Performance Analysis of Cooperative and Range Based Localization Algorithms for Zigbee and 802.15.4a Wireless Sensor Networks

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Abstract—This paper deals with the effect of mesh and cluster-tree topologies (that are defined in 802.15.4/Zigbee or 802.15.4a standards) in the performance of cooperative and range-based localization algorithms. In this type of localization at least four reference or anchor nodes within range are needed for location estimation. Therefore the successful localization depends on the connectivity between nodes. Mesh topology allows complex networks because the connectivity between nodes is high, thus this is an advantage for range-based localization. But the mesh structure is energy-consuming. On the other hand, cluster-tree topology simplifies routing and allows energy saving. But in cluster-tree topology the connectivity between nodes is reduced to parent-children relationships. It affects to the range-localization because of nodes can not do ranging with all nodes within range. In order to reach a trade-off between energy saving and low connectivity, in this paper we propose two new solutions for the localization in a cluster-tree Wireless Sensor Network.

Index Terms—Sensor Networks, distributed localization, Zigbee, 802.15.4a, cluster-tree, mesh.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) consist of smart sensors, networked through wireless links and deployed in large numbers. For WSN nodes it is crucial to employ energy-efficient protocols to minimize the lifetime of their batteries. The IEEE 802.15.4 standard is a suitable candidate for this kind of networks. It defines Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs). An alternative Ultra-wide band (UWB) physical layer (PHY) for IEEE 802.15.4 [1] is provided by the standard IEEE 802.15.4a [2] that defines data communication devices with precision ranging. Finally, ZigBee [3] is an industrial standard that defines the network and application layers for sensor networks based on IEEE 802.15.4 PHY and MAC layers. One of the features that the standards characterize is the topology of the WSN. Besides a star topology, the 802.15.4/Zigbee standard supports mesh topology and cluster-tree topology.

WSNs provide applications for monitoring and controlling homes, cities and environment. We focus on positioning (one of the expected applications for the 802.15.4/Zigbee standard) because it is a key enabler for many of the WSN applications. In general, most sensors do not know their location. Sensors with a priori known location are called beacons or references (Ref). Sensors with unknown location information are called non-reference nodes (Nref) and their coordinates need to be estimated using a sensor network localization algorithm [4]. A variety of them, named beacon-based algorithms [5], use the available a priori knowledge of positions of Ref nodes in the network. In this context, localization range-based algorithms [5] rely on distance between nodes that is usually implemented with received signal strength intensity (RSSI), time of arrival (TOA) or time difference of arrival (TDOA) techniques.

In the literature a number of beacon and range-based localization algorithms have been proposed for sensor networks [6], [7], [8] and [9]. Moreover localization with TOA and UWB is performed in some works ([10] and [11]). As most of the previous references are based on mesh WSNs, they do not work with all the 802.15.4/Zigbee and 802.15.4a topologies. Localization with Zigbee and RSSI in a cluster-tree WSN is studied in [12]. However all previous works do not take into account that 802.15.4/Zigbee topologies could limit the localization process. Therefore, a study about the localization for 802.15.4/Zigbee and 802.15.4a based WSNs is needed. In this direction and due to the advantages of the standards in terms of energy consumption, the formation of complex networks and routing facilities, we focus on studying the effect of mesh and cluster topologies that are defined in 802.15.4/Zigbee and 802.15.4a standards in the performance of cooperative and range-based localization algorithms.

The remainder of the paper is organized as follows: in Section II, we introduce the IEEE 802.15.4/Zigbee and 802.15.4a standards. In Section III, we explain the considered range-based localization algorithm. In Section IV, we explain the range-based localization for the mesh and cluster-tree WSNs. Based on this analysis, we propose schemes for localization in a cluster-tree topology. Numerical results are provided in Section V and the conclusions are at the end of the paper.

II. ZIGBEE AND IEEE 802.15.4A OVERVIEWS

A. 802.15.4/ZigBee and 802.15.4a Protocol Stack

The 802.15.4/ZigBee protocol stack is presented in Figure 1. MAC and PHY layers are defined by IEEE 802.15.4 standard [1]. MAC is responsible for the channel access mechanism, acknowledged frame delivery and network association/disassociation. Related to Zigbee, a network (NWK) layer provides network self-organization and multihop routing...
capability. Finally, an application layer (APS) at the top of the stack determines node relationships, and supervises network initiation and association functions. On the other hand, an alternative UWB PHY layer is defined by IEEE 802.15.4a [2] which provides enhanced ranging capabilities. Upper layers are not addressed by this standard.

