A Convex Hull-based Approximation of Forest Fire Shape with Distributed Wireless Sensor Networks

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Abstract—**Monitoring of physical phenomena is one of the most promising application fields of wireless sensor networks. In this work we focus on obtaining the shape of a forest fire. In this kind of applications, the information sensed by network nodes is usually transmitted to a base station located at the border of the network, where it is finally processed. However, such an approach requires that a large amount of data is transmitted through the network. In this paper, we assume that network nodes are able to collaborate in order to obtain an approximation of the forest fire shape without any base station, in a completely distributed way. We propose and analyze two techniques for performing this approximation. The first one makes intensive use of resources, while the second model incorporates an aggregation technique, reducing significantly resource requirements.**

I. INTRODUCTION

Wireless Sensor Networks (WSNs) are recently widely adopted for situation management applications [12]. Situation management deals with dynamic and unpredictable scenarios, where a distributed system deployed over a wide area captures real time data from a large number of heterogeneous information sources. The final goal of this system is to provide support for decisions making. Usually, the role of the WSN consists in obtaining a representation or a model for a physical phenomenon.

An example of this kind of applications is the EIDOS (*EquIpment Destined for Orientation and Safety*) architecture [8], in which a large WSN is deployed over the area affected by a forest fire, in order to collect environmental data and compute a map of the fire. This map is provided directly to the firefighters, who are equipped with mobile handheld devices. The fire model is obtained by the network nodes in a completely distributed and collaborative way, starting from their readings, and without the participation of any base station.

In the current design of EIDOS, the first task performed by each sensor node consists in determining its own spatial location. It can be either obtained directly from an internal GPS (*Global Positioning System*) receiver, or estimated running a distributed localization process [7]. From this point, each time the fire reaches the position of a sensor node, a broadcast is triggered so that every node in the network receives information about that event. For this purpose, several dissemination techniques have been analyzed [21].

In this work we present and analyze two approaches for processing the information received by each node during this broadcast. The first one consists in storing all the received data by each node. As a result, in each moment all network nodes would know the set of points reached by the fire so far. Obviously, a representation of the fire computed with this data would be fairly accurate. As the second approach, which is the main contribution of this paper, we propose to apply an in-network data aggregation technique [4], in order to obtain a more compact fire model. In particular, we suggest to use a convex hull representation [20] of the fire perimeter. As we will show in the evaluation section, the new approach saves memory and reduces the overhead transmitted by the shared wireless medium, maintaining at the same time the fidelity of the fire representation.

The rest of this paper is organized as follows. Next section provides some background in the area of physical phenomena monitoring with WSNs. Then, Section 3 describes the techniques considered in this work for approximating a forest fire. After that, Section 4 presents a comparative performance evaluation of both techniques. Finally, some conclusions and future work are given.

II. RELATED WORK

Lots of mechanisms have been proposed in the literature for estimating or approximating the contour (also referred to as edge and boundary) of a physical phenomenon by using WSNs. Some examples can be found in [1][3][11][17][19][22]. However, although some of these proposals are partly distributed (usually they employ some *clustering* technique), to the best of our knowledge, in all of them the participation of a base station is required at some point of the process.

The technique recently presented in [14] also relies on a root node for obtaining the phenomenon boundary. However, it is particularly interesting, due to it incorporates a strategy to minimize overall data communication. In this proposal, sensors exchange information only when the process under study does not proceed as expected. However, it involves programming sensor nodes with a model of the phenomenon (referred to as *tiny model*).

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Apart from the convex hull, there are many other proposals for representing in a compact way the spatial shape of a physical phenomenon starting from the set of localizations where its presence has been detected. In [16], authors analyze the use of lines and Bezier curves for approximating a set of data points provided by a WSN. In [6] a set of polygons are used for representing the contour of the phenomenon, being the number of vertices employed a user-specified parameter. Finally, some complex analytical frameworks, such as Voronoi diagrams [11], kernel linear regression [10], and Gaussian kernel estimation [13] have been also proposed for modeling sensor data.

