IMPROVING THE DESIGN OF WIRELESS SENSOR NETWORKS USING QOS-AWARE OPPORTUNISTIC TECHNIQUES

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ABSTRACT

The design of a Wireless Sensor Network with Quality of Service (QoS) is a challenging and complex topic especially when the post-deployment corrections are expensive. This paper proposes a design methodology of Wireless Sensor Networks to estimate network performance in terms of end-to-end delay and reliability. It uses a probabilistic model to determine the needed node density, then adopting a variant of geographic routing it lets to calculate the number of path hops. The introduced opportunistic mechanism offers a trade-off between low end-to-end delay and reliable packets delivery. The modeled network with the adopted Geographic Opportunistic Routing has been evaluated through simulations and some guidelines about its design in order to obtain desired performance are given.

KEYWORDS

Wireless Sensor Networks, Quality of Service, Geographic Opportunistic Routing.

1. INTRODUCTION

The growing diffusion of *Wireless Sensor Networks* (WSN) opens new challenges concerning their design, the requested performance, and their reliability. In particular the increasing complexity of WSN usage scenarios and the service requirements of the applications running on the nodes introduce the need of *Quality of Service* (QoS) support and suggests new questions during the network project and deployment. Furthermore, if WSN operating in hardly reachable or human hostile environments (like underwater networks or that used to monitor factories producing hazardous goods) are considered, it is expected that the designed network is really suitable to provide the desired behavior, and that the post-deployment setup corrections (e.g. topology change) are minimized because of their high costs.

Hence we focused our attention on a methodology able to provide yet at the design stage an evaluation of the probability to meet QoS requirements expressed by the nodes applications. In order to limit the complexity of the problem we considered as QoS parameters end-to-end delay and reliability in the message delivery toward the destination, whereas at the present time the problem of energy consumption optimization has been postponed to a future work. Such methodology is based on: i) building a suitable model for calculating the probability to reach the next hop, and ii) selecting a routing algorithm which can assure the reliable packets delivery with the lowest end-to-end delay.

The model provides an abstract description of the region where we are looking for the forwarding nodes considering as network design parameters the nodes density and the model resolution, that is strictly related to the probability level that the network can assure the QoS requested by the nodes applications. The model allows to tune the nodes density and its resolution in order to improve end-to-end performance. The considered routing algorithm is based on geographic routing [1, 10], initially introduced for ad hoc networks and then naturally extended to WSN; it relies only on the use of local information (the position of the source, the destination and of the intermediate nodes forwarding the messages along the source-destination path) for the nodes localization, without using the network address. This make it scalable and performing in the presence of mobile nodes and of nodes with active-sleeping periods, reducing the system overhead due to the update of all routing tables. Selecting the geographic routing algorithm lets us to calculate the numbers of hops a packet needs to reach the destination. Then to control the flooding of packets transmissions while keeping the packets delivery reliable, we modify the routing algorithm introducing an opportunistic mechanism in order to improve the network reliability, taking advantage from the broadcast nature of wireless transmissions.

The proposed design methodology of WSN with QoS constraints, based on a probabilistic model refined with the use of a geographic opportunistic routing algorithm, aims to evaluate network expected performance before its deployment and can be helpful in such environments where it is hard and expensive to correct the network behavior on the fly after its implementation. The network validation, obtained by using the Castalia simulator [11], shows that the proposed methodology is suitable to provide a WSN that guarantees at the design stage a desired end-to-end delay. Moreover performance evaluation shows that the geographic opportunistic routing guarantees a trade-off between low end-to-end delay and reliable messages delivery.

The paper is organized as follows: in Section 2 a brief summary of significant results about geographic and opportunistic routing is reported. In Section 3 the design methodology is described, while in Section 4 performance of the designed network are analyzed. Finally, Section 5 concludes the work.

2. RELATED WORKS

In this section, without the aim to provide a fully comprehensive overview of the state of art about the geographic and opportunistic routing, some algorithms are briefly summarized that, to the best of our knowledge, can help to understand the proposed design methodology. An important distinction between routing algorithms is the criterion used in the selection of the next-hop node along the path toward the destination. In the following we limit our attention only to the *greedy* algorithms.