B. Network Topologies

The 802.15.4 [1] standard defines two types of devices: reduced function device (RFD) a low-complexity node, and FFD, with the complete set of MAC services. In a personal area network (PAN) there is one PAN coordinator that initiates the network. While coordinators collaborate with each other, devices can communicate only with coordinators. FFD can act as coordinator and device, while RFD only can act as a device and can communicate with one FFD. ZigBee [3] uses a different terminology, but we will use the naming of 802.15.4.

The 802.15.4/Zigbee standard supports both the star and peer-to-peer topologies. For large network coverage, a peer-to-peer topology is most suitable. A peer-to-peer topology allows mesh and cluster-tree networks presented in Figure 2. In a mesh network, any coordinator may communicate with any other coordinator within its range and messages can be routed by coordinators. This enables the formation of complex self-organizing network topologies. The network may contain also RFDs as devices. Mesh topologies are suitable for applications where efficient self-configurability and large coverage are important. A disadvantage is the increased network latency due to message relaying. Also coordinators need to listen to the medium continuously to be able to receive data from any node in the range which is energy-consuming. In a cluster-tree network defined by ZigBee, a PAN coordinator initiates the network and becomes root. Nodes are grouped in clusters where a coordinator is the cluster head and multiple devices are leaf nodes. The parent coordinator sends periodic frames to synchronize the child nodes of its cluster. A new candidate device within range receiving a frame may join the cluster as child device. Then the newly joined device begins transmitting periodic beacons as a coordinator; other candidate devices may then join the network from that device. Also the network may contain RFDs as devices that can not send periodic frames to join new nodes. This structure allows energy saving and simple routing because nodes of a cluster maintain synchronization with its parent, while the rest of the time nodes may save energy in a sleep mode [13]. On the other hand, the 802.15.4a standard also supports star and mesh topologies. A cluster-tree topology is not defined since the 802.15.4a standard does not address the upper layers.

C. MAC Layer

The 802.15.4 standard [1] specifies two modes of operation for MAC layer: beacon-enabled and non-beacon modes. Normally, for large network coverage, the non-beacon mode is used in mesh networks and the beacon-enabled mode in cluster-tree networks. In the non-beacon mode, nodes access the medium with a Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) protocol. The power saving features that are critical in WSN applications are provided by the beacon-enabled mode. In the beacon-enabled mode, all communications are performed in a superframe structure. A PAN coordinator sends beacon frames periodically, which are used by network nodes to synchronize themselves to the network. An active part of a superframe is divided into the beacon, a contention access period (CAP) and a contention-free period (CFP). At the end of the superframe there is an inactive period, during which nodes may enter a power saving mode. During CAP, channel is accessed using a slotted CSMA-CA scheme. Coordinators must listen to the channel during the whole CAP to receive data. The CFP optional part of a superframe does not utilize any collision avoidance mechanism, therefore the applicability for large peer-to-peer networks is very limited. In cluster-tree networks, all coordinators transmit beacons to maintain synchronization with other nodes. For minimizing inter-cluster interference, it is desirable to concatenate superframes of neighboring clusters. An example is presented in Figure 3, where the rectangles are the active part of the superframe: black part is the beacon and white is the CAP. The defined parameters that configure the superframe are adjustable by 802.15.4/Zigbee or 802.15.4a standards.

III. COOPERATIVE RANGE-BASED LOCATION

Cooperative and range-based localization algorithms in a WSN consist of four main phases [7]:

• Distance measurement to the Ref nodes with ranging techniques.
• Position computation of a Nref node that can be located.
• Cooperation: once a Nref node has estimated its position, it becomes a reference for other nodes.
• Iterative algorithms refine the estimated positions.

In the application layer shown in the stack of Figure 1, the user can program the functionalities of the node. In our case the
network localization algorithm is controlled by the application layer of the sensor node.

Although there are different techniques for ranging in WSNs, based on [5] and [14], we consider RSSI and TOA based techniques as the most suitable. RSSI technique measures the signal power at the receiver. The advantage of RSSI method vs. TOA technique is that it requires no additional hardware. However while RSSI is greatly affected by amplitude variations of the received signal, TOA with UWB is a much more robust ranging technique since the large bandwidth of an UWB signal provides high time resolution [6]. Concerning TOA based ranging, IEEE 802.15.4a [2] standard defines a mandatory ranging protocol called two-way time-of-arrival (TW-TOA) and an optional Symmetric Double Sided (SDS) TW-TOA Protocol that reduces the effect of the finite crystal tolerances at the local oscillator [2]. The ranging protocol starts when a upper layer (Figure 1) calls a MCPS-DATA.request primitive of 802.15.4a MAC layer with the corresponding attribute to start ranging [2].

