Localization Error-resilient Geographic Routing for Wireless Sensor Networks

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***Abstract*—This paper concerns the demonstration of the resilience to localization errors of ALBA–R, a protocol for geographic routing in wireless sensor networks (WSNs). In particular, we show that thanks to a simple yet effective nodal coloring mechanism for handling nodal connectivity holes, ALBA–R achieves the further desirable benefit of being totally resilient to localization errors, which are unavoidable in WSNs. Via ns2-based simulations we show that independently of fundamental network parameters such as network density, and also independently of errors in nodal coordinate estimations as high as the node transmission radius, ALBA–R is successful in delivering all generated packets while incurring reasonable degradation for metrics such as route-length and end-to-end latency and still remaining and energy efficient protocol.**

I. INTRODUCTION

Wireless sensor nodes localization [1], [2] provides sensor nodes with the necessary information for associating sensed events to their place of occurrence, an invaluable information for the users of the data. Equally important, it enables *geographic routing* [3], i.e., forwarding strategies where the next hop relay for a packet is selected according to the geographic advancement that this relay is able to provide toward the packet destination (the *sink*).

The vast majority of works on geographic forwarding assume that the location information available at each node is perfect. This is of course quite a strong assumption, since in practice only a rough estimate of a node location is available. Few papers are available that investigate the impact of localization errors on geographic routing [4]–[9]. All these works evaluate the performance of various routing protocols in presence of localization errors. It is shown that even errors as small as one tenth of the node transmission radius r can lead to incorrect, non-recoverable geographic routing with noticeable performance degradation. Some of these papers also propose modifications to protocols for geographic forwarding that attenuate the effects of the errors on localization [10]. However, these new solutions are either still suffering the detrimental effects of inaccurate coordinates on geographic routing, or they achieve good performance at the expenses of using face routing, that in turn greatly suffers of localization errors [11].

In this paper we show that geographic forwarding protocols that deal with the problem of handling connectivity holes in the network topology provide an effective mechanism to obviate the inaccuracies of localization mechanisms. In particular, we consider a cross-layer approach to geographic routing, termed ALBA–R for Adaptive Load-Balanced Algorithm [12], [13], that uses a clever coloring mechanism called "Rainbow" (hence the –R extension in the name) for handling connectivity holes. We show that this same mechanism provides total resilience to localization errors, independently of the network density, and of how inaccurate are the localization measurements. Via ns2-based simulations that consider realistic WSNs parameters and random localization errors as high as the node transmission radius r we demonstrate that ALBA–R is able to deliver basically 100% of the generated packets. Only when congestion builds up and packet loss is unavoidable we notice that packets start being discarded. However, in the considered scenarios, the percentage of the dropped packets is always below 2%. ALBA–R performance is compared to that of *GeRaF* [14], a geographic routing protocol for WSNs that is considered the paradigm protocol for geographic forwarding with no connectivity hole handling mechanism. Our results show that, while GeRaF greatly suffers the inaccuracies of localization, even when they are small, ALBA–R provides total delivery of all generated packets while incurring reasonable performance degradation in terms of other crucial metrics such as route length and end-to-end packet latency. Through measurements of the energy needed to deliver packets we also show that despite the mentioned performance degradation, ALBA–R still remains an energy efficient protocol.

The rest of the paper is organized as follows. We describe ALBA–R in the next section. The following Section III presents our simulation-based investigation of the localization error resiliency of ALBA–R and compares its performance with that of GeRaF. Section IV concludes the paper.

II. ALBA AND THE RAINBOW MECHANISM

In this section we review ALBA–R, and in particular the RAINBOW mechanism.