One of the first position-based routing schemes is *Most Forward within Radius* (MFR) [22], where the progress of the message toward the destination is intended as the projection onto the line source-destination of the line connecting the source S and the considered node; the node with the greater progress toward the destination D is chosen as next-hop node. Differently, the *Random Progress* method [16] randomly selects the forwarding node between all the neighbors reached using the minimum transmission power, facing off to the collision probability increase with the distance from the source. Finn [9] uses the geographic distance as progress and chooses the node closest to the destination. The *Compass Routing* method [13] chooses the node with the minimum angle composed by the line connecting this node to the source and the line connecting source and destination.

The guaranteed delivery of the messages to the destination, that affects network reliability, implies the use of recovery strategies in case of concave nodes, i.e. of nodes nor closer to the destination than the current source. The *guaranteed forwarding with memorization* uses the information about the concave nodes to recover the algorithm evolution. In presence of concave nodes [21] employs greedy routing scheme to switch the protocol from the greedy to the recovery mode, whereas the concave nodes are memorized in a list to take care of the previous experiences. The *Terminode routing* [8] forwards the message not to the nodes, that can be mobile, but to fixed geographical points, the anchors nearest to the destination. In *Geographic Routing Algorithm* (GRA) [12] nodes store the routes toward the destinations for which they are concave thus, when the destination is reached using *breadth first search* or *depth first search*, the stuck message can be sent to the destination. The guaranteed forwarding without memorization, also called stateless routing with guaranteed delivery takes the route decisions by considering only the local information about the geographical position of source, forwarding nodes and destination [20] uses the two-hop neighbors information and the dominating set concept; the message delivery is ensured by the use of the *Gabriel subgraph* algorithm.

Opportunistic routing has be introduced in order to face off the limit of best-path algorithms that select a unique optimal path toward the destination by using *a priori* established link performance metrics. This type of routing methods experiences retransmissions and path recomputations due to packets loss caused by the wireless channel conditions and packets collisions; these effects increase end-to-end delay and power consumption and reduce network throughput. The basic common idea of the different proposed opportunistic algorithms [2, 3, 14, 18, 19, 25] is to take advantage from the current and local information available to the nodes, due to the broadcast nature of wireless transmissions, to dynamically reduce packets retransmissions. Using the state information of nodes that have received the message the network layer chooses at each hop and for each packet a set of candidates forwarding nodes able to guarantee the successfully packet delivery toward the destination (sample-path dependent routing [15]). Then the MAC layer makes the final decision about the actual forwarding nodes, taking into account local information about connectivity.

Expected Any-path transmissions [24] uses EAX metric to compute the expected number of transmissions to successfully deliver the packet (thus it corresponds to ETX [6] in the case of best path algorithms with one candidate) and the lower EAX value is used to select the next-hop forwarding node, introducing a hop-by-hop routing. The ExOR algorithm [4] chooses as forwarding node the higher priority receiver between all the possible forwarders, prioritized in dependency of their distance from the destination. After receptions all receivers discover what candidates are in the subset and then only the higher priority node, i.e. the closest to the destination, forwards the message. Moreover the packets are collected in batches in order to reduce the cost of communications agreement required by the protocol. Finally robust acknowledgement prevents unnecessary retransmissions and avoids duplications. *Opportunistic Multipath Scheduling* [5] is a multi-path routing protocol that adaptively selects the path with lower delay or higher throughput. GeRaF [25] is a region-based opportunistic routing that defines a set of regions where looking for the forwarding nodes; the different regions priorities are set considering the distance from the destination, whereas the method minimizes collisions inside each region using a RTS/CTS scheme.

3. DESIGN METHODOLOGY

We consider a connected network populated by homogeneous wireless sensor nodes with a density ρ and located in fixed positions. Their transmission coverage is approximated with a step function on the basis of the *Nakagami model* and, referring to the *unit graph model*, two nodes are assumed as neighbors if their Euclidean distance is at most equal to the transmission radius r_0. Finally, all nodes in the transmission area are supposed to be awake with enough energy to operate correctly.

3.1 The Next-Hop Model: How to Meet End-to-End Delay Requirements Using Geographic Routing

The model [17] introduces the selection criterion of next-hop node inside a region that assures the requested QoS. This model provides a probabilistic evaluation of WSN performance at the design stage and a method to set the values of the nodes density, suitable to meet the minimum acceptable level of probability to have a desired end-to-end delay as required by the application running on the nodes. In particular the model selects the next forwarding node closest to the destination, considering a digitalization of distances by dividing the coverage circle in slices that introduce a set of distance bands corresponding to different levels of probability to assure a desired end-to-end delay. This is equivalent to ask that will be at least one listening/forwarding node at a certain distance from the source.