III. FOREST FIRE APPROXIMATIONS

In this section we detail the mechanisms proposed in this work to obtain the map of a forest fire. First, we establish some general assumptions. Then, we describe the data dissemination technique employed to transmit fire detections to the entire network. Over the previous dissemination layer, we can define a fire representation layer. In this paper, we analyze two different approximations at this level: the punctual model and the convex hull-based model.

A. General Assumptions

We assume that the WSN is deployed from the air. This implies that the resulting topology of the network is highly irregular and unknown.

We assume that every node in the network is able to obtain its own location once it was dropped to the floor. This position can be obtained either through a built-in GPS receiver, or through a distributed localization process (outside the scope of this paper). Each node broadcasts its position (p) to the entire network when it detects an approaching fire front. In addition, all nodes receiving the broadcast message (m_p) will store the initiator position p in an internal data structure (described later).

We also assume that network nodes neither maintain any hierarchy nor have preliminary information about the network topology (including the amount of neighbors it has or their locations).

Finally, regarding the radio propagation, we assume the use of ideal omni-directional antennas, resulting in circular coverage areas. All the sensors use the same transmission power, so their coverage areas have the same size.

B. Data Dissemination Algorithm

As broadcast dissemination mechanism, we have implemented ABBA (*Area-based Beaconless Algorithm*) [18]. This mechanism is based on the concept of the perimeter covered by the received messages. For example, in Fig. 1, node J has received a message m_p^I from node I, related to a certain position p. The portion of the perimeter covered by the transmission (c_p) is given by the intersection of two circles, and it is denoted by the difference between the initial (α) and final (β) angles. Later, node J may receive other copies (m_p^K, m_p^L…) of m_p^I from different neighbors (K, L…). These copies will generate new covered segments in its perimeter, which can be totally or partially merged. Moreover, the fact of using the same radio circles ensures that the perimeter presents, at most, two different covered segments, reducing the amount of information to store at each node. In this case, c_p will represent the sum of both segments.

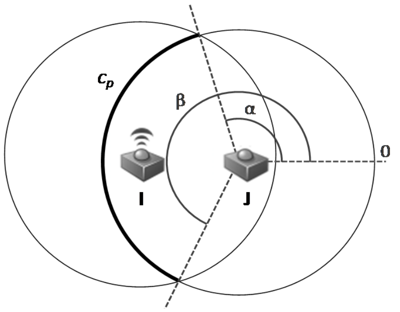


Fig. 1. Perimeter of node J covered by a message received from I.

When a node receives a broadcasting message from a neighbor, it is not forwarded instantaneously. Instead, the node establishes a timeout (d_p), defined by

$$d_p = \left(\frac{c_p}{360}\right) \times d_{max}$$

where c_p is expressed in degrees, and d_{max} is a pre-defined upper limit for this delay (in seconds). Later, when this timeout expires the message will be forwarded. However, the reception of additional copies of the same message before the timeout d_p ends will modify c_p and d_p, delaying the transmission again. Finally, the message forwarding is cancelled if $c_p = 360º$, i.e., if the whole perimeter has been covered by the transmissions of the neighbors.

This algorithm requires that each node maintains a list of messages waiting to be broadcasted, along with the perimeter not covered yet by previous copies if those messages. Hereinafter, we will refer this data structure as TL (*Transmission List*). Note that to allow the updating of the perimeter covered at a receiver node, messages have to explicitly include the transmitter position, introducing an additional communication overhead.

C. Punctual Model

In this proposal, each node stores in an internal list all the fire positions collected from the network. This data structure will be referred as PL (*Position List*).

Fig. 2 shows the flow chart representing the behavior of a network node obtaining a punctual approximation. At a glance, when a new fire point is received, it is inserted into TL, and it is not inserted into PL until it is removed from TL. This occurs when its transmission has been performed or cancelled. Fig. 4(b) shows the aspect of the fire (a) approximated by this model.

D. Convex Hull-based Model

Fig. 3 shows the behavior of a network node computing a convex hull-based approximation of the fire. The main difference between this approach and the punctual model is that, in this case, PL only contains the set of positions composing the perimeter of the convex hull.