As a forwarding method ALBA implements a series of features that are highly desirable for WSNs. For instance, nodes are allowed to follow asynchronous awake/asleep schedules (duty cycle), so that they can save the energy that would be otherwise wasted on idle communication time. In this scenario, routing happens in the following way. When a node has a packet to transmit it initiates a contention, looking for a relay

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between its awake neighbors (eligible relays) in the direction of the sink. All the eligible relays of a node compute two values, namely, the Geographic Priority Index (GPI), which indicates the advancement toward the sink they can provide for the packets, and the Queue Priority Index (QPI), which measures how fast the node can relay the packets to the destination (the QPI depends on the status of a node queue and how effective a relay is in transmitting burst of packets). Based on their GPI and QPI eligible relays are partitioned into regions which are scanned sequentially. The contention mechanism leads to the selection of a relay in the first non-empty region, i.e., the one with eligible relays with the highest GPI and QPI. In this way both positive advancement and balancing of the traffic among the possible relays are enabled. Transmissions of bursts of packets is also enabled for improving channel usage, thus catching up on the time spent in searching for a relay.

The described forwarding mechanism can fail when there are no relay able to provide positive advancement, i.e., when a packet get stuck in a dead end. In order to deal with this problem, which affects particularly sparse networks, ALBA has been extended with a mechanism based on a simple node coloring scheme [13]. The mechanism is termed *RAINBOW*, and the obtained extended version of ALBA is called ALBA–R. The functions of ALBA–R are described below. Let us consider a node x that has (received) a packet that needs to be forwarded. We denote with F the region of node x transmission area where there are relays that offer positive advancement toward the sink. Similarly, we call F^C the remaining part of x transmission area (Figure 1).

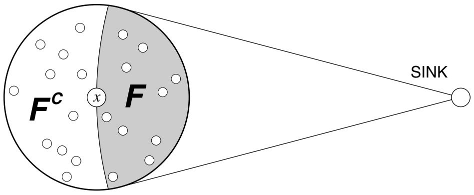


Figure 1. Forwarding regions of node x

With $C_0, \dots, C_h$ we indicate the *colors* (or labels) that nodes assume according to their perceived ability to forward packets directly to the sink or not. Initially, all nodes are colored C_0 (yellow, or Y) and function according to the basic advancement rules of ALBA. If a node can reach the sink with a path made up only of nodes closer to the destination than itself, it remains yellow. However, if a node x is unable to relay a packet for more than a fixed number of attempts (depending on its neighbors duty cycle), it deduces that it may be a dead end. In this case x changes its color to C_1 (i.e., it becomes a red node, R). In this way the nodes that progressively realize to be either a dead end or on a path leading to a dead end stop volunteering as a relay for yellow nodes. In order to route packets around the hole, red nodes behave differently in the relay search phase. They try to send the packet away from the sink by searching for yellow or red relays in region F_C. When a yellow node is reached, regular ALBA–R operations are resumed. Red nodes may be unable to find routes that lead to the sink through red or yellow nodes only. In this case, a red node switches its color again, turning to C_2 (blue, B). According to this new color, it resumes relay searches in F (instead of in F_C) looking only for blue or red neighbors. Blue nodes do not volunteer to be next hops relays for red or yellow nodes, but they resort to them to find a route. Packets generated by a blue node will advance toward the sink through blue nodes till they reach a red node. Then they will travel away from the sink (via red nodes) till they reach a yellow node. From that point on, they will be routed on the "yellow brick route" (i.e., on a route to the sink traversing only yellow nodes).

Figures 2 through 5 show an example of coloring for a specific topology. The sink is the green square node. The figures show how the coloring happens in time. Nodes are initially all yellow (Figure 2). All nodes that can find a route to the sink for their packets, say yellow. Those that cannot, turn their color to red and search for a relay in F^C (Figure 3). Some of the red nodes, however, cannot find a relay in F^C and go back to search in F turning blue, as shown in Figure 4. Finally, some of the blue nodes that cannot find relays in F that are blue or red, turn to purple. In this example, all nodes are colored with 4 colors. The final coloring of the network is shown in Figure 5.