The expression of the probability that collects all the parameters of interest influencing the delay is:

P = *Pr (In a network with nodes* density ρ *and node coverage radius* r_o*, the packets sent by the source node S arrive to the destination node* D, *respecting the end-to-end delay bound required by the application, integrating the MAC scheduling and the physical effects and using the geographic routing to forward the packet to D (directly or by means of a multi-hop path)).*

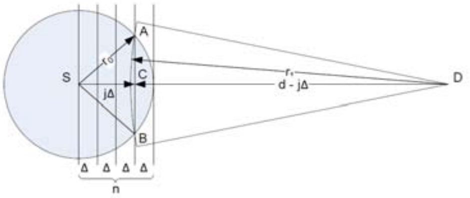


Figure 1. Graphical representation of the next-hop node selection criterion.

Assuming a multi-hop scenario, the modeling task firstly provides the mathematical expression of P to transmit a message from S to the next-hop node in the transmission circle at a given distance, dependently from the expected delay. Then it determines how many times the first problem can be replicated along the path toward D, i.e. how many hops are necessary to reach D from S. Comparing the delay assured with an accepted level of probability with that required by the applications, it is possible to verify if the designed network is able to meet the application requirements. Otherwise the method has to be reiterated, tuning the design parameters values until the desired network behavior is reached.

3.1.1 The Probability to Reach the Next-Hop Node

The coverage circle is divided in $\mathrm{n} = \frac{\mathrm{r_0}}{\Delta}$ slices, each one of Δ width, see Fig. 1, obtaining a distance discretization. Tuning Δ, the model *resolution*, we can increase or not the chance to find the next-hop node and the number of nodes, thus the choice of *n* is strictly related to the number of path nodes.

When the source is far away from the destination we examine the last slice of the S coverage circle, i.e. the slice that starts at distance $(n - 1)\Delta$ from S and finishes at distance $n\Delta$. Since this slice is the nearest one to D, this choice can assure a path with fewer hops. Moreover we consider a circle centered in D and intersecting the transmission circle of S in A and in B points, determined by the chosen resolution. At long distance, the portion of the circumference delimiting the intersection of this circle and of the S transmission circle can be approximated with a straight line. When the current source is not enough far away from D the farthest node from D belongs to the edge of the circular sector DAB placed to the left of the chord *AB*, hence the mathematical expression of the area must be updated to include the contribution of this portion of DAB.

Finally the probability *P* to find a candidate forwarding node in the specified region is obtained considering both the contributions of S far away and not from D, deriving the following expression:

$$P = \frac{1}{\pi}\left\{\cos^{-1}\left(\frac{n-1}{n}\right) - \frac{n-1}{n\cdot\sqrt{n}}\right\} + \cos^{-1}\left[\frac{d-(n-1)\Delta}{r_1}\right]\cdot r_1^2 - [d-(n-1)\Delta]\cdot\sqrt{r_1^2 - [d-(n-1)\Delta]^2}. \tag{1}$$

Eq. 1 is function only of the S-D distance *d*, of the model resolution *n* and of the used geographic routing algorithm. At its turn *n* is dependent on the minimum accepted number of nodes that can forward the packets and that we expect to find in the last slice to meet the required probabilistic service level.

3.1.2 The Number of Hops and the Delay Computation

In the case of a multi-hop path, the method to find the next node forwarding the packets toward the destination can be replicated for each step. At each hop we will have a new intermediate source $\mathrm{S_i}$ with $0 \leq \mathrm{i} \leq \mathrm{N}$, where N is the number of the path nodes, and with the same transmission radius r_0, as assumed. Since, in the worst case, the next-hop node is at distance $j\Delta$, with $j = n - 1$, from the current source $\mathrm{S_i}$, the maximum number of hops is $N_{max} = \frac{d}{(\mathrm{n}-1)\Delta}$. This is the final result needed to estimate the delay performance of the network. In fact, taking into account the MAC protocol parameters used to manage the access to the medium and the physical layer features, now it is possible to evaluate the network delay and, consequently, to specify the nodes density required to probabilistically guarantee the expected end-to-end delay. Finally we can conclude that, knowing the approximated coverage radius of the nodes and the network performance required by the applications, using the proposed model it is possible to find a minimum value of the nodes density ρ suitable to probabilistically assure the desired end-to-end delay.

