ALBA-R: Load-Balancing Geographic Routing Around Connectivity Holes in Wireless Sensor Networks

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Abstract—This paper presents ALBA-R, a protocol for *convergecasting* in wireless sensor networks. ALBA-R features the cross-layer integration of geographic routing with contention-based MAC for relay selection and load balancing (ALBA), as well as a mechanism to detect and route around connectivity holes (Rainbow). ALBA and Rainbow (ALBA-R) together solve the problem of routing around a dead end without overhead-intensive techniques such as graph planarization and face routing. The protocol is localized and distributed, and adapts efficiently to varying traffic and node deployments. Through extensive ns2-based simulations, we show that ALBA-R significantly outperforms other convergecasting protocols and solutions for dealing with connectivity holes, especially in critical traffic conditions and low-density networks. The performance of ALBA-R is also evaluated through experiments in an outdoor testbed of TinyOS motes. Our results show that ALBA-R is an energy-efficient protocol that achieves remarkable performance in terms of packet delivery ratio and end-to-end latency in different scenarios, thus being suitable for real network deployments.

Index Terms—Wireless sensor networks, cross-layer routing, connectivity holes, geographic routing, localization errors

1 Introduction

Distributed sensing and seamless wireless data gathering are key ingredients of various monitoring applications implemented through the deployment of wireless sensor networks (WSNs). The sensor nodes perform their data collection duties unattended, and the corresponding packets are then transmitted to a data collection point (the *sink*) via multihop wireless routes (WSN *routing* or *convergecasting*). The majority of the research on protocol design for WSNs has focused on MAC and routing solutions. An important class of protocols is represented by *geographic* or *location-based* routing schemes, where a relay is greedily chosen based on the advancement it provides toward the sink. Being almost stateless, distributed and localized, geographic routing requires little computation and storage resources at the nodes and is therefore very attractive for WSN applications. Many geographic routing schemes, however, fail to fully address important design challenges, including 1) routing around connectivity holes, 2) resilience to localization errors, and 3) efficient relay selection. Connectivity holes are inherently related to the way greedy forwarding works. Even in a fully connected topology, there may exist nodes (called *dead ends*) that have no neighbors that provide packet advancement toward the sink. Dead ends are, therefore, unable to forward the packets they generate or receive. These packets will never reach their destination and will eventually be discarded. Many solutions have been proposed to alleviate the impact of dead ends. In particular, those that offer packet delivery guarantees are usually based on making the network topology graph planar, and on the use of face routing [1]. However, planarization does not work well in the presence of localization errors and realistic radio propagation effects [2], as it depends on unrealistic representations of the network, such as a unit disk graph (UDG [3]).

In this paper, we propose an approach to the problem of routing around connectivity holes that works in any connected topology without the overhead and inaccuracies incurred by methods based on topology planarization. Specifically, we define a cross-layer protocol, named ALBA for *Adaptive Load-Balancing Algorithm*, whose main ingredients (geographic routing, load balancing, contention-based relay selection) are blended with a mechanism to route packets out and around dead ends, the *Rainbow* protocol. The combination of the two protocols, called ALBA-R, results in an integrated solution for *convergecasting* in WSNs that, although connected, can be sparse and with connectivity holes.

The contributions we provide to WSN research with this paper include the following:

1. We enhance greedy geographic forwarding by considering congestion and packet advancement

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jointly when making routing decisions. The new relay selection scheme, which implements MAC and routing functions in a cross-layer fashion, achieves performance superior to existing protocols in terms of energy efficiency, packet delivery ratio (PDR), and latency.

2. The Rainbow mechanism allows ALBA-R to efficiently route packets out of and around dead ends. Rainbow is resilient to localization errors and to channel propagation impairments. It does not need the network topology to be planar, unlike previous routing protocols. It is, therefore, more general than face routing-based solutions and is able to guarantee packet delivery in realistic deployments.
3. Extensive ns2-based simulation experiments are performed that demonstrate how the unique features of ALBA-R determine its overall performance, and that show its superiority with respect to previous exemplary solutions for geographic-based and topology-based convergecasting, such as GeRaF [4] and IRIS [5]. We have also investigated the performance of Rainbow in sparse networks, where dead ends are likely to occur, with and without localization errors. We show that Rainbow is an effective distributed scheme for learning how to route packets around connectivity holes, achieving remarkable delivery ratio and latency performance. Our simulation results also show better performance than that of two recent proposals for routing around dead ends by Rührup and Stojmenovic [6].
4. The critical metrics of packet delivery ratio and end-to-end (E2E) latency are further investigated through experiments in an outdoor 40-node testbed of TinyOS-based sensor nodes. Besides validating our simulation model, the obtained results confirm the effectiveness of ALBA-R in supporting long-lived and reliable wireless sensor networking in practice.

A succinct version of this paper has appeared in [7]. The current version presents a considerably larger set of experiments and comparisons with previous solutions. Supplemental material, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TPDS.2013.60, provides proof of correctness of the Rainbow mechanism, further simulation experiments, and detailed results from testing the deployment of a 40-node network in a vineyard outside of Roma, Italy. Some results on ALBA resilience to localization errors have appeared in [8].

The paper is organized as follows: Section 2 reviews the state of the art on geographic routing and handling dead ends. ALBA-R is described in detail in Section 3 (ALBA) and Section 4 (Rainbow). Section 5 shows the results of an extensive ns2-based performance evaluation of our protocol. It includes a comparison of ALBA-R with geographic (GeRaF) and nongeographic (IRIS) cross-layer routing protocols, and a demonstration of the effectiveness of ALBA-R in efficiently handling dead ends even in presence of localization errors. The section also contains a comparative performance evaluation of Rainbow and Rotational Sweep (RS), a recently introduced set of mechanisms to route packets around connectivity holes. Conclusions are provided in Section 6.