In this paper we work with two WSN standards depending on the ranging technique: Zigbee standard with RSSI based method and the 802.15.4a standard with TOA based technique. Also we consider four types of WSNs based on the different topologies: 802.15.4a mesh WSN, Zigbee mesh and cluster-tree WSNs, and a WSN based on 802.15.4a PHY layer with cluster-tree topology similar to Zigbee. For all the considered WSN, we assume a uniform random deployment of nodes. Our WSNs consist of nD devices D and nCoord coordinators C. The group of coordinators consist of nN target nodes Nref and nR reference nodes Ref. In order to locate the jth Nref node we need to calculate its coordinates with a set of Ref nodes within its range. Considering that the positions of the Ref nodes are known, the distances \(d_i\) between the jth Nref node and the reference nodes Ref are estimated. Therefore, \(l = [\hat{x} \; \hat{y} \; \hat{z}]^T\) is the estimate of the target node Nref location, \(l_i = [x_i \; y_i \; z_i]^T\) is the position of the ith Ref node and \(d_i\) is the measured distance between the Nref node and the ith Ref node. For TOA based ranging \(d_i\) is commonly modeled as

\[
d_i = d + g_i, \quad i = 1, 2, \ldots, nR
\]

where \(d_i\) is the actual distance between the jth Nref node and the ith Ref node and \(g_i \sim \mathcal{N}(0, (\sigma_i)^2)\) is additive white Gaussian noise (AWGN) with variance \((\sigma_i)^2\). For RSSI based ranging, \(d_i\) is modeled using the log-normal model [15] as

\[
d_i = d_i \cdot 10^{\frac{V_i}{10p}}, \quad i = 1, 2, \ldots, nR
\]

where \(V_i \sim \mathcal{N}(0, (\sigma_i)^2)\) and \(p = 3\) is the channel path loss exponent.

For positioning, we consider a simple algorithm based on iterative multilateration method with 1-hop ranging is suitable for the purpose of this paper. 1-hop ranging means that the distance calculation is performed with nodes within range. The position of the target node Nref is determined as the intersection of spheres. The centers of these spheres are the coordinates of the reference nodes Ref and their radiiuses are the ranges between the reference nodes Ref and the target Nref within range. The spheres may be described as

\[
(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 = d_i^2, \quad (i = 1, 2, \ldots, nR)
\]

The accuracy of range estimation is affected by noise and the multipath components, thus the spheres will not always intersect at one single point. We consider the Least Squares (LS) method to solve (3). LS minimizes the function:

\[
\hat{i} = \arg\min_{i=1}^{n} R(d_i - ||l - l_i||)^2
\]

The LS solution [16] is given by:

\[
\hat{i} = \frac{1}{2} (H^TH)^{-1} H^T b
\]

\[
H = \begin{bmatrix}
x_2 - x_1 & y_2 - y_1 & z_2 - z_1 \\
x_3 - x_1 & y_3 - y_1 & z_3 - z_1 \\
\vdots & \vdots & \vdots \\
x_{nR} - x_1 & y_{nR} - y_1 & z_{nR} - z_1
\end{bmatrix}
\]

\[
b = \begin{bmatrix}
K_2 - K_1 - d_2^2 + d_1^2 \\
K_3 - K_1 - d_3^2 + d_1^2 \\
\vdots \\
K_{nR} - K_1 - d_{nR}^2 + d_1^2
\end{bmatrix}
\]

where \(K_i = x_i^2 + y_i^2 + z_i^2\). For three-dimensional position estimation at least four reference sensors \((nR \geq 4)\) are required for the location estimation. In conclusion the proposed steps for our network localization algorithm are detailed as follows:

1) 1-hop ranging to Ref nodes: Ref nodes start the ranging phase with coordinators of its range.

2) Positioning with multilateration: if Nref coordinator \(j\) has four or more Ref nodes within its range, its position is estimated with LS algorithm. \(j\) becomes a located node (LN) that can be a reference for locating other Nref nodes within range. Otherwise, coordinator \(j\) continues trying to learn its position.

3) Cooperation: this process is repeated until the positions of all the nodes that eventually can have either four Ref or LN nodes are estimated.

4) Refinement: for LS, a larger value of \(nR\) results in more accurate position estimation of a LN.

