbed data.

A. Simulation setting

In the simulations, 50$\sim$300 nodes, with a communication radius of 10 feet, are deployed uniformly to cover an interest area of 50 $\times$ 50 Sq. Ft., creating different densities (nodes per Sq. Ft.) ranging from 0.02 to 0.12. The source is randomly selected with a distance of 5$\sim$8 hops to the farthest node.

Firstly, in the round-based system, we compare the best existing solution with conflict awareness known to date (i.e., the 26-approximation in [2]) with our approaches: the optimal solution with Eq. (5) for any color scheme, the optimal solution with Eq. (7) for the greedy color scheme, and the approximation solution with Eq. (10). Simply, they are denoted by 26-approximation, OPT, G-OPT, and E-model, respectively. In each round, we simulate the node action under all models. Under 26-approximation model, the BFS is built and the greedy color scheme is applied. After that, the color is selected and its broadcasting advance is launched. However, the propagation with the same hop distance to the source in the BFS requires a synchronization process. Under the new models in this paper, the color scheme and its selection is applied for each broadcasting advance based on the evaluation of M for the optimal solutions and E for the approximation solution. At the end, we count the number of rounds that are needed to accomplish the broadcasting in each model.

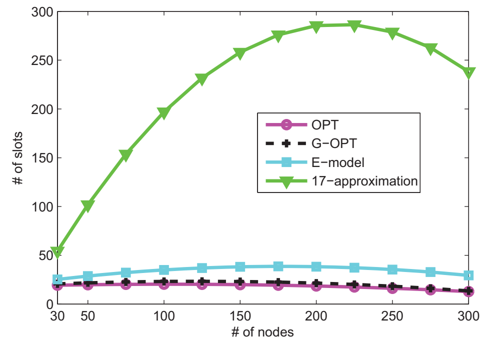

Fig. 4. Experimental results of $P(A)$ in the duty cycle system with $r = 10$.

Next, in the duty cycle system with $r = 10$ (slots), we compare the best solution known to date (i.e., the 17-approximation in [12]) with our approaches: OPT with Eq. (6), G-OPT with Eq. (8), and E-model with Eq. (10). Our network model is applied. The BFS color scheme in [12] is applied based on the hop distance while our color scheme is applied at each slot for any possible advance. After the color is selected, its relays will be initiated and will advance 1-hop at each slot. But for any color backing off, it requires a wait of k slots ($1 \leq k \leq 2r$) to re-initiate. After that, we run the simulation in a light duty cycle system (i.e., 2% duty cycle system with the rate $r = 50$ slots).

B. Simulation results

The substantial improvement on the end-to-end delay of our approaches in the round-based synchronous systems is shown in Figure 3, which suggests the validity of our pipeline approach. The analytical results of Theorem 1, denoted by OPT-analysis, are also shown in Figure 3.

Figure 4 shows the experimental results of our approaches that are collected from the duty cycle system with $r = 10$. Figure 5 shows the corresponding analytical results from Theorem 1, compared with the upper bound described in [12].

Figure 6 shows the experimental results of our approaches

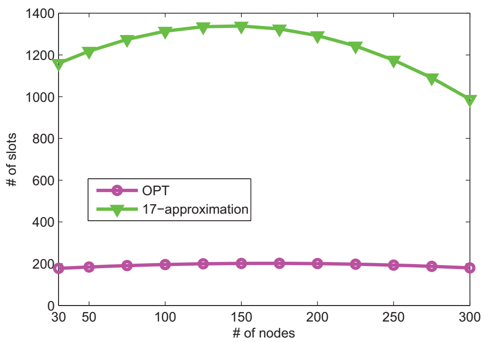

Fig. 5. Analytical results of $P(A)$ (upper bound) in the duty cycle system with $r = 10$.

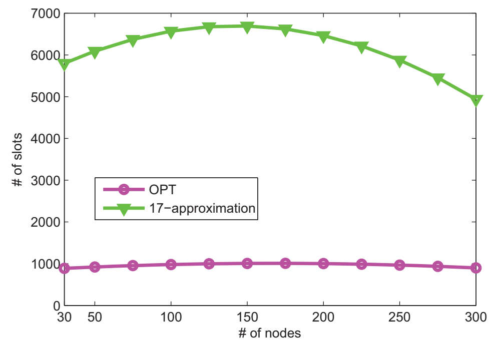

Fig. 7. Analytical results of $P(A)$ (upper bound) in the duty cycle system with $r = 50$.

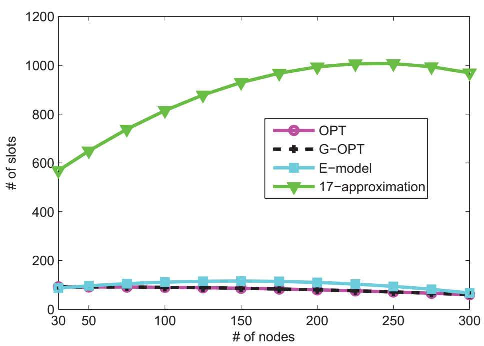

Fig. 6. Experimental results of $P(A)$ in the duty cycle system with $r = 50$.

in the light duty cycle system (with $r = 50$), compared with those results of the approach in [12]. Figure 7 shows the corresponding analytical results.