2 Related Work

According to its first and simplest formulation, geographic routing concerns forwarding a packet in the direction of its intended destination by providing maximum per-hop advancement [9], [10]. In dense networks, this greedy approach is quite successful, since nodes are likely to find a path toward the sink traversing a limited number of intermediate relays. Conversely, in sparse networks, packets may get stuck at dead ends, which are located along the edge of a connectivity hole, resulting in poor performance. A number of ideas have, therefore, been proposed to address the problem of routing around dead ends. A first set of approaches stems from the work of Kranakis et al. [11]. WSN topologies are first "planarized" [12]. Geographic routing over planarized WSNs is then obtained by employing greedy routing as long as possible, resorting to planar routing only when required, for example, to get around connectivity holes. Heuristic rules are then defined for returning to greedy forwarding as soon as next-hop relays can be found greedily. Examples of this approach include [13], [14], [15], [16], [17], [18]. Solutions based on planarization have several drawbacks. First of all, a spanner graph of the network topology needs to be built (and maintained in the presence of node dynamics), and this incurs non-negligible overhead. Planar routing may then require the exploration of large spanners before being able to switch back to the more efficient greedy forwarding, thus imposing higher latencies [19]. Moreover, in realistic settings, localization errors and nonideal signal propagation may lead to disconnected planar graphs or to topology graphs that are nonplanar. This is because spanner formation protocols assume that the network topology is modeled by a UDG, and the correctness of the approach cannot be guaranteed when this is not the case, as in most realistic situations. To make planarization work on real networks, a form of periodic signaling must be implemented to check that no links cross, as performed by the Cross-Link Detection Protocol (CLDP) [20]. However, this is a transmission-intense solution for WSNs, which eventually affects the network performance. For a comprehensive overview of planar graph routing, the reader is referred to the survey by Frey et al. [21].

A different class of solutions for handling dead ends is based on embedding the network topology into coordinate spaces that decrease the probability of connectivity holes. This category includes algorithms using virtual coordinates [22], [23], [24], [25], and those that perform some sort of topology warping [26]. In the former case, the coordinates of each node are the vector of the hop distance between the node and each of a set of beacons. Greedy forwarding is typically performed over the virtual coordinates space. This decreases the occurrence of dead ends, but does not eliminate them. Topology warping schemes are based on iteratively updating the coordinates of each node based on the coordinates of its neighbors, so that greedy paths are more likely to exist. These approaches are referred to as "geographic routing without location information," as they do not require accurate initial position estimates. Both methods, however, present a non-negligible probability that packets get stuck in dead ends.

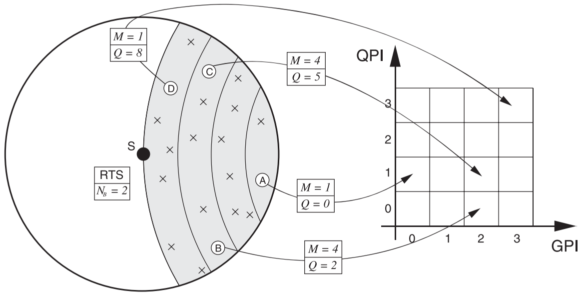


Fig. 1. Computing QPI and GPI values.

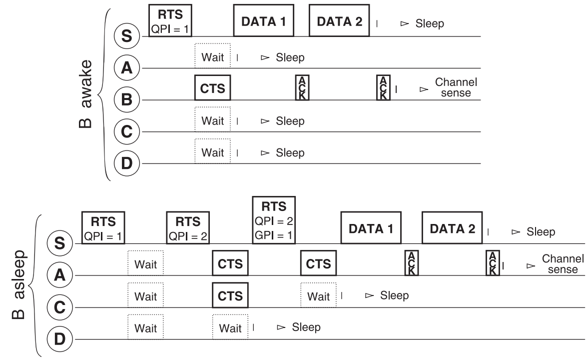


Fig. 2. ALBA handshakes.

RS is a recent contention-based protocol presented by Rührup and Stojmenovic [6] to route packets around connectivity holes without requiring planarization. The protocol is designed to complement any greedy forwarding algorithm (including ALBA) by determining a next hop relay through a timer-based contention. The relay is chosen so that a traversal path is found that ensures progress after a greedy failure. Upon receiving a request-to-send (RTS), each possible candidate relay starts a timer whose value (called the *delay function*) is computed based on the relative position of the candidate, the sender, and the predecessor of the sender, i.e., the node that selected the sender as relay. Specifically, the candidate selects a delay proportional to the time it takes for being hit by a *sweep curve* (SC) that rotates counterclockwise hinged at the sender from the starting line between predecessor and sender. (The candidate receives information about predecessor and sender coordinates in the RTS.) RS is based on two delay functions, namely, *sweep circle* and *twisting triangle* (TT), providing different lengths for traversing paths, and is shown to achieve guaranteed delivery in UDGs. As such, however, it is not generally applicable, and it can be detrimentally affected by localization errors.

3 The Adaptive Load-Balancing Algorithm

The protocol we propose in this paper, ALBA, is a cross-layer solution for convergecasting in WSNs that integrates awake/asleep schedules, MAC, routing, traffic load balancing, and back-to-back packet transmissions. Nodes alternate between awake/asleep modes according to independent wake-up schedules with fixed duty cycle d. Packet forwarding is implemented by having the sender polling for availability its awake neighbors by broadcasting an RTS packet for jointly performing channel access and communicating relevant routing information (cross-layer approach). Available neighboring nodes respond with a clear-to-send (CTS) packet carrying information through which the sender can choose the best relay. Relay selection is performed by preferring neighbors offering "good performance" in forwarding packets. Positive geographic advancement toward the sink (the main relay selection criterion in many previous solutions) is used to discriminate among relays that have the same forwarding performance. Every prospective relay is characterized by two parameters: the *queue priority index* (QPI), and the *geographic priority index* (GPI). The QPI is calculated as follows: The requested number of packets to be transmitted in a burst (back-to-back transmissions) is N_B, and the number of packets in the queue of an eligible relay is Q. The potential relay keeps a moving average M of the number of packets it was able to transmit back-to-back, without errors, in the last κ forwarding attempts.[1] The QPI is then defined as $\min\{\lceil (Q + N_B)/M \rceil, N_q\}$, where N_q is the maximum allowed QPI. The QPI has been designed so that congested nodes (with a high queue occupancy Q) and "bad" forwarders (experiencing high packet transmission error, i.e., with a lower M) are less frequently chosen as relays. The selection of relays with low QPI, therefore, aims at decreasing latency at each hop by balancing the network load among good forwarders.