3.2 The Improved Opportunistic Geographic Routing Algorithm: how to Increase Network Reliability

The explained model assures that there is almost one node a such distance to forward the packet toward the destination in order to assure end-to-end delay by tuning nodes density. Since in general there are more next-hop nodes, packets broadcasting is considered, but this increases collisions that, at their turns, impact on delay, even if flooding is the easier solution to provide successfully packets forwarding. Moreover if we try to reduce end-to-end delay increasing nodes density, we jeopardize reliable packets delivery due to the increased risk of collision. Thus it is necessary to refine the design process in order to provide a network that meets both end-to-end delay and reliability requirements of the nodes applications. The trade-off between flooding, i.e. high reliability, and end-to-end delay control is obtained introducing an opportunistic selection of forwarding nodes, that allows to reduce collisions and retransmissions when we increase nodes density. The proposed method is an enhanced opportunistic version of the *Greedy Forwarding* [9] and adopts a multi-path strategy with partial flooding to guarantee successfully message delivery. This algorithm searches for the candidate forwarder nodes between these belonging to the coverage circle of the current source. Each candidate node does not simply forward the received message, as in flooding strategy but, in order to make the decision to deliver the packet, it has to verify the selection criterion that uses nodes state information: it checks if it has already received the message or if it has listened a corresponding *ACK* from a different node. Each node keeps the array of the sequence number of the listened packets and, if the acknowledgement mechanism is used, the array of the sequence number of the listened *ACK* packets. Thus, when a node receives a packet, depending on whether the packet is *DATA* type or *ACK* type, it checks if it is eligible to forward the *DATA* packet or register the *ACK* event, that allows to conclude that at least one delivery of the considered message has been performed. A node is eligible to forward a packet if: 1) it is not the *Source* or the *Sink*, 2) it is nearest to the *Sink* than the sender node, 3) it listens that packet for the first time, and 4) if the acknowledgement mechanism is enabled, it has never listened the *ACK* for that packet. The conditions (iii) and (iv) avoid to flood the network with unnecessary copies of the packet. This algorithm is illustrated in the following listing:

```
int msgIdListened[MAX_SEQUENCE_NUMBER];
int msgIdAcknowledged[MAX_SEQUENCE_NUMBER];

void handleMessage(rcvPacket) {
 int sequenceNumber = getSeqNum(rcvPacket);

 switch (type(rcvPacket))
 case (DATA_PACKET):
  msgIdListened[sequenceNumber]++;
  if (checkForward(rcvPacket) == true)
   forward(rcvPacket);
  else
   return;
  break;
 case (ACK_PACKET):
  msgIdAcknowledged[sequenceNumber]++;
  break;
}

boolean checkForward(rcvPacket) {
 Node currentNode = getCurrentNode();
 Node senderNode = getSenderNode(rcvPacket);

 if (currentNode == senderNode || currentNode == SINK)
  return false;
 else if (distance(currentNode, SINK) < distance(senderNode, SINK)) {
  if ((OR_enabled == 0) ||
    (msgIdListened[sequenceNumber] == 1) ||
    ((ACK_enabled == 1) &&
     (msgIdAcknowledged[sequenceNumber] == 0)))
   return true;
  else
   return false;
 } else
  return false;
}

void forward(rcvPacket) {
 int sequenceNumber = getSeqNum(rcvPacket);

 forwardToSink(rcvPacket);
 if (ACK_enabled)
  sendAck(sequenceNumber);
}
```

This simple rule allows to limit the network flooding, limiting the messages collisions and ensuring an acceptable level of reliability in the message delivery.

4. PERFORMANCE ANALYSIS

In this section we illustrate the performance evaluation of the network in terms of number of hops, end-to-end delay and number of message copies received at *Sink* destination. The obtained results validates the analysis carried out in the previous sections and provides guidelines for choosing the design parameters values. The simulation tool used is the *Castalia* simulator [11], that is suitable for the algorithms first-order validation before the network deployment, exactly matching our goal. The radio module adopted is the TI/Chipcon CC2420 transmitter and we chose to integrate the routing protocol only with the well-known *Sensor-MAC* (S-MAC) protocol [23]. We will show in Sec. 4.2 that changing the MAC protocol only affects the computed end-to-end delay and not the routing algorithm behavior, as expected.