IV. TOPOLOGY CONSTRAINED NETWORK LOCALIZATION

A. Mesh Topology

Mesh topology allows a high connectivity between nodes. In fact in a Zigbee or 802.15.4a mesh WSN any coordinator may communicate with any other coordinator within range. For cooperative and iterative range-based localization the success of the location discovery depends on the network connectivity (7]). Therefore the connectivity allowed by mesh topology is an advantage because the topology does not limit the communication between nodes within range of each other. In our case, range-based techniques for positioning such as multilateration need at least four 1-hop range estimations (three dimensions) with Ref or LN nodes. However in a 802.15.4/Zigbee or 802.15.4a network there is a limitation: RFD devices may communicate with one coordinator within its range, therefore in our case RFD devices can not be located.
Without cooperation between nodes, the probability to locate a node follows a three-dimensional Poisson distribution $f_P(k, \lambda)$, where we consider $\lambda$ is density and $k$ the number of deployed Ref nodes within range. Therefore the probability to locate a node is the probability with at least $k \geq 4$. It is given by

$$Pr(k \geq 4, \lambda) = 1 - f_P(k < 4) = 1 - (f_P(k = 0) + f_P(k = 1) + f_P(k = 2) + f_P(k = 3))$$

However with cooperation, the new deployment of LN nodes does not follow a Poisson distribution because these deployments are not random.

B. Cluster-Tree Topology

In a cluster-tree topology of Zigbee (and in our 802.15.4a WSN with cluster-tree topology) nodes are grouped in clusters. Thus any coordinator may communicate only with its parent and its children of its cluster (Figure 2). Therefore the connectivity between nodes is limited by these parent-child relationships. This excludes communication with other coordinators that may be in range. As a result, less nodes are available for multilateration-based localization, which is more likely to fail. In our case, as we consider 1-hop ranging between nodes, one coordinator $j$ could be located with LS under the conditions: 1) it has at least four range estimations with Ref coordinators, and 2) these Ref coordinators have parent or children relationship with the $j$ coordinator. As in the mesh topology, RFD devices can not be located with 1-hop ranging and LS.

C. Improved Localization in a Cluster-Tree Topology

Mesh topology allows high connectivity between nodes which is an advantage for range-based localization. But mesh networks are energy-consuming and its network latency is increased due to message relaying. On the other hand, a cluster-tree network is formed by parent-child relationships limiting the connectivity between nodes. This is a limitation for range-based localization, but this structure allows energy saving and simple routing. By trying to reach a trade-off between connectivity and energy saving, we propose that ranging is controlled by MAC layer: the ranging application is done in a MAC level, as in the IEEE 802.15.4 standard (Figure 1). The application layer (that controls the localization algorithm) calls the corresponding MAC primitives directly for doing ranging between two nodes. In order to follow this solution, the MAC level frames for ranging should work with the Zigbee or upper layer superframe structures without collisions. For that two schemes are proposed:

1) Ranging during the CAP of the superframe that consists of a CAP and an inactive period (RCAPS): nodes access the medium with CSMA-CA protocol during the CAP of the superframe to exchange ranging frames (Figure 3). A coordinator $j$ uses the CAP of its parent cluster superframe for ranging with its brother coordinators (coordinators with same parent or coordinators following the same superframe) and its parent coordinator of the cluster. And this coordinator $j$ also performs ranging with its child coordinators during the CAP of its child cluster superframe. An example is shown with coordinator C in Figure 5.

2) Ranging during the CAP of the superframe without inactive period (RINPS): nodes access the medium and do ranging with CSMA-CA protocol (Figure 4). The main advantage of RINPS is that any coordinator can do ranging with any other in range. An example is shown with the coordinator C in Figure 5. Besides its brother coordinators, it also can do ranging with coordinators within range of other clusters.

For 802.15.4/Zigbee standard, ranging process is done with RSSI technique [3] and the 802.15.4a standard uses the TOA-based ranging method and (SDS) TW-TOA protocol [2].

While RINPS scheme does not suffer of the limitations of the communication between nodes due to topology, in the RCAPS case there are some limitations that will cause a lower number of located nodes with respect to RINPS. In the RCAPS solution the coordinators will follow the superframe
structure for doing ranging, therefore they will be in sleep mode during the inactive period saving energy. Also in this solution the beacons of the brothers clusters are concatenated following Zigbee standard and avoiding collisions. In RINPS scheme the value of the parameter Beacon Interval (BI) equals Superframe Duration (SD) value (BI=SD). This situation is allowed in 802.15.4 standard. Also since this situation is not forbidden in Zigbee specification, we consider it is allowed in both standards. Coordinators will waste more energy during the network localization because there are not inactive period in the superframes. Methods to reduce collisions as well as energy consumption are suited. For example, one method for saving energy could control BatteryLifeExtension parameter to disable the receiver of the beaconing node if there are not pending packets [1] or if that node finished the cooperation in the network localization. After network localization is finished, coordinators can configure again the superframes with CAP and inactive periods.