Based on positioning information (as provided to a node by GPS, or computed through some localization protocol [27], [28]), and on the knowledge of the location of the sink, each node also computes its GPI, which is the number of the geographic region of the forwarding area of the sender where a potential relay is located. The numbering of GPI regions ranges from 0 to $N_r - 1$. Numbers are assigned so that the higher the number of the region, the further from the sink are the nodes it contains, i.e., nodes in region 0 provide the maximum advancement toward the sink. An example of QPI and GPI assignment is provided in Fig. 1. The sender S is represented by a black circle, while crosses and white circles denote asleep and awake neighbors, respectively. Awake nodes are the only ones available at the time the RTS is broadcast. The forwarding area is colored light gray, and the GPI regions are delimited by arcs centered at the sink (not shown in the figure). In this example, the source S wants to send a burst of $N_B = 2$ packets. Among the awake nodes, A has an empty queue, but also a bad forwarding record ($M = 1$); hence, its QPI is 2. Nodes B and C have both $M = 4$. However, B has a smaller queue and therefore its QPI is 1, whereas that of C is 2. A sender node queries neighbors in increasing order of QPI. The sender performs channel sensing prior to packet transmission, to make collisions with ongoing handshakes unlikely. After channel sensing, the sender proceeds as depicted in Fig. 2. It broadcasts a first RTS, asking eligible forwarders to compute their QPI and GPI, and inviting answers from nodes whose QPI is 1. The RTS contains all the information required by the relays to compute their QPI and GPI, namely, the location of the sender, the location of the sink, and the length of the data burst N_B. Only nodes

1. In our implementation, the computation of M is made easier by having the receiver acknowledge separately every packet of the burst.

with $\text{QPI} = 1$ are allowed to answer the first RTS with a CTS packet. If nobody answers, other RTS packets are broadcast calling for answers by nodes having an increasingly higher QPI. If a single node answers, it is immediately sent to the data packets, which it ACKs one by one. In case more nodes with the same requested QPI respond, ties are broken via the GPI. To select the node with the best GPI, a new RTS packet is broadcast calling for answers only from nodes whose GPI is 0, i.e., from nodes providing the highest advancement. If no nodes are found, successive RTS are broadcast calling for nodes with progressively higher GPI. Further ties from multiple nodes replying with the same (QPI,GPI) pair are broken by a binary splitting tree collision resolution mechanism. This relay selection process can fail in two cases: 1) If no node with any QPI is found, or 2) if the contention among nodes with the same QPI and GPI is not resolved within a maximum number of attempts N_{MaxAtt}. Both situations cause the sender to back off. If the sender backs off more than N_{Boff} times, the packet is discarded.

Let us assume that node B is awake and that it is the only available relay whose QPI is 1 after the first RTS (upper part of Fig. 2; all other neighbors are asleep). Node B replies to S with a CTS and is selected as a relay. In the case when B is asleep (lower part of Fig. 2), only A, C, and D would be available. In this case, no node with QPI equal to 1 exists, so that the first RTS is not answered. Both A and C answer the second RTS, as both have the QPI equal to 2. The second phase (best GPI search) is then started, which terminates with the selection of node A, whose GPI is equal to 0.

Once a relay is selected, a burst of data packets is sent (as many as the relay can queue, up to N_B), and each packet is individually acknowledged.[2] If the ACK for one of the packets is missing, the sender stops the transmission of the burst, rescheduling the unacknowledged packet and the following ones in the burst for a later time, after a back off period. The sender updates its expected maximum burst length M, by taking into account the number of correct packets that have been received (if errors occurred), or by optimistically assuming that a certain burst of length M_B packets was received correctly, even if $N_B < M_B$ (in case of no errors). M_B is a tunable protocol parameter limiting the maximum number of packets that can be transmitted back-to-back in a burst.

Nodes that lost the contention overhear data transmissions, understand from the header that they have not been selected as relays, and go back to sleep. Similarly, the nodes that during a handshake realize that they will not be selected as relays go to sleep immediately.

We have observed that significant performance improvements can be obtained by allowing awaking nodes to join a relay selection phase that has already started. Upon waking up, nodes enter the QPI search phase and can answer an RTS packet with a CTS, provided their QPI index is lower than or equal to the one that is currently being searched for. When a nonempty QPI region is queried and one or more eligible forwarders answer the RTS, the best GPI search starts, and the set of eligible forwarders is frozen (no node that wakes up after this time can enter the contention). This choice has been made to favor a fast relay selection once a region with active neighbors has been found.

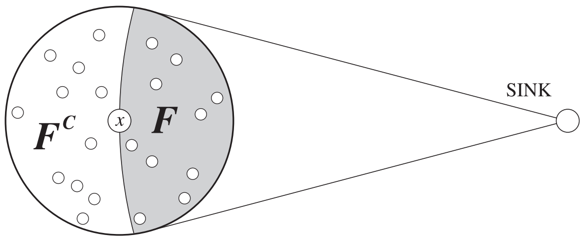


Fig. 3. The F and F^C regions.