When a new fire point is received, it is inserted into both lists simultaneously. If the point being included in the convex hull is inside the current shape, it must be ignored. Otherwise,

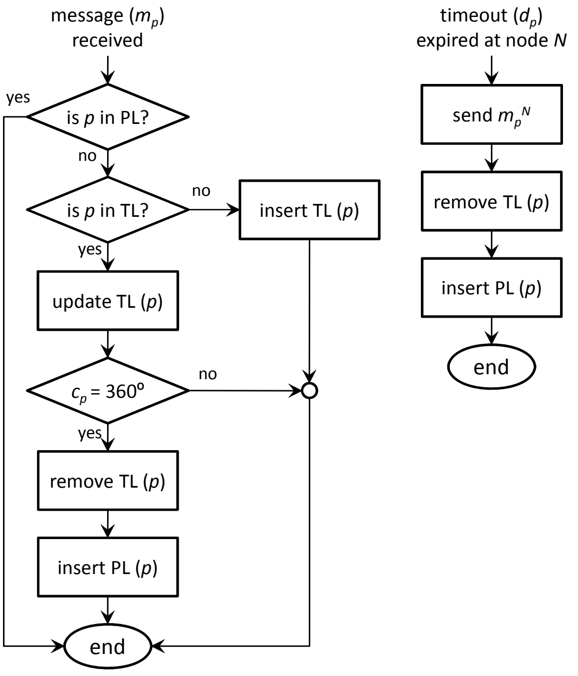


Fig. 2. Node behavior for punctual approximation.

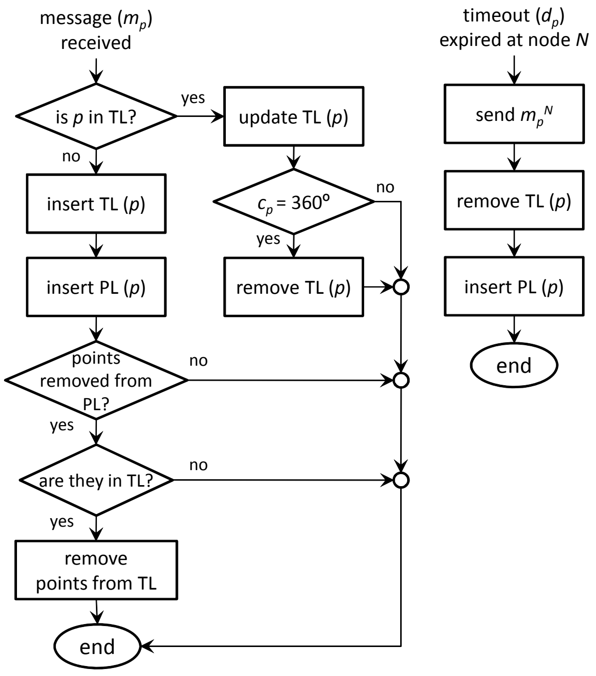


Fig. 3. Node behavior for convex hull-based approximation.

the point is outside the shape, and its addition will modify the perimeter. A perimeter updating may involve removing other nodes in the perimeter. Fig. 4 (c) shows the aspect of the fire (a) when it is approximated by this model.

This approach reduces the resources required by network nodes, due to they determine whether the new information contributes to their current fire model. If this is the case, nodes will act as a relay for this information. In other case, neither data forwarding nor its storing is required.