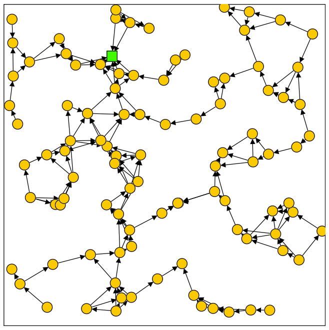


Figure 2. Y nodes

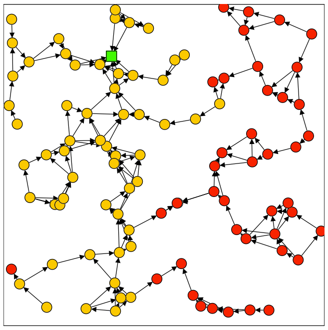


Figure 3. Y + R

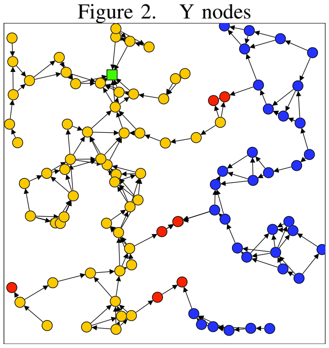


Figure 4. Y + R + B

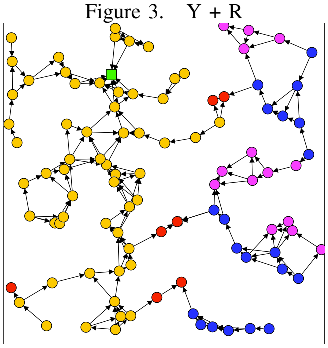


Figure 5. Y+R+B+P

The RAINBOW mechanism can be generalized to any number of colors, $C_0, \dots, C_h$, necessary to color all nodes in the topology. In particular, C_0-nodes are part of a direct route to the sink passing only through other C_0-nodes. When a node is forced to switch its color to C_k, it searches region F_C (if k is odd) or region F (if k is even), looking for relays between nodes colored C_{k-1} or C_k. The correctness of ALBA–R is proved by the following two theorems, where with *alternation* we indicate a change in the region (F or F^C) queried for relays [13].

Theorem 1: All and only the nodes that have routes to the sink with exactly h alternations assume the color C_h at the end of the transient phase. The transient phase has finite time.

Theorem 2 (Rainbow is loop-free): The Rainbow extension to ALBA always finds loop-free routes to the sink once nodes have converged to their color.

A. Resiliency to localization errors

Geographic forwarding protocols rely on each node being able to estimate its own coordinates. These estimates are highly likely affected by a non-negligible error, which in turn affects the estimated distance $d'(x)$ from a node x to the sink used for packet forwarding. ALBA–R defines the network topology graph based on the actual ability of nodes to communicate with each other. In other words, ALBA–R does not define two nodes as neighbors depending on their (estimated) coordinates and inter-nodal distance. As a consequence, each node has the same set of neighbors that it would have if the nodes had exact coordinates.

In terms of geographic forwarding, however, localization errors affect the orientation of the link between two nodes, i.e., which of the two nodes is perceived to be closer to the sink. The estimated distance from the sink d' may generate different sets F and F^C.

The proof of ALBA–R resiliency to errors [15] stems from noticing that theorems 1 and 2 hold also for the estimated distance d'. In other words, the theorem proofs are independent of the orientation of the link, i.e., of who is in F or in F^C. The theorems hold for different distances, and the only thing that changes is the node coloring, and therefore, route length, etc.

This is why, from those two fundamental theorems [13], the following corollary holds.

Corollary 3: ALBA–R finds loop-free routes from any node x to the sink even when x coordinates are affected by localization errors.

