Poster Abstract: Towards Integrated and Self-configuring Routing and Interest Dissemination Strategies for Wireless Sensor Networks

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***Abstract*— The focus of this abstract is on a complete system for interest dissemination and routing in wireless sensor networks. To this end, we integrated algorithms developed in the recent literature, which we modified by optimizing their efficiency under very low duty cycle operations. Each sensor is autonomously capable of initiating neighbor estimation procedures, forwarding data traffic towards the sink or propagating interests (sink → sensor nodes). These operations are executed in parallel and as different tasks of the same protocol. Routing is carried out by exploiting hop count coordinates, which are proactively propagated along with interest dissemination packets. Moreover, MAC and routing algorithms are jointly designed to improve both energy consumption and the quality of the selected paths. Finally, neighbor estimation algorithms are activated on demand and exploited to optimize the operations during all phases of the protocol.**

I. INTRODUCTION

Many solutions for wireless sensor networks have been proposed in the recent literature [1][2][3][4][5][6]. This work ranges from data dissemination algorithms [3] to channel access techniques [2][5][7][6] as well as solutions for interest dissemination [1][8][9] and neighbor estimation [7]. The work on interest dissemination starts with the directed diffusion protocol [1]. In [1] flooding is used to propagate interests and set up a gradient which is subsequently used in the data retrieval phase (nodes → sink). In [8][9] more refined techniques were proposed to lower the energy consumption and overhead incurred in flooding. This objective is achieved at the cost of a minimal decrease of the reliability performance (number of nodes reached by an interest message). Forther methods to increase energy efficiency can be found in [2], where the authors present a channel access scheme which exploits the node sleeping behavior. Data delivery protocols (nodes → sink) can be found in [3] and [4]. Here, geographical coordinates are used to build a gradient to be followed to transmit data to the sink. Moreover, MAC and routing protocols are integrated and work under aggressive awake/asleep sleeping cycles. Recent work [5][7][6] focuses on both refined MAC procedures and to the estimation of the number of neighbors (local density) at each sensor device. We note that previous research mainly focuses only on some aspects of the whole sensor system, by either addressing the forward (interest dissemination) or backward (data delivery) communication phases, without considering them together. Integrating these two phases poses some challenges. For instance, interested dissemination algorithms such as [9] assume that each node knows its neighbors and their awake/asleep schedule, whereas the techniques in [3] have their strenght in that no such knowledge is required. The work described in this abstract is a step towards the design of a complete and self-adaptable wireless sensor system, where most of the above schemes should work in a coordinated manner. We jointly account for 1) awake/asleep scheduling protocols (Section II-A), estimation of the number of neighbors of each sensor node (Section II-B), MAC/routing schemes (Section II-C) and interest dissemination methods (Section II-B). Each sensor communicates with its neighboring nodes in three cases: 1) to send a data packet towards the sink node, 2) to propagate an interest (broadcast communication) and 3) to estimate the number of neighbors. These three tasks are interleaved during the node lifetime and their settings may be dynamically changed according to the node requirements.

II. DATA DISSEMINATION FRAMEWORK

A. Sleeping behavior

Sleeping modes are implemented to reduce energy consumption and prolong network lifetime. When a node does not have data traffic to send, it follows the so called *basic sleeping behavior*. According to this algorithm, a given node divides time into periods of T seconds (*sleeping cycle* periods). At the end of every sleeping cycle it randomly picks a real number $t_a \in [0, T(1-d)]$, where $d > 0$ is the duty cycle. During the subsequent sleeping cycle, the node will sleep for the first t_a seconds, after which it will wake up and remain in the active state (listening to the wireless medium) for Td seconds, and then it will go back to sleep up to the end of the sleeping cycle. Note that sleeping cycles at different nodes are not synchronized. The sleeping mode dynamics are slightly different when a node has data to send. In our work, we adopt a CSMA-based MAC. Hence, before sending its data a node first senses the channel to detect ongoing transmissions. If the channel is sensed idle, then it starts the channel contention with its active neighbors in order to elect a relay node. The node remains active during the whole channel contention until a relay node is finally elected and the packet forwarded. The contention follows the procedure described in Section II-C.

B. Node density estimation

For proper operation, many of the techniques considered in our approach require local density estimates. In this section, we briefly discuss the estimation procedures that we implemented in