IV. PERFORMANCE EVALUATION

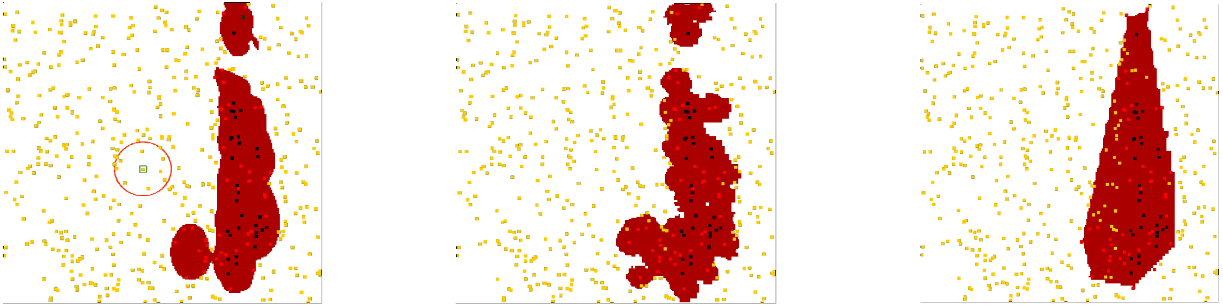
In this section, we analyze the two proposals described above. First, we present the simulation environment, including aspects such as forest fire spreads, network deployments, and the wireless signal propagation model. After that, we establish a criterion to evaluate the quality of the model (how well the approximation fits the real fire). Before comparing both proposals, the punctual approximation should be tuned in order to obtain its best performance. The comparative focuses on the accuracy, resources consumed, and scalability of the representations.

A. Simulation Environment

In the context of the EIDOS architecture, we have developed a forest area simulation environment [9], in which we can deploy a WSN, spread a forest fire, place firefighters, and see the evolution of the fire fronts that they perceive. This tool is composed of several independent and interconnected modules, which share information by means of a global MySQL database. In short, first we use Farsite [5] to simulate a fire over a particular forest area, by using real geographical, environmental and vegetation data. After that, a WSN simulator (developed in Python/TOSSIM [15]) executes the EIDOS application in each network node.

In order to obtain realistic results, the simulator incorporates a noise and interference model and the Friis free-space signal propagation model. We have modeled the Crossbow Iris radio [2], applying a transmission power of 3 dBm and a minimum reception power of -90 dBm. Under these conditions, we obtain an approximate radio range of 87 meters. The simulated protocol for media access control is basic CSMA [15].

In each simulation run, network nodes are distributed randomly in a square area of 1000×1000 meters. We have considered network sizes varying from 200 to 1000 nodes, what corresponds to connectivity degrees from 4 to 22.



(a) Fire spread (b) Punctual (c) Convex hull-based

Fig. 4. Forest fire approximations.

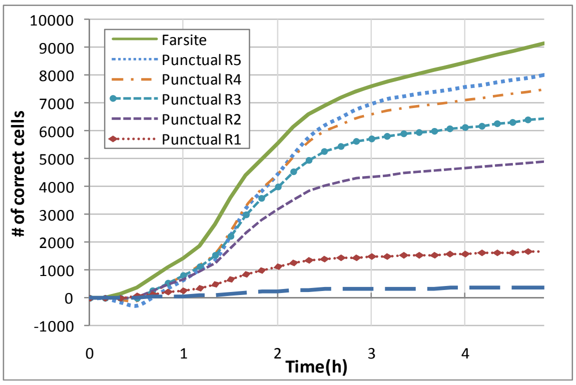


Fig. 5. Quality of the approximation (Farsite vs punctual models) (network size: 500 nodes).

For each experiment, we simulate the spreading of a fire in the deployment area, so that the fire reaches almost nodes of the network (burning them). Each time a node detects fire in its proximity (by a sudden rise in the sensed temperature), it broadcasts its position to the wireless medium. For localization purposes, we have assumed that all network nodes are equipped with a GPS receiver. For the execution of the dissemination mechanism, the value of d_{max} has been set to 5 seconds.

Finally, in order to increase the representativeness of results, experiments were repeated five times for each network size and approximation technique, showing here average values.

B. *Evaluation Methodology*

The Farsite simulator represents the area in which the "original" fire has spread as a raster (grid) called TOA. The value of each cell in this raster provides the Time Of Arrival of the fire to its center, and it can be defined as a function $t_{burning}$ = TOA(*cell*), assuming that an infinite value will indicate that the fire has never reached this position. The TOA information allows us to analyze how the fire spreads along time. In particular, for a given time t, a cell is burning if $t \leqslant$ TOA(*cell*). In Fig. 5, the "Farsite" series shows how the amount of burning cells increases with time. In the plot, horizontal axis represents time (it shows five simulated hours). Vertical axis represents the amount of current burning cells. As the forest fire spreads over an area of 1000×1000 meters, and cell size has been set to 10×10 meters, the amount of burning cells has an upper bound equal to 10000.