III. PERFORMANCE EVALUATION

In this section we evaluate the resilience to localization errors of ALBA–R via simulations. To this aim, we implement the protocol in the VINT project network simulator ns2 [16]. We compare our results to those obtained for GeRaF [14], a cross-layer solution for geographic routing for WSNs that represent the typical geographic forwarding protocol. The version of GeRaF here implemented, differently from the one published originally, manages bursts of packets efficiently, therefore making the comparison with the naturally load balancing ALBA–R fairer. (This version of GeRaF has been defined and investigated in details in [17].)

Simulation scenarios and metrics. We consider networks made up of $n \in \{100, 200, 300\}$ nodes scattered in a square area of side $L = 320m$. The nodes are distributed randomly and uniformly throughout the deployment area. The average network degree ranges from 5 to 15 neighbors per node. The increasing number of nodes allows us to evaluate the resilience of the protocols in networks with different densities. The radio range of each node is set to $r = 40m$. Their duty cycle is set to $d = 0.1$. Packets are generated according to a Poisson process with rate ranging from $\lambda = 0.25$ to $\lambda = 1.0$ packets per second. This way allows us to evaluate the impact of different traffic conditions on protocol performance. Generated packets are assigned to a source node picked randomly and uniformly among all nodes. The selected source accepts the packet only if its buffer is not full. Every node has a buffer capable of storing 20 packets. The packet is discarded otherwise. The size of each data packets is 250 Bytes. ALBA–R control packets are instead considerably shorter (one order of magnitude). The channel data rate is $38.4Kbps$. The energy spent by each node for transmitting and receiving bits, as well as when in idle or sleep modes, is 53.7mW, 19.2mW, 19.2mW and 19.2μW, respectively. In each topology 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 and with radius E_{max}. In our simulations we have varied E_{max} between $0.1r$ and r (i.e., from one tenth to the full 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 and their estimated position.

In order to evaluate the resilience of the considered protocols to localization errors we have considered, for each network density, 30 different topologies. The simulation time for each experiment has been set to $30,000$s, which include an initial transitory period after which we started collecting measurements. Our results achieve a 95% statistical confidence, with a precision within 5%. We have observed that localization error has an important impact on the number of direct routes to the sink (i.e., on the number of yellow nodes). In particular, as depicted in Figure 6, the number of yellow nodes decreases as the localization error increases. As expected, the impact is more important in network with lower densities.

We have investigated the following metrics. **1) Delivery ratio**, i.e., the percentage of data packets that are actually delivered to the sink. **2) The length of the routes followed by a data packets**. This metric is compared with the shortest paths on the connectivity graph where the nodes are not affected by localization errors (*stretch factor*). **3) The end-to-end latency** incurred by data packets. **4) The energy spent for packet delivery**.

Simulation results. Our first set of simulations concerns the packet delivery ratio when the localization error E_{max}, the network size n and the traffic load λ vary. We have observed that for $\lambda \leq 0.5$ (low to medium traffic load), independently of the localization error and of the network size, ALBA–R is always able to deliver *all* generated packets to the sink. This