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our framework. Each node turns on and off its radio according to a duty cycle d, which is assumed to be common to all nodes in the network. Our aim is to precisely estimate the total number of nodes within coverageof a *target node*, including both active and sleeping devices. To this end, we implemented an iterative estimation procedure as follows. The estimation algorithm is executed in rounds. At each estimation round the target node counts the number of active nodes within coverage. This can be achieved using known multiplicity estimation algorithms. To this end, we considered two alternative approaches: *the first approach*, exploits the Binary Tree Estimation (EBT) scheme proposed in [7]. This algorithm uses a binary tree search and allows for both a complete counting of the in-range devices as well as a partial counting. In the partial counting case, the algorithm provides estimates for the total number of in-range neighbors and indications of the estimation errors. Hence, one might use the algorithm to either count *all* active in-range devices or stop the procedure after having discovered *a sufficient* number of neighboring nodes. In this abstract, we consider the complete counting method. *The second approach*, that we call WINDOW, uses a simple protocol based on a contention window as follows. The inquirer (target node) starts the counting procedure sending a REQ message, which is followed by a window of W time slots. On receiving the REQ, each node randomly picks a slot in $1, 2, \dots, W$ and replies with a short packet (whose transmission time fits into the slot duration) including its own identifier (id). The interrogator collects the number of successfully transmitted packets in the window and memorizes the ids of the related nodes. For each subsequent estimation round, the window size is taken as twice the current estimate of the number of active neighbors. Note that EBT is more accurate than the window based approach as contentions are distributed along binary trees which eventually discover each active neighbor within range. In the window based approach, instead, collisions may always occur even if we increase the window size.

C. Routing and MAC algorithms

For the routing, we implemented SARA (Statistically Assisted Routing Algorithm), the solution in [10]. Packets are routed towards the sink node by exploiting hop count (HC) topologies.[1] Hop counts are propagated/updated during the interest dissemination phase according to a procedure similar to the one in [9], by accounting for backoff intervals as in [11]. Routing is modeled as a sequential decision process[10], where at every decision stage a node has to take a specific action, which consists of selecting the best relay node for the current transmission. Assume that the currently occupied node is node i, that its hop count is $\text{HC}(i) = n$ and that the forwarding process is at stage $t \in \mathbb{N}$, where time evolves one unit every decision stage (forwarding action). We define $\mathcal{N}_i(n)$, $\mathcal{N}_i(n-1)$ and $\mathcal{N}_i(n+1)$, $n \in \mathbb{N}^+$ as the sets of neighbors of node i with HC equal to n, $n-1$ and $n+1$, respectively. The problem to be solved is to decide which is the best relay among the nodes in sets $\mathcal{N}_i(n)$ and $\mathcal{N}_i(n-1)$. Nodes in set $\mathcal{N}_i(n+1)$ are not considered as they very unlikely lead to satisfactory solutions [10]. In addition, at the current node i, we associate a (normalized) cost $c_j \in [0, 1]$ to each link (i, j), $j \in \mathcal{N}_i(n-1) \cup \mathcal{N}_i(n)$. These costs may be related to queue lengths (congestion), node residual energies, link states in terms of success probability, etc. We refer to $j^t_{n-1} \in \mathcal{N}_i(n-1)$, $j^t_n \in \mathcal{N}_i(n)$ and to c^t_{n-1}, c^t_n as the minimum cost nodes in sets $\mathcal{N}_i(n)$ and $\mathcal{N}_i(n-1)$ and their associated costs, respectively. We further define *forwarding cycle* as the sequence of steps between the forwarding stage where a node with hop count n is reached for the first time and the stage where a neighbor with hop count $n-1$ is eventually selected as relay. In order to minimize the delay, the optimal choice would be to always forward the packet towards node j^t_{n-1}. However, when the cost of link (i, j^t_{n-1}) is high, it might make sense to route the node towards node j^t_n, with the hope that this node has a more convenient neighbor with a HC equal to $n-1$. In this way, we actually postpone the hop count advancement ($n \to n-1$) to the next forwarding step. In mathematical terms, this strategy makes sense when $c^t_{n-1} - c^t_n \leq \mathcal{E}$, where $\mathcal{E}$ is the expected minimum cost among nodes with HC $n-1$ at the next stage $t+1$. In the following, we refine this concept by presenting the online optimal routing policy in our settings. See [10] for a formal proof of its optimality. At every stage $t \geq 0$, a decision has to be made on whether the packet has to be forwarded to node j^t_{n-1} or node j^t_n. The cost accumulated (assuming additive costs) from the beginning of the current forwarding cycle[2] $C_{tot}(t)$ is defined as $C_{tot}(t) = C_{par}(t) + c^t_{n-1}$, where $C_{par}(t)$ is given by

$$C_{par}(t) = \begin{cases} 0 & t < 1 \\ \sum_{k=0}^{t-1} c^k_n & t \geq 1 \end{cases} \tag{1}$$

The minimum cost of all paths to a node with hop count $n-1$ encountered by the packet from step 0 to step t (the current step) is evaluated as $C^{min}_{tot}(t) = \min_{0 \leq k \leq t} \left\{ C_{tot}(k) \right\}$. It can be proven [10] that the online optimal routing policy obeys the following stopping set $\mathcal{B}_2 = \left\{ X_t : C^{min}_{tot}(t) - C_{par}(t+1) \leq \mathcal{E} \right\}$. That is, at time t the packet is routed towards node j^t_{n-1} if the inequality in set $\mathcal{B}_2$ is verified. These routing procedures have been integrated with a cost-based probabilistic CSMA-CA scheme as detailed in [12]. The result is a cross-layer based routing algorithm where next hops are selected during the channel access, by leading to a routing table free scheme.