The considered network topology is a square grid of nodes, where the inter-nodes distance is increased at each run of the simulation until a successful transmission is possible, i.e. until the maximum nodes distance equal to the coverage radius is reached. Thus all performance evaluations has been done varying the nodes density that is the network design parameter. The source node is placed at the right bottom of the grid, while the Sink node is placed at the left top of the grid. The distance between *Source* and *Sink* is kept firm at the value of 100 meters.

The analysis has been carried out using the method of independent replications, running independent replications until the 95% confidence interval is reached for each performance measure, plotting only the mean values and ignoring the error when it is negligible. Finally, the analysis has been carried out comparing the performance of the simple Geographic Routing and of the proposed opportunistic improvement of

Geographic Routing in both cases of simple implementations and implementation with *ACK* that by itself increases network reliability, in order to highlight the mechanisms efficiency. In the legend of the illustrated graphs we adopt the following acronyms: *GR NoAck* = Geographic Routing without *ACK*, *GR Ack* = Geogr. Rout. with *ACK*, *GOR NoAck* = Geogr. Opportunistic Rout. without *ACK*, *GOR Ack* = Geogr. Opport. Rout. with *ACK*.

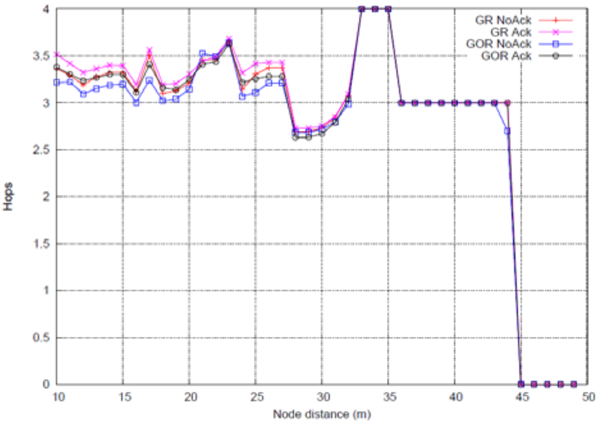


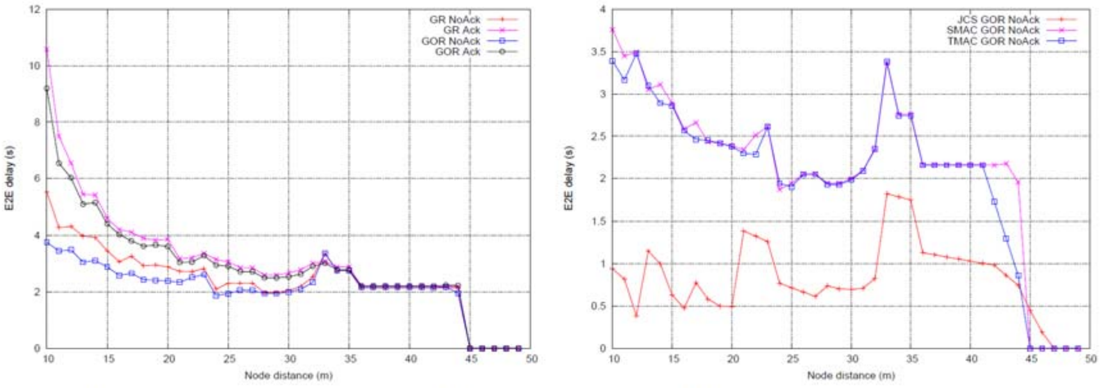
Figure 2. Number of hops needed to transmit a packet from the *Source* node to the *Sink* node, when the grid nodes distance increases.

4.1 The Number of Hops Computation

Fig. 2 shows the average number of hops needed to send the message from the *Source* to the *Sink* nodes, when we increase the distance between each node in the network. In particular the routing protocol has been evaluated turning on and off both the opportunistic and the acknowledgement mechanisms. The differences between such variants are quite small: the former mechanism reduces the number of transmissions, while the latter introduces new traffic into the network and, then, increases the number of collisions which can cause longer path to the destination. However Geographic Opportunistic routing with *ACK*, that is the most reliable method, allows performance comparable to that of Geographic routing without *ACK*, showing a more efficient behavior.