4 The Rainbow Mechanism and ALBA-R

In this section, we describe *Rainbow*, the mechanism used by ALBA to deal with dead ends. The basic idea for avoiding connectivity holes is that of allowing the nodes to forward packets away from the sink when a relay offering advancement toward the sink cannot be found. To remember whether to seek for relays in the direction of the sink or in the opposite direction, each node is labeled by a color chosen among an ordered list of colors and searches for relays among nodes with its own color or the color immediately before in the list. Rainbow determines the color of each node so that a viable route to the sink is always found. Hop-by-hop forwarding then follows the rules established by ALBA.

More formally, let x be a node engaged in packet forwarding. We partition the transmission area of x into two regions, called F and F^C, that include all neighbors of x offering a positive or a negative advancement toward the sink, respectively (see Fig. 3).

When x has a packet to transmit it seeks a relay either in F or F^C according to its *color* C_k, selected from the set of colors $\{C_0, C_1, C_2, C_3, \ldots\}$. Nodes with even colors $C_0, C_2, \ldots$ search for neighbors in F (positive advancement). Nodes with odd color $C_1, C_3, \ldots$ search for neighbors in F^C (negative advancement). Nodes with color C_k, $k \geq 0$, can *volunteer as relays* only for nodes with color C_k or C_{k+1}. Nodes with color C_k, $k > 0$, can only *look for relays* with color C_{k-1} or C_k. Finally, nodes with color C_0 can only look for relays with color C_0.[3] The nodes assume their color as follows: Initially, all nodes are colored C_0 and function according to the standard ALBA rules (see Section 3). If no connectivity holes are encountered, all nodes remain colored C_0 and always perform greedy forwarding. Since the nodes on the boundary of a hole cannot find relays offering positive advancement, after a fixed number N_{hsk} of failed attempts, they infer that they may actually be dead ends and correspondingly increase their color to C_1.[4] According to

2. The choice of individual acknowledgments versus a cumulative one resulted from an investigation showing that the actual number of packets that can be transmitted back-to-back depends on the current load, i.e., it is unpredictable. Individually acknowledging packets favors adjusting the number of packets in the burst dynamically. In addition, individual ACKs avoid adding long carrier sensing, which would otherwise be needed to deal with hidden terminals in networks with nodes operating at low duty cycle.

3. The relay search takes place as in ALBA, properly extended so that the selection of C_{k-1} nodes is favored, i.e., C_{k-1} nodes are polled before those with color C_k.

4. N_{hsk} consecutive attempts are necessary for a node to decide whether it is a dead end or not. N_{hsk} has been tuned by considering the worst-case number of attempts required to safely switch color at a given duty cycle. No false positives were observed in our experiments.

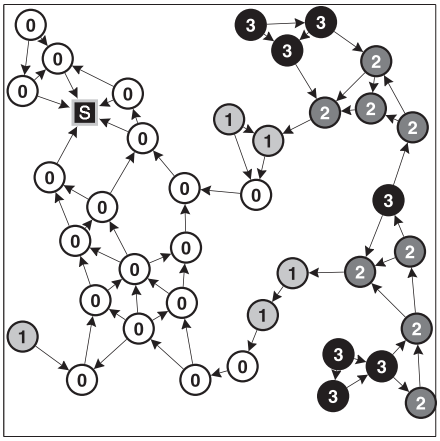


Fig. 4. Rainbow coloring.

Rainbow, C_1 nodes will send the packet away from the sink by searching for C_0 or C_1 nodes in region F^C. If a C_1 node cannot find C_1 or C_0 nodes in F^C, it changes its color again (after N_{hsk} failed forwarding attempts), becoming a C_2 node. Therefore, it will now look for C_2 or C_1 relays in F. Similarly, a C_2 node that cannot find C_2 or C_1 relays in F turns C_3 and starts searching for C_3 or C_2 nodes in F^C. This process continues until all nodes have converged to their final color. Note that, at this point, any node that still has color C_0 can find a greedy route to the sink, i.e., a route in which all nodes offer a positive advancement toward the sink. In other words, once a packet reaches a C_0 node, its path to the sink is made up only of C_0 nodes. Similarly, packets generated or relayed by C_k nodes follow routes that first traverse C_k nodes, then go through C_{k-1} nodes, then C_{k-2} nodes, and so on, finally reaching a C_0 node. As soon as a C_0 node is reached, routing is performed according to ALBA greedy forwarding. A sample topology where four colors are sufficient to label all nodes is given in Fig. 4. In the figure, the numbers in the nodes indicate the color they assume. Higher colors are rendered with darker shades of gray. A proof of the correctness of the Rainbow mechanism is given in the supplemental material document, available online. That proof, including convergence of the coloring mechanism in finite time and the loop-freedom of the determined routes, is performed through mathematical induction on the number h of changes of color in the route from a node to the sink. ALBA-R correctness is not affected by the presence of localization errors or by the fact that the topology graph is not a UDG, showing that our protocol is robust to localization errors and realistic propagation behaviors.