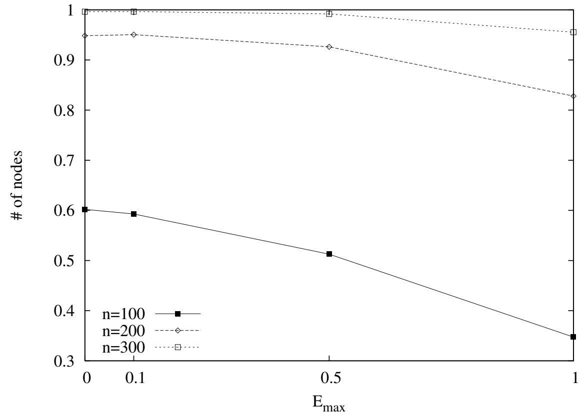


Figure 6. Number of yellow nodes for increasing localization errors

is clearly shown in Figure 7 that shows the packet delivery ratio when $\lambda = 0.25$. When congestion builds up ($\lambda = 1.0$) ALBA–R experiences some level of packet dropping, which however never reaches 2% (Figure 8). The effect of density is beneficial for ALBA–R even at congestion level. Since the higher densities remarkably decrease congestion, we observe negligible packet loss in networks with 200 nodes, and a 100% delivery ratio when $n = 300$ (that is why Figure 8 shows only results for ALBA–R in networks with 100 nodes). Packet dropping is instead very significant for GeRaF, which does not include the coloring mechanism that while bypassing connectivity holes also comes handy when such "holes" are due to localization errors. Specifically, whenever a packet is generated at a non yellow node, i.e., at a node that does not have a path advancing at each hop toward the sink in the original network topology, packet dropping occurs. Moreover whenever a packet generated by a yellow node is relayed to a non yellow node, that packet will be discarded. Packet dropping in GeRaF can be as high as 80% when $E_{max} = 1.0$. We have observed that for high traffic load GeRaF delivery ratio increases (this is seen by comparing Figure 7 and Figure 8). This is because when traffic increases the dead ends, which cannot relay packets, soon become congested, and this congestion propagates back to nodes on the path to the dead ends. It therefore becomes less and less likely for GeRaF to select those congested nodes as relays for a packet. GeRaF packet delivery ratio, however, still remains low, ranging between 50% and 20% for different values of E_{max} when $n = 100$. GeRaF delivery ratio increases with density, since the presence of a higher number of direct routes to the sink (i.e., more yellow nodes) helps GeRaF greatly. However, the nodes might not be able to find these routes because of the localization error. When $E_{max} = 1$ GeRaF suffers severe packet loss (from 25 to 42%) even in dense networks ($n = 300$)!

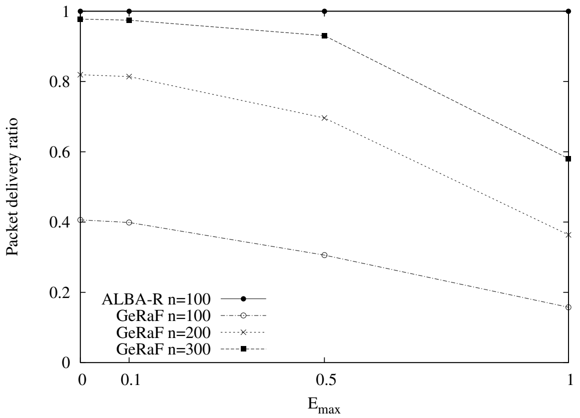


Figure 7. Packet delivery ratio, $\lambda = 0.25$

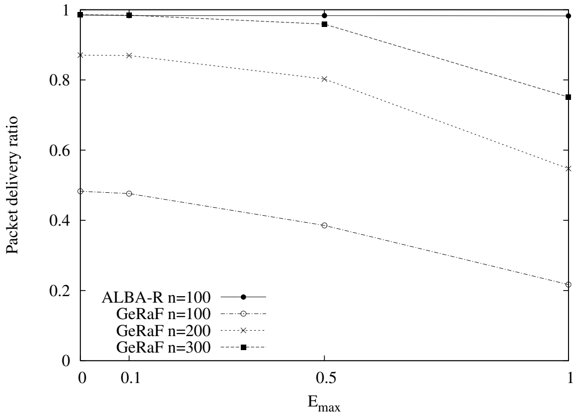
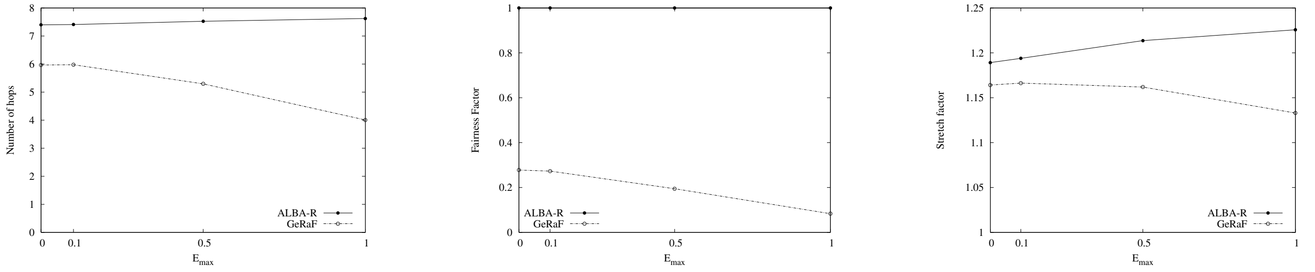