For comparative purposes, each proposed model should provide its results by using the same representation. Once we have two TOA files (the original TOA_{fire} and the proposed $\text{TOA}_{\text{model}}$), we estimate how well the second fits the first by analyzing its instantaneous burning cells, and determining the portion of them that have been correctly detected. Note that the fire representation obtained by each node depends on the amount of information it receives. In this study, we have considered, for both the punctual and the convex hull-based model, the node receiving the largest number of fire positions during the simulation.

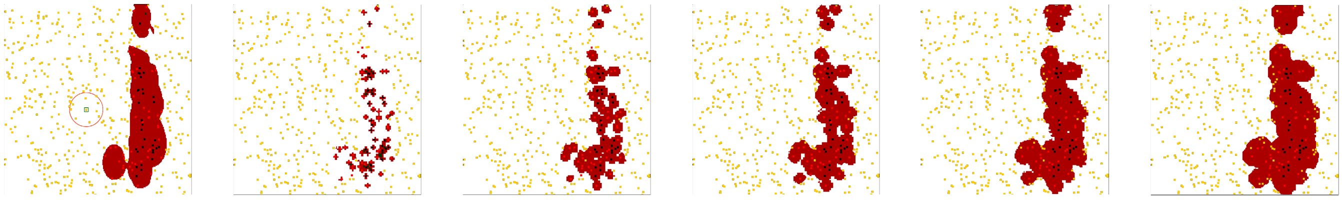
C. *Simulation Results*

1) *Tuning the punctual model*: In the punctual model explained in Section 3, the fire is represented as a collection of burning points gathered from the network. This model assumes that the fire is active in the respective surroundings of each point. In our analysis, we will consider that the burning area is a circle centered in that point. Fig. 6 shows several punctual representations of a forest fire, obtained by using circles with radius ranging from 1 to 5 cells. Next, we analyze the influence of the size of these circles on the accuracy of the resulting representation.

Apart of the "Farsite" series, Fig. 5 shows the amount of burning cells correctly represented by the punctual model, applying circles with radius ranging from 0 to 5 cells. Negative values mean that the amount of burning cells incorrectly detected overcomes the amount of those correctly detected. From this plot we may conclude that small circles represent the fire better at the beginning of the simulation. On the other hand, after two hours, the fire is wide enough to be better represented by bigger circles. Moreover, for circle R5 (or bigger radius), improvements obtained with wide fires do not compensate initial inaccuracies when approximating an outbreak of fire. For this reason, we select circles R3 and R4 (discarding circles R0, R1, R2, and R5) as the most suitable ones to represent the fire in the following analysis.

2) *Accuracy of the approximation:* Once the punctual representation has been tuned to R3 and R4 in order to obtain its optimal results, we compare it with the convex hull-based approximation. Fig. 7 shows these results in the same way that Fig. 5. We can see that the convex hull exhibits a good average behavior. During the first 30 minutes, it is the best representation. After that, we can notice a clear reduction on its accuracy (t = 1.2 hours). The reason is that sudden changes in wind direction are not well assimilated by the convex hull. Finally, as the fire spreads, its accuracy increases again. After two simulated hours, the convex hull-based approximation overcomes R3 and exhibits a behavior similar to R4.

3) *Resources consumed in the WSN:* In the punctual model, each node of the WSN stores all the gathered points in the PL list (see Section 3.3). On the contrary, in the convex hull-based model, only the points located in the fire perimeter are



(a) Real fire (b) Radius = 1 (c) Radius = 2 (d) Radius = 3 (e) Radius = 4 (f) Radius = 5

Fig. 6. Approximating the punctual model by means of circles.