5 Performance Evaluation

5.1 Simulation Scenarios and Metrics

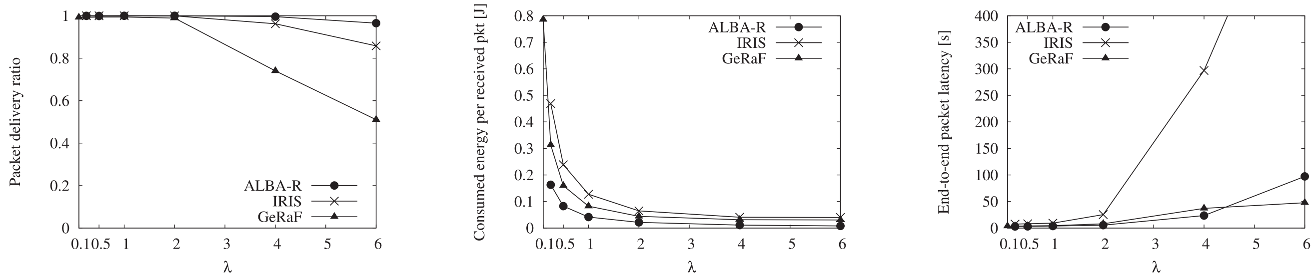
All investigated protocols have been implemented in the ns2 simulator [29]. We used the simulator Friis propagation loss model. The transmission power has been set to achieve successful delivery to nodes within a distance equal to the selected transmission range. The MAC layer is based on CSMA/CA with energy levels and packet reception thresholds typical of carrier sensing. We consider networks with n nodes, where n ranges in {100,200,600}. The sensors are randomly and uniformly deployed in a square area of size 320×320 m^2. The node transmission range is set to 40 m. Therefore, the average degree of a node ranges between 5 and 30 nodes, which spans a wide range of realistic values. Nodes go to sleep and wake up according to independent awake-asleep schedules with a fixed duty cycle $d = 0.1$. The energy consumption when transmitting, receiving, and when in sleep mode follows the first-order energy model described in [30]. The energy E_{RX} consumed for receiving a bit is constant, while the energy consumed for transmitting a bit is $E_{TX}(r) = E_{TX_e} + E_{TX_a}(r)$, where E_{TX_e} is the energy needed by the transmitter circuitry (and is set equal to E_{RX}). $E_{TX_a}(r) = \varepsilon_a \cdot r^2$ models the energy required to cover the transmission range r. We choose the value of ε_a as in [30]. The energy cost when in sleep mode is a very low, nonzero value, that we set equal to $1/1,000$ of the energy spent for receiving. According to this energy model, $E_{TX_a}(r) > E_{TX_e}$ for $r > 22.5$ m. Data traffic is generated according to a Poisson process of intensity λ packets per second over the whole network. Each packet is randomly and uniformly assigned to a source, excluding nodes that are one hop from the sink. The chosen source queues the assigned packets and transmits them as soon as possible. The maximum queue length per node is set to 20 packets. A newly generated packet is accepted by the source only if its buffer is not full. The traffic rate λ varies from 0.25 to 6 packets per second. Data packets are all 250B long. The length of control packets is 25B. The channel data rate is 38.4 kbps.[5] ALBA parameters κ and M_B have been set to 5.

All our results have been obtained by averaging the outcomes of 100 simulations, each running for 30,000 s, each time on a different connected topology. The resulting confidence interval of our results has a width within 5 percent of the value shown. Since we are interested in steady-state performance, all metrics have been collected after 1,200 s from the start of each simulation run.

We have investigated the following metrics: the *normalized node energy consumption*, defined as the ratio between the total energy consumed by all nodes over a given time and the energy that the nodes would consume by strictly following the duty cycle, if there were no packets to transmit and receive; the *per packet energy consumption*, defined as the average amount of energy spent by all nodes to successfully deliver a packet to the sink; the *packet delivery ratio*, defined as the fraction of packets that are successfully delivered to the sink; and the *end-to-end latency*, defined as the time from packet generation to its delivery to the sink. The latter metric is computed only for successfully delivered packets.

We perform three sets of experiments. The first set concerns moderately high-density network scenarios, where dead ends do not occur (higher density results are shown in the supplemental material document, available online). In this setting, we compare the performance of ALBA to that of other cross-layer protocols specifically designed for high-density WSNs (see Section 5.2). The

5. These values are those of the EyesIFX ver. 2 motes, developed by Infineon Technologies, a typical representative of TinyOS-based sensor nodes operating in the 868 MHz band. ALBA-R was initially implemented and tested on these platforms.



(a) Packet delivery ratio. (b) Per packet energy consumption. (c) End-to-end packet latency.

Fig. 5. Performance comparison of ALBA, GeRaF, and IRIS in networks with 600 nodes.

effectiveness of Rainbow in dealing with connectivity holes is demonstrated on scenarios with dead ends (sparse networks) in Section 5.3. In Section 5.4, we compare Rainbow with Rotational Sweep, the dead end handling mechanisms presented in [6]. We implemented both delay functions: Sweep Circle and Twisting Triangle. Finally, Section 5.5 discusses the performance of ALBA-R in networks affected by localization errors.

5.2 ALBA versus GeRaF and IRIS

We compare ALBA with two protocols that are exemplary of cross layer routing in dense WSNs, i.e., in networks where dead ends are not likely to occur. The first protocol is GeRaF, one of the first cross layer protocols based on geographic greedy forwarding [4]. The other protocol is IRIS [5], which performs convergecasting based on a hop count metric and on a local cost function. (For details on the description of the two protocols, the reader is referred to the original papers and to the supplemental material document, available online.)

Results are shown in Fig. 5 for networks with 600 nodes. ALBA achieves the best performance in terms of all investigated metrics (packet delivery ratio, per packet energy consumption, and end-to-end latency). It scales to increasing traffic much better than the other two protocols because of the effectiveness of the QPI-based selection scheme in balancing the traffic among relays, of its low overhead, and its being able to aggregate packets into burst. The ability of ALBA in balancing traffic is shown in Fig. 6 for a given topology with 300 nodes. It depicts nodes surrounded by "halos" colored depending on the amount of packets they handle. Nodes closer to the sink (square), as expected, are more congested (darker "halos"). However, traffic is fairly shared by the nodes.

Among the three compared protocols, GeRaF shows the worst performance. In GeRaF, a node currently handling a packet stops volunteering as a relay. Therefore, as traffic grows, it becomes harder and harder to find relays, resulting in high number of retransmissions and packet loss. Since GeRaF is based only on geographic advancement, the nodes tend to pick less reliable relays. IRIS finds routes that are shorter than those traveled by packets in ALBA. However, it shows worse latency performance since, although longer, ALBA routes are faster because of its QPI-based relay selection method. ALBA is also the most lightweight protocol among the three.

