COOPERATIVE DETECTION IN COGNITIVE NETWORKS TO INTERFERENCE CONTROL IN LICENSED SYSTEMS

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ABSTRACT

In cognitive networks, opportunistic network devices can be programmed to take advantage of licensee idle time and dynamically adapt their operational parameters to improve transmissions. In order for this to be successfully accomplished, it is critical that these idle periods be detected reliably. Promoting this requirement, the work presented here proposes a cooperative detection mechanism for signals transmitted by the licensed system, through the use of location sensing equipped devices. Such devices can provide information for transmission and control of the opportunistic network devices to limit the interference in the licensed system. The simulations performed show that in an ad hoc scenario it is possible to improve the quality of opportunistic network communications by maintaining the interference within the specification limits.

1. INTRODUCTION

The increasing demand for radio frequency bands together with the inefficient use of licensed bands [10] has given rise to the possibility of opening these sub-utilized frequency ranges for dynamic and opportunistic spectrum access [2]. Much of the recent research into reconfigurable networks (fixed and mobile) has focused on devices such as cognitive radio [6], a natural evolution of software-defined radio technology that fuses aspects of artificial intelligence with radio communications that are capable of dynamically adjusting its transmission power according to the environmental conditions.

Cognitive networks [14], as opposed to legacy networks, are capable of adapting their operations (proactively or reactively) in response to external stimuli. It is possible through mechanisms that can read environmental stimuli and learn from these interactions exploiting this knowledge to make future decisions.

Despite this flexibility, it is not clearly known that cognitive radios, integrating part of an opportunistic cognitive (or, secondary) network, work without causing excessive interference in licensed (or, primary) systems. This understanding is essential in allowing secondary systems to share and regulate frequency ranges. In the USA, analogue TV band is governed by the FCC (Federal Communications Commission) which has established new usage rules for 2009 [3]. In addition to this issue, there is no consensus that distinct wireless networks, sharing the same frequency ranges, work properly under transmission control power without causing interference to other networks and systems.

The problem of interference among primary and secondary devices has been receiving great attention lately [7, 8, 9, 21, 22, 23]. In all cases, the approaches used theoretical and probabilistic analysis, based on a primary network model with one transmitter and multiple passive receivers.

Varying this network model somewhat, we have proposed a secondary ad hoc network of FIXED and MOBILE nodes, composed of cognitive radios, that cooperatively detect the primary network transmissions and use that information to adjust transmission power while maintaining interconnectivity between each and dynamically controlling the interference seen by the primary network. In this instance, communication connectivity is commonly understood as a simple quality indicator.

In this article, an overview of the basic concepts needed to understand the work is presented along with a description of the component elements of primary and secondary networks. In Section 3 the parameters used are quantified, the scenarios employed are described and the results of the simulation are presented. Finally, article is concluded in section 4 and future works are mentioned.

2. DESCRIPTION AND SYSTEM CONCEPTS

The proposed system is composed of a secondary *ad hoc* network with FIXED and MOBILE nodes consisting of cognitive radios that enable the cooperative detection of primary network transmissions. This information is used to adjust the transmission power. The connectivity between each node is maintained and the interference detected by the primary network is controlled dynamically.

The primary network is a licensed network that uses the frequency band (the band of interest). The secondary network operates in an opportunistic way, and avoids exceeding the interference limits as specified (and communicated) by the primary network.

In both networks, all nodes are transceivers that do not use spread-spectrum techniques, exchange data always within the same frequency band (interest band), and use a medium reservation mechanism similar to RTS/CTS in IEEE 802.11b in order to reduce the hidden terminal problem and maintaining other nodes within range aware of the communication underway.

No control channel is established, but distributed control is exercised in the secondary network via a message exchange. A description of the networks is follows this section.

Primary Network. Primary network nodes (P) are only capable of communicating between each other and have a fixed transmission range (standard range) that is used as

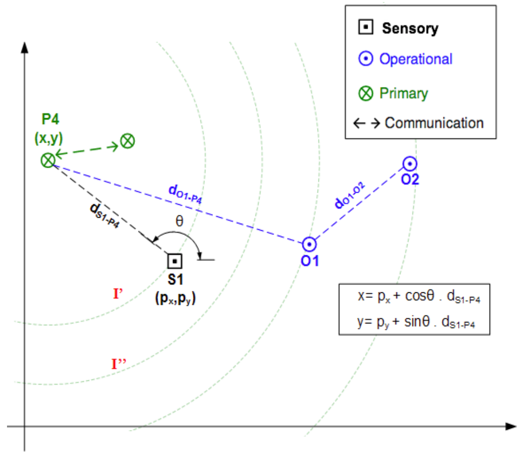

Figure 1: Interference circles and primary nodes localization mechanism.

the reference value for other nodes. While they are transmitting (location window), the primary nodes can be detected and located by sensory nodes of a secondary network.

The interference limit (I) is specified by the primary nodes and communicated to the secondary network. The value, *a priori*, is referenced to the node position, but it could be calculated for another position if the existence of *permissible interfering signal level circles* that increase with distance were to be considered (Figure 1).