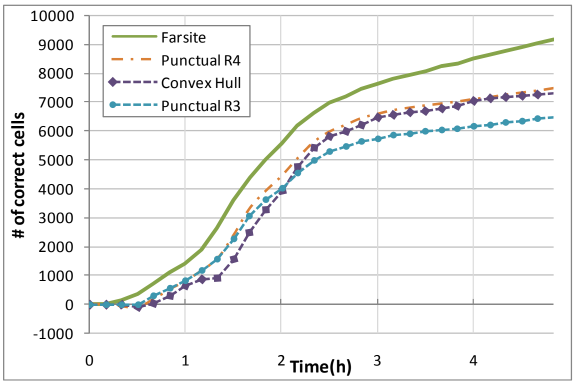


Fig. 7. Quality of the approximation (Farsite vs punctual and convex hull-based models) (network size: 500 nodes).

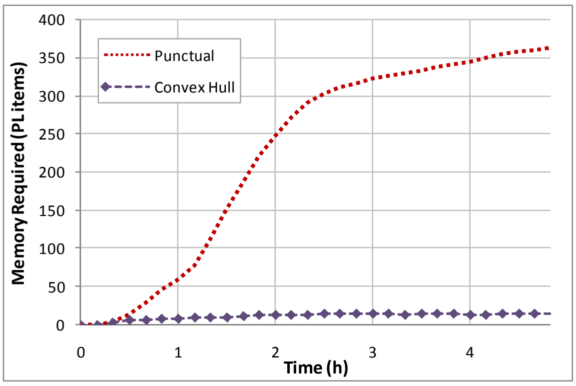


Fig. 8. Memory requirements (network size: 500 nodes).

relevant for this list, and points inside the shape may be discarded.

Fig. 8 shows the average amount of points collected along the time for a network of 500 nodes. Note that the resources consumed by the punctual approximation are independent of the circle considered (there is only one "Punctual" series in the plots), and they are proportional to network size. In the plot we can see that, in average, only 360 points (instead of 500 points) have been gathered after 5 simulated hours. This is due to two reasons. The first one is that the forest fire does not cover the entire deployment area and, consequently, there are nodes that do not detect the fire. The second reason is that, as the fire spreads and the nodes are burned, the network is more and more disconnected, reducing the efficacy of the corresponding broadcastings.

On the other hand, we can see in the plot that the convex hull-based approximation only consumes a few memory resources into the devices. Additionally, these requirements are constant and not dependent on network size.

4) *Scalability of the approaches*: The previous study has been performed for a fixed network size of 500 nodes, analyzing the behavior of the different proposals while a fire is spreading for 5 hours. Next, we analyze the scalability of the different approximations by modifying the amount of nodes deployed over the same area and, consequently, varying network degree.

Fig. 9 shows the amount of correct cells detected by the different proposals in function of connectivity degree. In this case, performance has been evaluated after 3 hours of simulated time. As expected, all the algorithms obtain better approximations when increasing network density. We can notice that highly dense networks provide very similar results, close to the optimal. On the other hand, the performance of the punctual approximations is significantly degraded when they are executed over sparse deployments. On the contrary, the convex hull-based approximation is less sensible to this fact, obtaining better results.

Fig. 10 shows the average amount of points collected (elements in PL) after 3 hours, according to network size. We can see that memory resources required by the punctual approximations increase linearly with network size. The reason is that the amount of fire points increases linearly with network size, and this approximation does not discard any gathered information. On the other hand, the convex hull-based approximation scales very well, because the required resources are constant and not dependent of network size. The reason is that the set of points involved in the perimeter remains relatively stable, whereas the amount of points discarded (due to they are inside of the perimeter) increases linearly with network size.

Finally, Fig. 11 shows the impact of the approximation mechanisms on the overhead transmitted in the wireless medium, through the amount of sent messages (a), pending retransmissions (b), and collisions (c) per node, in function of connectivity degree. As mentioned above, the punctual approximation must retransmit all the gathered points. Therefore, in the plots, pending retransmissions, sent

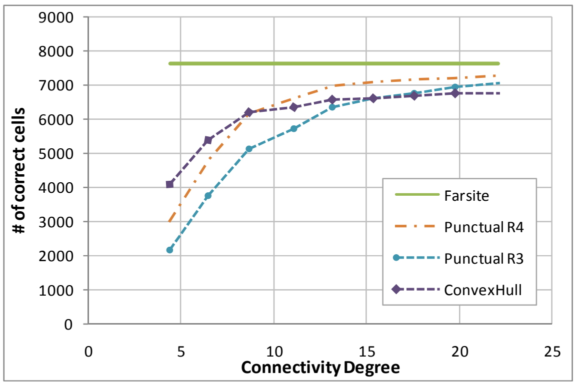


Fig. 9. Quality of the representation for different densities.