D. Interest dissemination algorithms

Algorithms for interest dissemination are a fundamental part of the overall network system. This operation usually involves one-to-all communication which is initiated and governed by the sink. However, we observe that broadcasting data in sensor networks may be expensive and, at the same time, challenging. This is mainly due to the sparse and very often unconnected topology arising from the nodes' sleeping behavior. In spite of

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[1] Hop counts are defined as the minimum number of transmissions to reach the sink from a given node, according to the logical topology considered, which is not necessarily the radio connectivity structure [9].

[2] We assume that the current cycle started at time 0.

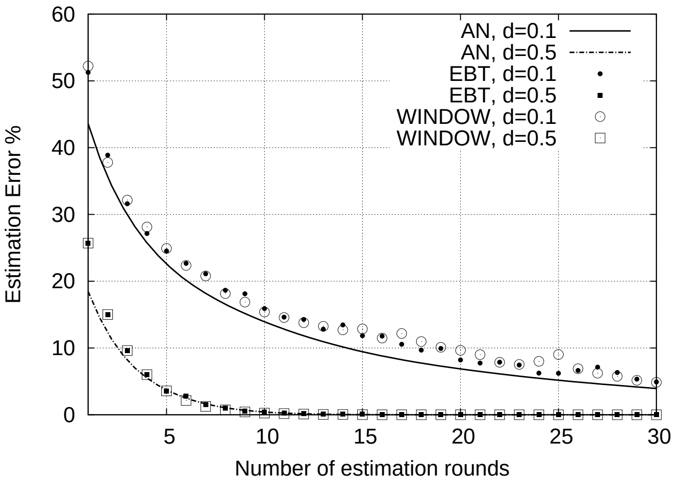

Fig. 1. Comparison of estimation procedures

this, however, good broadcast algorithms should be able to reach all nodes in the network within a single flood, including those nodes that are asleep. To achieve these goals, we adopt the *fireworks* protocol in [9]. fireworks is a simple probabilistic scheme which does not require any overlay network to be set up in advance. If the forwarding probabilities are correctly configured, all nodes in the network are reached with high probability and with low overhead. The analytical properties of the scheme are detailed in [9] together with extensive performance comparisons with respect to flooding and gossiping. Our interest here is in implementing the approach in practice and integrating it with the forward data dissemination phase (nodes → sink). Next, we briefly describe how fireworks works. The sink transmits to all its neighbors. Whenever a node receives a new broadcast message it tosses a coin. With probability p it re-broadcasts the message to all its neighbors, while with probability $1-p$ it sends it to c randomly selected neighbors. c is usually lower than or equal to 4 [9]. This algorithm has been implemented in our framework by integrating it with neighbor estimation procedures (see Section II-B). That is, neighbor estimations are executed/refined during interest dissemination pahses. The lenght (number of rounds) of these algorithms can be tuned for optimal performance.

III. PRELIMINARY RESULTS

A. Neighbor estimation

In Fig. 1 we plot the average estimation error obtained by ns2 simulation by considering both the EBT and the WINDOW counting procedures. Moreover, we compare simulation results against the minimum achievable estimation error, which is obtained by analysis (AN). The results are plotted for two typical values of the duty cycle $d \in \{0.1, 0.5\}$ and confirm the validity of the estimator and also the goodness of both counting methods.

B. Data dissemination

In this section we present preliminary results from an ns2-based performance evaluation of our system. For the simulation scenario we considerd $n = 150$ to 300 nodes, which are uniformly and randomly scattered in a square region of size 200m. The sink is placed at the center of the area. Channel capacity is typical of sensor networking (38400bps). All the nodes have a fixed transmission range of 30m. Two types of nodes are considered: Resource-rich nodes (*rich* nodes in the following), equipped with 240 Joules of initial energy, and *poor* nodes, that have only 48 Joules. Generation of new packets follows a Poisson process. A new packet is generated roughly every two seconds and a sensor node is selected randomly and uniformly as its source.

The effectiveness of SARA in choosing as relay rich nodes more likely than poor ones. At high network densities and for high duty cycles, each node can select among a large number of neighbors. This allows SARA to exploit at best the weight-based relay selection. When $n = 300$ and $d = 0.5$, 70.5% of the forwarded packets are handled by rich nodes, leading to effective energy balancing. In sparser scenarios and low duty cycles ($n = 150$ and $d = 0.1$) the degree of freedom of each node in selecting relays is lower. We observe that when no rich nodes are available which are closer to the sink, a node prefers to forward the packet to a same-layer rich node. This happens from 38 to 42% of the times.

Routing delivered packets to the sink in 100% of the cases and interest dissemination was able to reach the majority of nodes ($\geq 90\%$) in all experiments. Overall, the integration of SARA and the fireworks-like interest dissemination algorithm proves to be a promising approach for reliable, and energy efficient operations in wireless sensor networks. Further results, as well as the development of an experimental testbed are the objective of our current work.

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