A detailed analysis of the relative performance of the protocols, together with a thorough discussion of the impact of the different design choices on performance, is included in the supplemental material document, available online.

5.3 ALBA-R on Sparse Topologies

This set of experiments concerns the performance of Rainbow. We only consider ALBA-R$_h$, $h = 0, 1, \dots, \infty$, ALBA-R$_0$ being ALBA without Rainbow, ALBA-R$_h$, $h > 0$, being ALBA-R where nodes cannot change color after reaching color C_h, and ALBA-R$_\infty$ being ALBA-R as described.

Results refer to scenarios with 100 and 200 nodes. Each node has a limited number of neighbors (sparse networks), dead ends occur, and greedy forwarding has been shown to fail often. For example, with 200 nodes, only about half of the nodes are colored C_0 and can, therefore, greedily deliver packets to the sink. This percentage falls to 10 percent in topologies with 100 nodes.

Fig. 7 depicts the average packet delivery ratio, the end-to-end packet latency, the normalized energy consumption per node, and the normalized overhead incurred by ALBA-R$_h$, for $h = 0, 1, \infty$. For $h = \infty$, all packets are delivered to the sink (except at very high load, due to congestion). However, from Fig. 7a, we note that a few colors suffice to greatly improve the packet delivery ratio: 99 percent (74 percent) of the generated traffic is correctly delivered when $n = 200$ ($n = 100$), and $h = 1$. By way of contrast, in ALBA-R$_0$, this percentage decreases to 85 percent (48 percent) or less. It may seem counterintuitive that the percentage of the packets discarded by ALBA-R$_0$ is higher than the average percentage of non-C_0

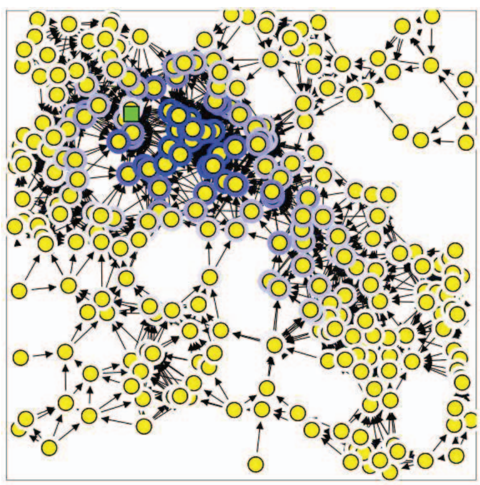
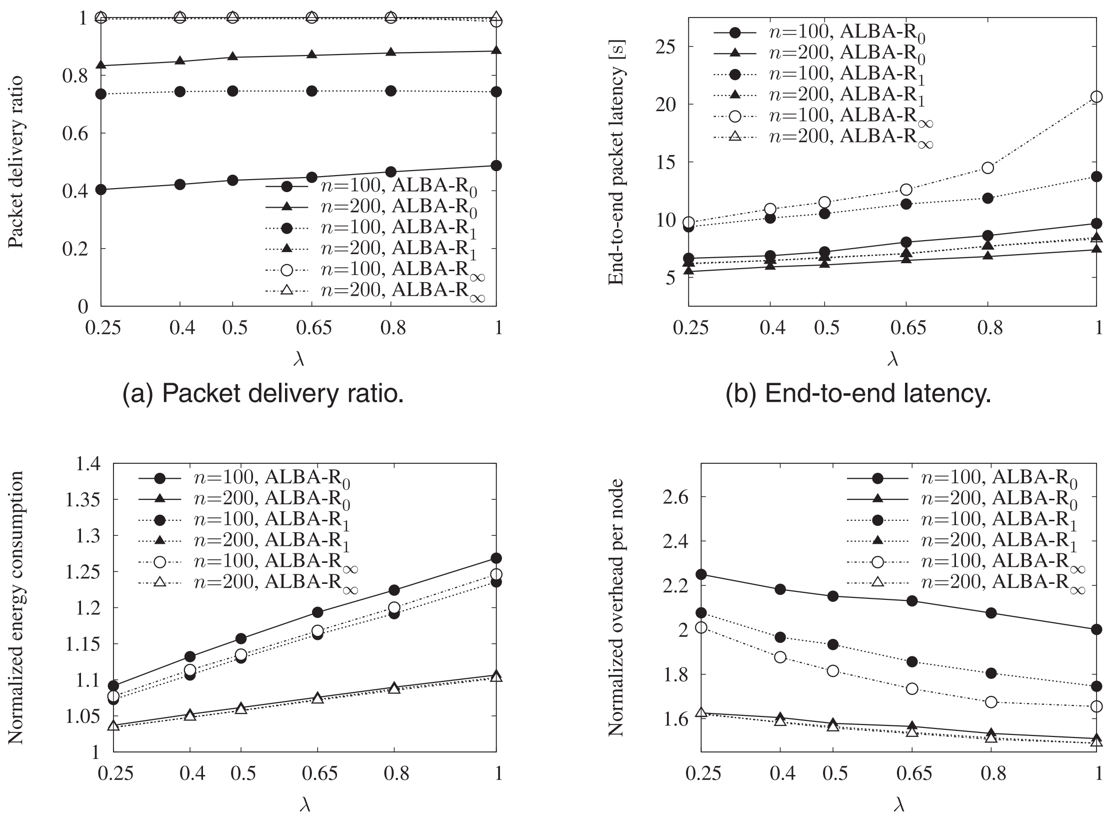


Fig. 6. ALBA distribution of the traffic among nodes.



(a) Packet delivery ratio. (b) End-to-end latency. (c) Energy consumption per node. (d) Overhead per node.

Fig. 7. Performance of ALBA-R$_h$, $h = 0, 1, \infty$ on sparse topologies ($n = 100, 200$).

nodes. This is because C_0 nodes may send some of their packets to nodes leading to dead ends; such packets will ultimately get stuck, since in ALBA-R$_0$, no node coloring (and subsequent packet rerouting) takes place.