Figure 8. Packet delivery ratio, $\lambda = 1.0$

For fairness in the comparison with GeRaF, results for the three other metrics of interest are shown only for packets generated by those nodes that in the topology not affected by localization error would be yellow. These are the packets that GeRaF could deliver in an error free scenario.

The results of our second set of experiments, depicted in Figure 9 for the most interesting case of sparse networks with low traffic, concern the impact of localization errors on the routes followed by the packets. Figure 9(a) shows the number of hops traversed by packets generated by yellow nodes. We have already observed that the localization error governed by E_{max} has an impact on node coloring (Figure 6). However, this impact does not considerably affect the routes followed by ALBA–R packets. Even if fewer nodes are yellow, ALBA–R knows how to deliver to the sink packets that are generated by nodes that have now different colors. The GeRaF route length is instead remarkably affected by localization errors because of the decreasing number of yellow nodes with increasing E_{max}. In GeRaF the only packets delivered to the sink are those generated by yellow nodes. As E_{max} increases these nodes tend to be closer and closer to the sink. This is the reason for the decrease in route length that can be observed at high E_{max}: GeRaF routes are shorter because there are less nodes whose packets actually reach the sink. This effect is also confirmed by the *fairness factor* shown in Figure 9(b). The fairness factor is defined as the ratio between the distance from the sink (in hops) of the sources of the delivered packets



(a) Yellow nodes-to-sink route length

(b) Fairness factor

(c) Stretch factor

Figure 9. Route related metrics, $n = 100$ and $\lambda = 0.25$

and the average distance in hops of all sensor nodes in the network. A low fairness factor means that only nodes close to the sink are able to deliver successfully their packets. We observe that independently of the localization error, ALBA–R fairness factor is always 1. Finally, Figure 9(c) shows the stretch factor of the two considered protocol for the case of packets generated by yellow nodes. Let us start by considering the case of nodes that are not affected by localization errors. In this case GeRaF routes are longer than shortest paths to the sink because of the selection of the next-hop relay, which is based only on a greedy choice of the node closest to the sink. This increase is as high as 15%. The negligible 3% increase of ALBA–R is due to the fact that the next hop relay selection is based on a criteria that always privilege the QPI over the GPI (Section II). The increase in the stretch factor for ALBA–R for increasing values of E_{max} is always below the 5%. When the localization error increases the path from a given node to the sink is highly likely to contain non-yellow nodes. Therefore, ALBA–R cannot always select relays based on best advancement. In the case of GeRaF we have observed that only the nodes physically closest to the sink have a yellow brick route to it. Therefore, the stretch factor is only computed for those few routes, which results in a route increase which is still modest. A similar trend has been observed for packets generated by non yellow nodes. In terms of stretch factor ALBA–R routes experience a 25% increase even in the case of denser topologies ($n = 200$ and 300).