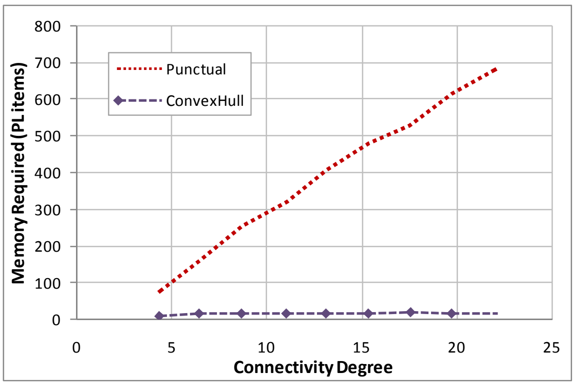
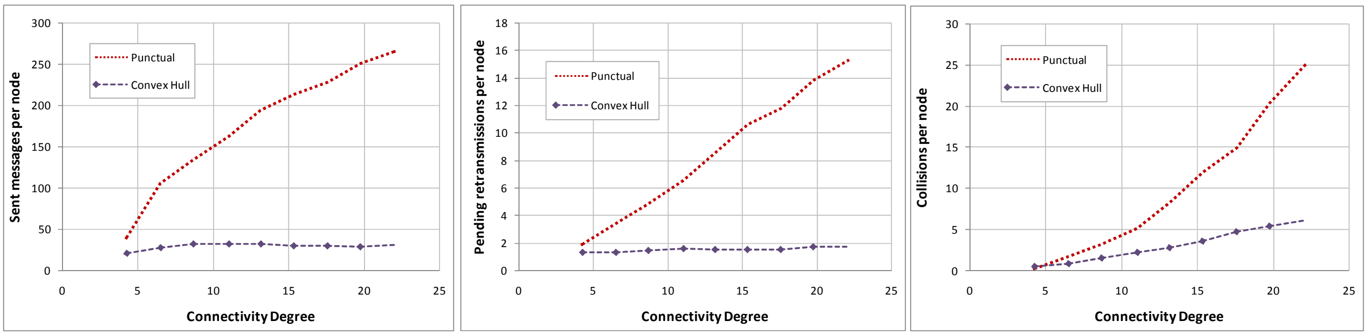


Fig. 10. Memory requirements for different densities.



(a) Messages (b) Pending retransmissions (c) Collisions

Fig. 11. Channel overhead for different densities.

messages, and collisions should exhibit the same behavior than the memory requirements analyzed in the Fig. 10.

On the other hand, in the convex hull-based model, the amount of sent messages is not sensitive to network density. We may conclude that a huge portion of the discarded fire points in Fig. 10 were deleted during the process of insertion into the convex hull, and before they were retransmitted. As a consequence, we get a low overhead, caused by the few points that remain in the perimeter of the fire. Obviously, as this approach reduces the overall amount of messages to transmit, pending retransmissions and collisions are reduced accordingly.

V. CONCLUSIONS AND FUTURE WORK

In this paper we have analyzed some schemes for approximating forest fire shapes with collaborative WSNs working in a completely distributed manner without any base station. First, we considered the punctual model, where each node stored and forwarded all the information it received from the network. However, this algorithm required broadcasting a large number of data packets. Thus, we proposed the convex hull-based model, where the nodes processed the information collected, discarding what was irrelevant. The evaluation of these techniques has shown that the use of the convex hull consumes less resources in both sensor nodes and the shared medium, providing a good approximation to the real fire.

As future work, we plan to improve the way of representing the fire. First, we can reduce the amount of necessary points for very dense networks. Also, we plan to employ better approximations for non convex fires. Taking advantage of the information about the positions not reached by the fire so far and enriching the model with information about the recent fire behavior (speed, direction, etc.) are other future works.

ACKNOWLEDGMENT

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