The better packet delivery ratio observed in Fig. 7a for greater h suggests that an increasingly larger fraction of nodes can correctly route their packets back to C_0 nodes, and from there to the sink. As expected, the end-to-end latency increases in this case, because farther nodes send their packets to the sink through longer routes. It is, therefore, more interesting to comment on the end-to-end latency experienced by the packets generated by C_0 nodes, as h increases. This comparison is shown in Fig. 7b, where we observe that ALBA-R$_\infty$ and ALBA-R$_1$ better packet delivery ratios translate into higher but reasonable end-to-end latency for the packets of C_0 nodes (the curves of ALBA-R$_\infty$ and ALBA-R$_1$ are hard to distinguish in the $n = 200$ case as they basically overlap). The limited latency increase shows that, despite the larger amount of traffic coming from the farther portions of the network (bridged by node coloring), ALBA QPI-based relay selection can still successfully balance traffic among nodes. The main drawback is a longer average route length, which is reasonable in light of the advantage yielded by load balancing. For example, for networks with 200 nodes, the length of routes through C_0 nodes is up to 5.5 percent (5.3 percent) for $h = \infty$ ($h = 1$) higher than for $h = 0$. When $n = 100$, the increase is up to 22.4 percent (21.8 percent) for $h = \infty$ ($h = 1$).

A separate study on the routing performance of re-routed packets (i.e., originated by non-C_0 nodes) is provided in Tables 1 and 2, which list the average number of traversed hops and the end-to-end latency of such packets in the case $h = \infty$. For example, around 14.8 hops are required in topologies with $n = 100$ nodes at $\lambda = 1$. The average length of purely C_0 routes is 7.5 hops in the same scenario: This corresponds to the latency increase from 9.5 to about 21 s observed in Fig. 7b at $\lambda = 1$.

Despite the increased traffic, the amount of energy consumption and overhead is smaller in ALBA-R$_1$ and in ALBA-R$_\infty$ than in ALBA-R$_0$ (see Figs. 7c and 7d). Nodes no longer waste time and energy searching for relays where packets will ultimately get stuck and discarded. It is also interesting to note that the overhead in sparse networks decreases with increasing traffic for any number of colors used, as observed in Fig. 7d. The reason is that the growing traffic causes the average node queue length to increase, which in turn triggers back-to-back packet transmissions more often. Sharing the relay selection overhead among

TABLE 1
Route Length for Re-Routed Packets [hops], $h = \infty$

	$\lambda = 0.25$	$\lambda = 0.5$	$\lambda = 1$
$n = 100$	13.46	14.61	14.81
$n = 200$	12.47	12.72	12.93

TABLE 2
Latency for Re-Routed Packets [s]

	$\lambda = 0.25$	$\lambda = 0.5$	$\lambda = 1$
$n = 100$	23.05	26.82	74.51
$n = 200$	10.96	12.1	14.47

TABLE 3
Comparison between Rainbow and Rotational Sweep

Number of nodes	*Scheme*	*PDR* (%)	*E2E latency* (s)	*Per packet energy consumption* (J)	*Stretch factor*
100	Rainbow	100	14.85	0.029	1.21
100	SC	81.5	149.37	0.046	4.38
100	TT	81.8	143.05	0.046	4.39
200	Rainbow	100	6.19	0.082	1.43
200	SC	98.5	23.94	0.088	2.98
200	TT	98.7	22.59	0.088	3.08

multiple packets ultimately results in lower overhead per packet, as observed in denser networks.

5.4 Comparison with Rotational Sweep

We have compared Rainbow with a recently proposed mechanism for handling dead ends in WSNs, namely, Rotational Sweep (see [6]). Both path traversal schemes of Rotational Sweep, i.e., SC and TT, have been implemented in ns2 and run on top of ALBA. We consider sparse topologies (networks with 100 and 200 nodes). Results are displayed for $\lambda = 0.25$. All other parameters are set as listed above.

We compare the three schemes with respect to the following metrics: PDR, E2E latency, per packet energy consumption, and stretch factor. The results in Table 3 show that Rainbow successfully delivers all generated packets, whereas the traversal schemes of Rotational Sweep suffer a packet loss ranging from 2 to 19 percent. This is essentially due to the higher congestion affecting Rotational Sweep, which results from longer routes and from a less effective data packet aggregation into bursts. When recovering from a dead end, SC and TT select the next hop relay based on the position of the predecessor of the sender from which the packet is received. Packets received by the sender from different predecessors are, therefore, likely to be forwarded to different relays, making the back-to-back transmissions of ALBA less effective. Rainbow is also able to deliver packets successfully to the sink with much shorter routes than those of Rotational Sweep. The reason is that the stretch factor of Rotational Sweep degrades when the best relays cannot be picked because they are asleep. Rainbow instead selects among relays that are awake based on their color, which ensures a limited route length increase independently of the nodes that are currently awake. The effectiveness of Rainbow in delivering all packets to the sink pays off also in terms of energy consumption per delivered packet. Rainbow energy consumption per packet is 38 percent lower than that of Rotational Sweep in the most critical case ($n = 100$). The improvement is 5 percent in networks with 200 nodes.