Secondary network. Use cognitive radios and are comprised of nodes carrying out a direct operational and sensory function. These nodes are responsible for network communication and sensing. They are responsible for cooperative detection of primary node transmissions and for signal direction and distance calculations. The *sensory nodes*, S, operate on the secondary network node performing sensory function; and the *operational nodes*, O, operate on the secondary network node performing operational function.

In order to reduce problems caused by multipath and shadow effects [15], and to improve accuracy of the primary users' detection, we implemented cooperative sensing for all sensory nodes .

The ability of secondary network nodes to estimate their own position is of a great importance for network operation. When choosing a positioning system, the most important requirements are precision, reliability, scalability and energy efficiency. Despite not having actually implemented them, we have supposed that all secondary network devices have a positioning system.

Most of the time, *sensory nodes* are in passive mode (not transmitting) and remain committed to reading primary node transmissions and estimating location. This, they do via two mechanisms:

- *Transmission detection mechanism*. Signal detection mechanisms have found a variety of scientific applications, including communications. In [20] we found a collection of techniques and results using signal detection techniques developed in the last few decades. Since then, some methods have been proposed with the goals of: energy detection [18], signal wave-shape detection [4], signal ciclostationarity detection [18], matched filter detection [1], and etc. Each with its advantages and disadvantages, according to the signal characteristics to be detected. To simplify the setup, we have assumed that sensory nodes within range can detect transmissions from other nodes using the energy detection method.

If the sensory node finds a detected signal to be other than a secondary network node, it will alert all in-range operational nodes that a primary node transmitter is present. These sensory nodes then begin calculating their position by way of a primary location mechanism. As soon as a transmitting primary node is located, the sensory node passes another message to the operational nodes with the estimated position of the primary node transmitter. This sensory node then resumes passive operation until another transmission is detected.

- *Primary location mechanism*. This mechanism is initiated after the detection of the transmission node by the mechanism above and its negative identification as a secondary network node.

The basic requirement of any location system is to allow the correct distance measurement between any two network nodes. Several proposals were made seeking the determination of that distance including the following: Time of Arrival (ToA), Time Difference of Arrival (TDoA), Angle of Arrival (AoA) and Received-Signal-Strength (RSS) [5, 17]. In such systems, the main sources of error originate from the non line of sight (NLOS) devices and the uncertainty in the measurement itself. Methods to detect and correct errors due to NLOS are presented in [13, 11].

In a general, errors in distance measurements vary over time or are static, but vary depending on the environment. Performing multiple measurements within a time window and calculating the average can reduce temporal variation errors caused, for example, by additive noise and interference. The static errors dependent on environment are mainly the result of obstacle disposition in the operational area. When the operational area is irregular, this type of error is considered unexpected and it can be modeled as a random variable.

For the purposes of this article, we assumed that the AoA method is used by the sensory node to obtain a position line on which the primary node transmitter is located. The RSS method has also been used to obtain distance estimates for the same primary node.

The (x,y) position of the detected primary node has been obtained according to Figure 1 and informed via a message sent for operational nodes within range. The precision for estimating the position of transmitter node and its distance will depend exclusively on the number of sensory nodes that perform the detection. In case of multiple simultaneous transmissions detected by the same sensory node (more than a detected node)[1], the location window is prolonged.

The *operational nodes* are capable of communicating between each other (point-to-point) in a similar way as the primary nodes and operate within the same frequency band, as long as it's not in use, so as not to exceed the interference limit, I. In exchange, they receive information from sensory nodes in order to control its transmission power. Their transmission range is adjustable between zero, corresponding to no transmission, and the standard range, correspond-

[1] The different simultaneous transmission detection is related to spatial separation of the signals detected concerning beam sensors that comprise a directional antenna used in the detection.

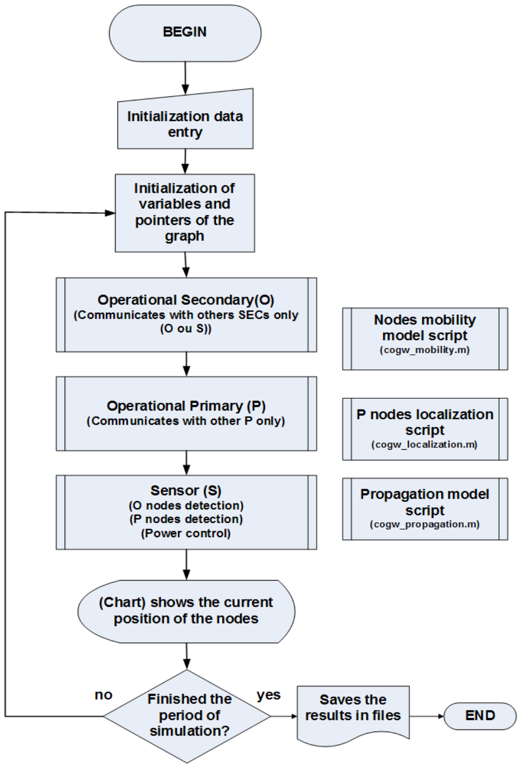

Figure 2: Simulator flow chart built using Matlab.

ing to using the maximum transmission power.