C. Simulation summary

We have the following observations.

After the node density reaches a certain point, say 0.1 nodes per Sq. Ft. (i.e., 250 nodes deployed in our networks), the more nodes added for a condensed deployment, the more receivers each relay will have. This will reduce the depth of the broadcast tree, making the entire process end faster.

Both 26- and 17-approximation solutions will be affected by neighbor configuration, not exactly in proportion to hop distance; although, they can be bounded within a threshold in proportion to hop distance.

In heavy duty cycle system, a node has more neighbors available than it has in the light duty cycle system. This increment of node degree incurs more interferences. CWT becomes more important in achieving the minimum latency broadcasting. For a relay in the light duty cycle system, the chance of being scheduled off becomes less. However, each 1-hop propagation requires longer cycle waiting. The end-to-end delay is more likely in proportion to the hop distance. In both cases, our approach achieves a better end-to-end performance because of the use of the pipeline process.

G-OPT is very close to OPT. In many cases, the solution for the greedy color scheme achieves the optimal end-to-end performance. From our experimental results, the difference between them is no more than 2 hops in the round-based system. In light duty cycle system, they achieve the same performance. In heavy duty cycle system, the difference is controlled within r slots. The results show the effectiveness of G-OPT solution as the replacement for OPT, as well as the greedy color scheme for saving the heuristic search for any possible color set from the current progress.

There exists a room of at least 70% improvement from the best results known to date. In the synchronous system, a 70% improvement is expected. In both the light duty cycle system and the heavy duty cycle system, the improvement from 85% up to 90% is expected. The results prove the necessity of our optimization work, and guide the development of a practical solution for achieving the minimum delay.

By adopting the appropriate pipeline process, even with a coarse-grained estimation, E-model can achieve a close performance as OPT and G-OPT, in all the network models; synchronous vs. asynchronous, heavy duty vs. light duty.

Our analysis of the performance upper bound is also proven accurate, in both the round-based system and the duty cycle system. Such analytical results can be used as the target for our further improvement of the color scheme.

VI. Related Work

Latency is a very important problem of an efficient broadcasting in the duty cycle system, and it has been addressed in past literature (e.g., [14]). [15] proposes a heuristic solution to schedules the activities of the sensor nodes. However, it does not take into account any interference. As indicated in [11], [20], the transmission time must also be considered, which is directly proportional to the hop number.

Many existing methods adopt the hop counter [8] as the metric in the delay evaluation. The problem of latency in broadcasting is studied in [4]. A BFS tree is built based on the connected dominating set (CDS). A color schedule is formed along this tree for each 1-hop propagation. That work is the first paper to prove a constant approximation ratio for the end-to-end delay. Another parallel work [16] focuses on the practical implementation of this approach in the distributed manner. Compared with the work in [4], a more efficient solution with a better approximation constant (a 26-approximation solution with respect to hop distance) is presented in [2]. [10] claims a 16-approximation solution with the geometric properties of the unit disc graph (UDG).

By extending the pipeline algorithm [5], a lower bound of $(1+O(\lg))$-approximation solution is achieved in a bottom-up construction [10]. Unfortunately, this improvement focuses on the delivery of the message and ignores the interference. It also ignores the change of link utilization in the succeeding relays after an early color selection. The pipeline is limited on the BFS and ends at a fixed set of nodes, i.e., the optimal end-to-end performance cannot be achieved because this approach cannot initiate all possible relays from the nodes that have received the message. Moreover, the BFS is a global information and the entire pipeline process must be rebuilt when the source changes. The overhead cost cannot be ignored.

The delay problem of broadcasting in the duty cycle system is studied in [20]. It proves the need for a heuristic evaluation in the broadcast tree construction. However, its approach relies on healthy, interference-free links. Any signal failure will incur message retransmission and even a live-lock, not only deferring the end-to-end communication, but also resulting in more redundancy, contention, and collisions [17]. [13] applies the *opportunistic routing* to ensure the greedy progress of the broadcast procedure. There is no guaranty to achieve the best of the end-to-end performance. The delay impact of interference cannot be avoided completely. [12] provides a BFS-tree-based approximation solution in the duty cycle system. Without an appropriate pipeline process in the color schedules, the total delay is accumulated by the cost of each hop and can be up to $(17k \times d)$, where k is the maximum wait slots required between any pair of neighboring nodes, and d is the hop distance.