We now proceed to investigate packet end-to-end latency. These results are again influenced by the fact that ALBA–R basically always delivers all the packets, and that for GeRaF only nodes closer to the sink get their packets to it, especially with higher localization errors. As a consequence, ALBA–R latencies are higher that those of GeRaF basically for all observed cases. For instance, in a low traffic scenario ($\lambda = 0.25$) the higher difference between ALBA–R and GeRaF is obtained in sparse networks. For high localization errors the latencies for ALBA–R packets are 2.77 times those of GeRaF. As observed, higher densities benefit both protocols, and in particular ALBA–R. In networks with 300 nodes the difference in latency for ALBA–R and GeRaF packets is negligible for localization errors with $E_{max} \leq 0.5r$ and reduces considerably when $E_{max} = r$: In this latter case ALBA–R latencies are only 23% higher than those of GeRaF.

The results for nodal energy consumptions are shown in figures 10 and 11 below. These figures refer to sparse networks with high traffic ($n = 100$ and $\lambda = 1$; Cases with higher densities and traffic show similar trends).

Figure 10 shows the energy consumed by a node during the simulation time normalized to the energy that the node would have consumed for strictly following the duty cycle. In Figure 11 we also show the average energy consumed by a node normalized to the successfully delivered packets (energy per packet).

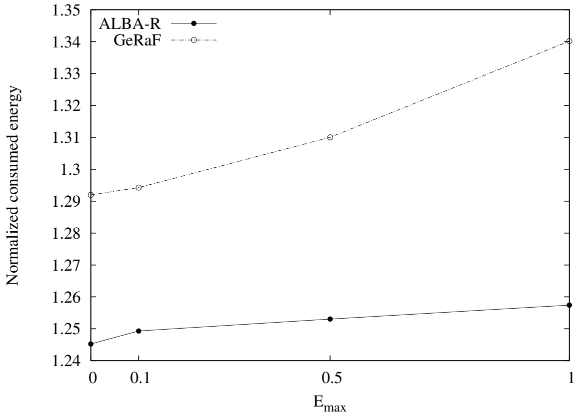


Figure 10. Node energy consumption

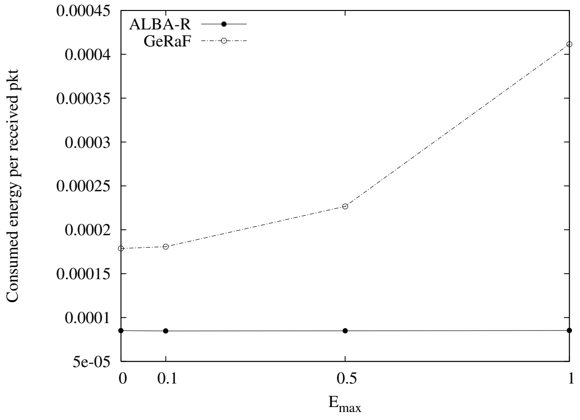


Figure 11. Energy consumed per received packet

ALBA–R consumes less energy than GeRaF because before discarding a packet stuck in a dead end, GeRaF tries to forward it several times before renouncing and dropping the packet. This number of times is necessary to GeRaF since it is not able to immediately distinguish that the lack of a relay is due to a connectivity hole rather than to sleeping nodes. This can be highly expensive, energy wise. ALBA–R, instead, knows a way out of the dead end, and the packets find relays at the usual cost. We observe that ALBA–R energy consumption does not increase with increasing localization errors, as the localization errors do not significantly affect protocol operations, as shown above.

IV. CONCLUSIONS

In this paper we have shown that a cross-layer, load balanced approach to geographic routing endowed with a mechanism for handling connectivity holes in the network topology, like the ALBA–R protocol, is capable of resilience to the errors that affect nodal localization. In particular, we have shown that ALBA–R, independently of network density, is not only able to always route every packet to the sink (over a connected network and until congestion builds up and packet loss is unavoidable), but that its performance in terms of route length, end-to-end packet latency and energy consumption, is negligibly degraded by localization errors. Comparison with a typical protocol for geographic forwarding (GeRaF) shows that the ALBA–R coloring mechanism is an effective tool for making geographic routing possible for real deployments of WSNs.

V. ACKNOWLEDGMENTS

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