4.2 Delay Analysis

In Fig. 3(a) we show the end-to-end delay when the Geographic Opportunistic Routing protocol is used with S-MAC. When the opportunistic mechanism is activated and the acknowledgement is disabled the traffic in the network is the smallest and, thus, the number of collisions is the lowest. Therefore in this condition we get the lowest end-to-end delay. Instead disabling the opportunistic mechanism and enabling the acknowledgment we increase the end-to-end delay, as expected since the source retransmits the packet until successfully reception acknowledgement. However, also in this scenario, GOR with *ACK* shows a lower end-to-end delay respect to GR with *ACK*. The obtained performance is affected by the adopted MAC protocol, whereas the consideration about the routing protocol remains still valid, as shown in the following Fig. 3(b). In such figure we compare



(a) Different routing protocols variants with S-MAC.

(b) Different MAC protocols with the same routing protocol.

Figure 3. End-to-end delay of a packet transmitted from the *Source* node to the *Sink* node, when the grid nodes distance increases.

different MACs – a simple *Just Carrier Sense* (JCS) MAC, S-MAC and T-MAC [7] that introduces a dynamic scheduling of active/sleeping periods – using the same routing protocol variant: the Geographic Opportunistic Routing without *ACK*. As expected, the presence of active/sleeping nodes impacts on the experienced delay.

4.3 Reliability Analysis

Fig. 4 shows the number of copies of the sent messages received by the *Sink*. Obviously, when nodes density is reduced the number of delivered copies by means of all the considered methods decreases since there are less forwarder nodes. This result shows as the network reliability has an opposite behavior when nodes density changes respect to the delay, and this justifies the adoption of the opportunistic improvement of GR in order to meet both and-to-end delay and reliability requirements. The higher number of copies is obtained with the simple Geographic routing, showing as the proposed opportunistic mechanism reduces the flooding. When the opportunistic mechanism is enabled and the acknowledgement is disabled the number of forwarded messages is the smallest, while it increases disabling the former and enabling the latter mechanism. Since the number of forwarded messages is strictly related to the number of the messages received by the *Sink*, these mechanisms affect the reliability and the effective trustiness of the designed network. However it is shown as GOR allows the delivery of a sufficient number of copies of the message along with it permits the keep down the end-to-end delay increasing the nodes density, as illustrated in the previous figures.

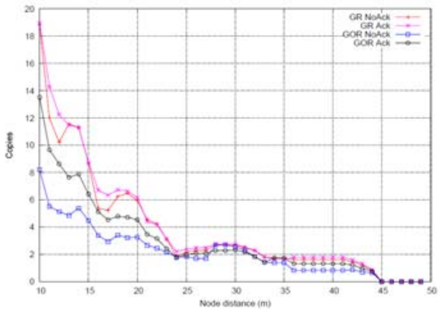


Figure 4. Number of received copies of the transmit- ted packet at the Sink when the grid nodes distance in- creases.

5. CONCLUSIONS

This paper presents a work about designing a WSN using a probabilistic model to estimate the number of path hops and refined with the use of a Geographic Opportunistic routing algorithm. The proposed design method aims to evaluate expected performance expressed in terms of end-to-end delay and network reliability, before the network deployment. The model, useful to set the needed value of the design network parameters, is described and a probabilistic estimation of the number of hops required to reach the destination is given. This outcome can be used to evaluate the expected end-to-end delay, when a particular MAC is adopted. Moreover the geographic opportunistic routing allows to guarantee an acceptable reliability in the messages delivery. The network scenario using the proposed model and the selected routing algorithm have been simulated, validating the proposed design method. Furthermore, the obtained simulations results let us to draw the following considerations: 1) the coordinated use of model and opportunistic mechanism, that compose the design methodology, allows to satisfies both end-to-end delay and reliability requirements tuning the nodes density; 2) the opportunistic geographic routing with ACK outperforms the simple geographic routing with ACK in terms of end-to- end delay since it reduces the number of retransmissions keeping the required level of reliable delivery; 3) the MAC protocol influences the end-to-end delay; 4) the opportunistic and the acknowledgement mechanisms of the Geographic Routing protocol can be used to tune the expected end-to-end delay and the reliability of the network, but they does not affect the hops number; 5) when the inter-node distance (i.e. the nodes density) is greater than about the half of the transmission radius the end-to-end delay and the reliability behavior become almost constant, while under such limit the number of collisions increases the values of both these parameters. In the future works different network topologies, further QoS metrics, as the packet loss, and a more realistic radio model will be considered. Moreover the hypothesis of all nodes in the transmission area awake will be relaxed to investigate the model behavior in presence of active/sleeping nodes and of switched off nodes due to exhausted batteries.

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