VII. Conclusion

In this paper, we provide an accurate time counter M and its non-heuristic and lightweight implementation E to measure the delay of a broadcasting. We study the mutual impact of the color schedule and the link utilization in the succeeding paths on the end-to-end delay. With our new color schedule, we can achieve the overall optimization with any possible color scheme and the optimal solution for the greedy color scheme, providing the performance target in further reducing the overhead cost. To make the optimization feasible not to rely on expensive off-line calculation, we propose our approach with the coarse-grained estimation (a 4-tuple E) of the delay to the edge of network at each node which is constituted in the proactive mode. Then, all of our solutions are extended to the duty cycle system. Both analytical and experimental results illustrate the correctness of our pipeline approach and its significant performance improvement.

In the future work, we will focus on a localized color scheme and its selection to provide a more reliable and scalable solution. Introducing the delay measurement to the color labeling process may help to further improve the broadcast performance. The further optimization can be conducted with other constraints, such as energy saving, traffic throughput control, etc. The duty cycle network model can be extended to other delay-sensitive communications, such as social networks.

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References

[1] N. Ahmed, S. Kanhere, and S. Jha. The holes problem in wireless sensor networks: A survey. *ACM Sigmobile Mobile Computing and Communication Review*, 9(2):4–18, 2005.

[2] Z. Chen, C. Qiao, J. Xu, and T. Lee. A constant approximation algorithm for interference aware broadcast in wireless networks. *Proc. of ACM/IEEE INFOCOM*, pages 740–748, 2007.

[3] Definition. Convex hull. http://en.wikipedia.org/wiki/Convex_hull.

[4] R. Gandhi, A. Mishra, and S. Parthasarathy. Minimizing broadcast latency and redundancy in ad hoc networks. *IEEE/ACM Transactions on Networking*, 16(4):840–851, 2008.

[5] L. Gasieniec, D. Peleg, and Q. Xin. Faster communication in known topology radio networks. *Proc. of ACM PODC*, 2005.

[6] D. Goldenberg, J. Lin, A. Morse, B. Rosen, and Y. Yang. Towards mobility as a network control primitive. *Proc. of ACM MobiHoc*, pages 163–174, 2004.

[7] S. Guha and S. Khuller. Approximation algorithms for connected dominating sets. *Algorithmica*, 20(4):374–387, 1998.

[8] T. He, J. Stankovic, C. Lu, and T. Abdelzaher. SPEED: A stateless protocol for real-time communication in sensor networks. *Proc. of IEEE ICDCS*, pages 46–55, 2003.

[9] S. M. Hedetniemi, S. T. Hedetniemi, and A. Liestman. A survey of gossiping and broadcasting in communication networks. *Networks*, 18:319–349, 1998.

[10] S. Huang, P. Wan, X. Jia, H. Du, and W. Shang. Minimum-latency broadcast scheduling in wireless ad hoc networks. *Proc. of ACM/IEEE INFOCOM)*, pages 733–739, 2007.

[11] Z. Jiang, J. Wu, and R. Ito. A metric for routing in delay-sensitive wireless sensor networks. *Proc. of IEEE MASS*, 2010.

[12] X. Jiao, W. Lou, J. Ma, J. Cao, X. Wang, and X. Zhou. Duty-cycle-aware minimum latency broadcast scheduling in multihop wireless networks. *Proc. of IEEE ICDCS*, pages 754–763, 2010.

[13] S. Lai and B. Ravindran. On multihop broadcast over adaptively duty-cycled wireless sensor networks. *Proc. of IEEE DCOSS*, pages 158–171, 2010.

[14] W. Lai and I. Paschalidis. Sensor network minimal energy routing with latency guarantees. *Proc. of ACM MobiHoc*, pages 199–208, 2007.

[15] G. Lu, N. Sadagopan, B. Krishnamachari, and A. Goel. Delay efficient sleep scheduling in wireless sensor networks. *Proc. of ACM/IEEE INFOCOM*, 2005.

[16] R. Mahjourian, F. Chen, R. Tiwari, M. Thai, H. Zhai, and Y. Fang. An approximation algorithm for conflict-aware broadcast scheduling in wireless ad hoc networks. *Proc. of ACM MobiHoc*, pages 331–340, 2008.

[17] S. Ni, Y. Tseng, Y. Chen, and J. Sheu. The broadcast storm problem in a mobile ad hoc network. In *Proc. of ACM/IEEE MobiCom*, pages 151–162, 1999.

[18] J. Redi, S. Kolek, K. Manning, C. Partridge, R. Rosales-Hain, R. Ramanathan, and I. Castineyra. JAVeLEN - an ultra-low energy ad hoc wireless network. *Ad Hoc Networks*, 6(1):108–126, 2008.

[19] I. Stojmenovic, M. Seddigh, and J. Zunic. Dominating sets and neighbor elimination-based broadcasting algorithm in wireless networks. *IEEE Transactions on Parallel and Distributed Systems*, 13(1):14–25, 2002.

[20] F. Wang and J. Liu. Duty-cycle-aware broadcast in wireless sensor networks. *Proc. of ACM/IEEE INFOCOM*, pages 468–476, 2009.