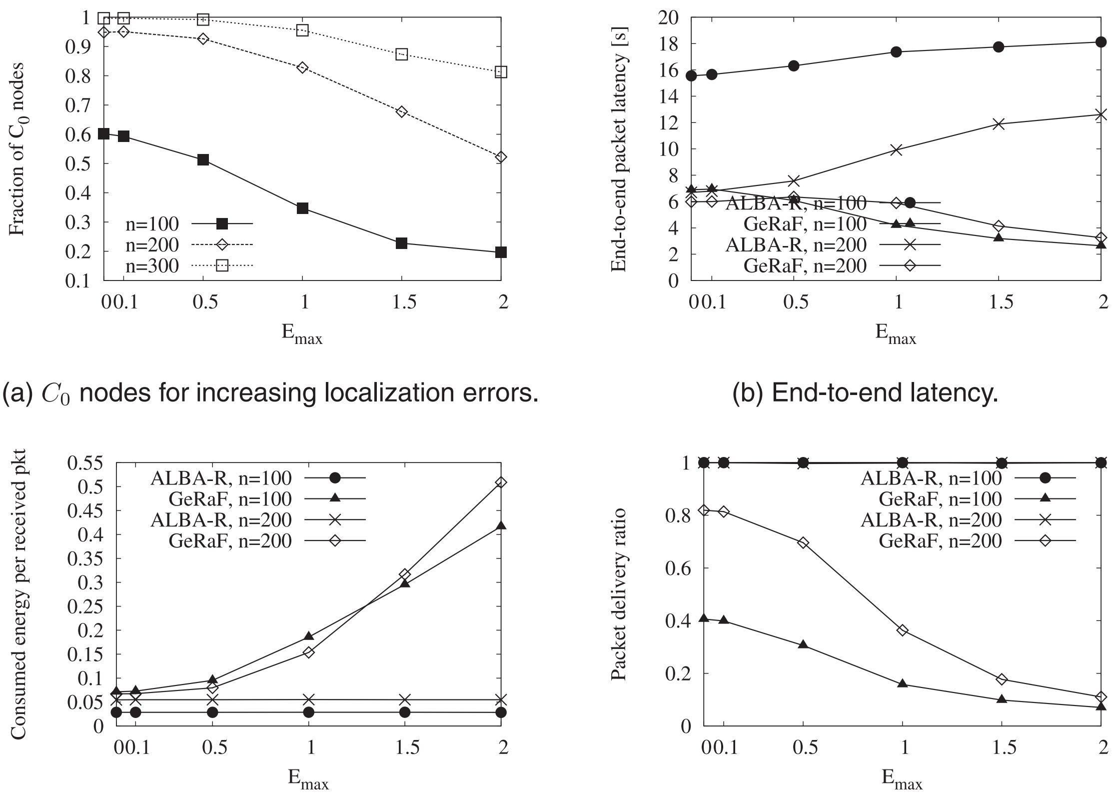
5.5 Resilience to Localization Errors

We have tested the impact of localization errors on the performance of Rainbow. To this purpose, we have run simulations in networks with 100, 200, and 300 nodes, at traffic $\lambda = 0.25$, where the estimated coordinates of each node have been obtained by randomly and uniformly selecting a point in the circle centered at the node real coordinates with radius rE_{max}. In our simulations, E_{max} ranges between 0.1 and 2 (so that the error ranges from one tenth to twice the node transmission range r). While neighbors relationships (i.e., the network topology) are determined by real coordinates, each node identifies the neighbors closer to the sink (and therefore its color) based on its own and the neighbors estimated position (i.e., the position estimated through a localization protocol affected by error).

The results in Fig. 8 show that ALBA-R can successfully deliver all generated packets to the sink, even in case of high localization errors. The only impact on the performance is a limited increase in route length. Specifically, Fig. 8a shows that increasing the localization error decreases the number of nodes colored C_0, requiring a larger number of packets to go through longer routes. The impact on the performance is however very limited. For instance, when $n = 100$, the ratio between the average route length and the shortest path (stretch factor) is 1.19. When $E_{max} = 1$ (2), the stretch factor increases only slightly, to 1.22 (1.23). Figs. 8b, 8c, and 8d investigate the performance of ALBA-R in the same scenario, in terms of end-to-end latency, per-packet energy consumption, and packet delivery ratio, respectively. Fig. 8b confirms the increase in latency experienced by packets routed by ALBA-R in presence of higher localization errors. All other metrics are, however, basically unaffected. In particular, Fig. 8d displays ALBA-R packet delivery ratio, which is always 100 percent. This is by no means a straightforward result: The performance of a typical georouting protocol such as GeRaF (also shown in the figure), instead, is significantly degraded by high localization errors. When $E_{max} = 2$, for instance, GeRaF is able to successfully deliver no more than 10 percent of the generated packets, suffering also a noticeable increase in energy consumption.

6 Conclusions

In this paper, we have proposed and investigated the performance of ALBA-R, a cross-layer scheme for convergecasting in WSNs. ALBA-R combines geographic routing, handling of dead ends, MAC, awake-asleep scheduling, and back-to-back data packet transmission for achieving an energy-efficient data gathering mechanism. To reduce end-to-end latency and scale up to high traffic, ALBA-R relies on a cross-layer relay selection mechanism favoring nodes that can forward traffic more effectively and reliably, depending on traffic and link quality. Results from an extensive performance evaluation comparing ALBA-R, GeRaF, and IRIS show that ALBA-R achieves remarkable delivery ratio and latency and can greatly limit energy consumption, outperforming all previous solutions considered in this study. The scheme designed to handle dead ends, Rainbow, is fully distributed, has low overhead, and makes it possible to route packets around connectivity holes without resorting to the creation and maintenance of planar topology graphs. Rainbow is shown to guarantee packet delivery under arbitrary localization errors, at the sole cost of a



(a) C_0 nodes for increasing localization errors.

(b) End-to-end latency.

(c) Energy consumption.

(d) Packet delivery ratio.

Fig. 8. Comparison of ALBA-R and GeRaF in sparse networks with localization error.

limited increase in route length. The comparison with Rotational Sweep, a set of recently proposed mechanisms for avoiding connectivity holes, shows that Rainbow provides a more robust way of handling dead ends and better performance in terms of end-to-end latency, energy consumption, and packet delivery ratio. Testbed experiments have validated our simulation model and have confirmed ALBA-R to be an energy-efficient protocol with remarkable throughput and limited latency, which makes it suitable for real-world applications.

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