V. Simulations and Results

In this section we present the simulations of the range-based localization algorithm explained in Section III in different WSN topologies: mesh topology defined by Zigbee and 802.15.4a standards, cluster-tree topology defined by Zigbee and a cluster-tree topology with 802.15.4a PHY layer. Also we present the results of our solutions (RINPS and RCAPS) for the cluster-tree topologies. All the considered WSNs consist of $nC = nN + nR$ coordinators $C$. There are $nN$ non-reference coordinators $Nref$ and $nR$ reference coordinators $Ref$. Nodes are randomly deployed in a cell of dimensions $Dim = 100x100m^2$. The range of the nodes equals 25m, the standard deviation for TOA $\sigma_t = 0.3$ and the standard deviation for RSSI $\sigma_s = 0.6$.

Taking into account the described scenario, Figure 6 and Figure 7 show the number of located coordinators (%) versus the density of coordinators within range. We considered two cases for the number of Ref nodes, in Figure 7 the Ref coordinators number increases as $nR = nN/6$, while in Figure 6, $nR = nN/3$. When there is no cooperation for localization, with mesh topology the number of located nodes is small and also follows a Poisson distribution. When there is cooperation for localization, once a node is located it becomes a reference for other nodes. This process depends on the connectivity between nodes. In this case, for cluster-tree topology, the number of located nodes is very small. However in a WSN with mesh topology, the localization of all nodes (100%) is performed for density of $Nref$ coordinators within range of 6 (and 3 Ref coordinators)(Figure 6). For cluster-tree topology with RCAPS solution, the total number of located coordinators increases with respect to cluster-tree topology, but this number is lower than for RINPS solution. For cluster-tree topology with RINPS solution, the total number of located coordinators is similar to mesh topology, therefore the limitations of localization in a cluster-tree topology are eliminated. Results show that in mesh topology and RINPS case with cluster-tree topology, coordinators estimate their positions doing ranging with all coordinators within range, while in RCAPS solution coordinators can do ranging with its parent, children and brothers (Figure 5). And for cluster-tree topology, the limitation is higher because of ranging only can be done between parent and children.

Figure 8 shows the RMSER of the located coordinators position with TOA based ranging versus the density of $Nref$ coordinators within range ($nR = nN/3$). For mesh and RINPS solution, the RMSER is smaller than for RCAPS solution due to the refinement phase. In this phase a larger value of $nR$ results in more accurate position estimation with LS method. For RCAPS solution, less LN coordinators can participate in the localization of another coordinator. For the cluster-tree topology, since the number of located nodes is smaller than in RINPS, the RMSER is also smaller. For RSSI based ranging (Figure 9), the results are similar, however the RMSER increases for all the cases.

For this work, we have considered 1-hop range-based localization to show the results. Because of this, in RCAPS case the number of located nodes is smaller than in RINPS and devices (RFD) can not be located. But our solutions can be used with multi-hop range-based algorithms such as [7] or [8] in which ranging can be done with reference nodes not within range. These algorithms can locate nodes with low connectivity and also the devices (RFD) that consume less energy than coordinators (FFD). With multi-hop ranging, our solution can increase the 1-hop ranging number between nodes. With 1-hop ranging the error positioning is more accurate than with multi-hop ranging, therefore our solutions allow to improve the distance estimation accuracy. In a future work, we will analyze all these situations.

VI. Conclusion

In this work we have focused on studying the effect of mesh and cluster topologies that are defined in 802.15.4/Zigbee and 802.15.4a standards in the performance of cooperative and range-based localization algorithms. In this type of algorithms
the success for localization depends on the connectivity between nodes. With a localization algorithm based on 1-hop ranging between nodes, the range-based localization is suitable with mesh topology because the connectivity between nodes is high. But the mesh structure is energy-consuming. On the other hand, cluster-tree topology with beacon-enabled frames structure simplifies routing and allows energy saving. But the range-based localization is not suitable in cluster-tree topology because the connectivity between nodes is limited a the parent-children relationships. Trying to find a trade-off between the connectivity of the mesh WSN and the energy saving of the cluster-tree WSN, we have proposed two new solutions for the limitations of the range-based localization in a cluster-tree WSN. Both solutions allow increase the nodes number to do ranging within range and results show they improve the number of located nodes. Also both solutions can be used with multi-hop range-based algorithms.

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REFERENCES