When the estimated position of primary node transmitter is known, the operational node accomplishes the adjustment of its transmission power. This adjustment is made possible via the information received by the sensory nodes that promoted detection and location.

In order to validate the proposed system, we made the following assumptions about the operation of the networks:

- All messages exchanged over the secondary network include identification of node origin, node destiny, position and transmission power;
- All sensory nodes have a receiver sensitivity of 10 dB above the noise floor in the frequency band of interest;
- All sensory nodes have a pair of antenna: one for communication and another (directional antenna array) to detect primary transmissions (AoA);
- In the operating area of the network there are no other radio frequency emissions capable of introducing significant errors in the proposed mechanisms;
- All communication occurs via error-free message exchange. However, at this stage of the evaluation, we do not consider the throughput or the use of routing protocols.

3. SIMULATION: DESCRIPTION AND RESULTS

To evaluate the behavior of the cognitive network, we built a simulator using Matlab [12]. This simulator was divided into blocks as is shown in the flow chart (Figure 2).

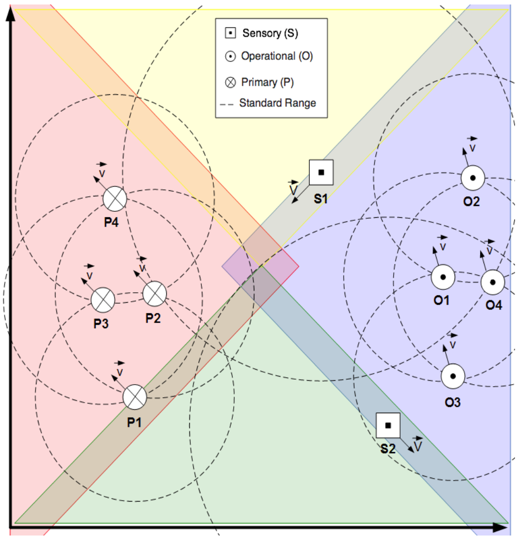

Figure 3: Positioning and mobility schemas for FIXED and MOBILE scenarios.

In order to evaluate our networks' behavior we created four scenarios: three FIXED and one MOBILE.

In the **FIXED scenarios**, initially we distributed the sensory nodes over the area and soon afterward, the other nodes. All were arranged so that the signals transmitted both by primary as well as operational nodes could reach the sensory nodes. The position of the nodes in both networks was important, the main requirement being that the primary and secondary networks did not totally intersect and cause transmission drop-outs in the secondary network while trying to maintain interference limits. Primary nodes were always within each other's range (Figure 3) as were the operational nodes initially. The scenarios were as follows:

- Scenario 1: 2 operational nodes (O1 and O2), 2 primary nodes (P1 and P2) and 2 sensory nodes (S1 and S2);
- Scenario 2: 4 operational nodes (O1 to O4), 2 primary nodes (P1 and P2) and 2 sensory nodes (S1 and S2);
- Scenario 3: 4 operational nodes (O1 to O4), 4 primary nodes (P1 to P4) and 2 sensory nodes (S1 and S2).

The initial transmission power of the operational nodes was between 80% and 100% of that needed to reach the standard range. Communicating primary nodes used the maximum transmission power, within the standard range.

Signal is received in the position of sensory node as pr, already attenuated according to the *log-normal shadowing* propagation model [16]. So, in the sensory nodes, we have to guarantee that $(\sum pr_O \leq I')$ (Figure 1) not causing interference above that allowed by the primary nodes.

Following the Figure 3, S1 node initially makes the detection before S2 and detects first O1 (and O3) and later P1 (and P3). In that case, we should point out that simultaneous transmission of operational nodes is prevented by the reservation mechanism of the operational nodes. Depending on the scenario, S1 node will make the following calculations where variable η represents the noise floor:

$$SINR_{O1} \approx \frac{pr_{O1}}{\eta} \;,\; SINR_{O3} \approx \frac{pr_{O3}}{\eta}$$

(Without interference among the P nodes)

$$SINR_{P1} \approx \frac{pr_{P1}}{pr_{O1|O3} + \eta}\ ,\ SINR_{P3} \approx \frac{pr_{P3}}{pr_{O1|O3} + \eta}$$

In the case of a packet collision in receiver S1, (due to simultaneous transmissions or RTS/CTS packets) measurements are rejected and instead, S1 waits to receive discrete signals.

In the **MOBILE scenario (4)**, composed by 4 operational nodes (O1 to O4), 4 primary nodes (P1 to P4) and 2 sensory nodes (S1 and S2), the available area was divided into four sections bounded by the diagonals of a square. The primary and operational nodes were positioned in opposite sections, with a small overlap near the center of the square (Figure 3), that within the respective sections follow the group mobility model based on *Reference Point Group Mobility (RPGM)*.

The movement of sensory nodes followed the *Fixed Waypoint (FWP)* mobility model. Movement was executed in opposing directions along two semi-diagonals of the square bounding the operational nodes. The mobility models are described in [19].

In this scenario, S1 and S2 can detect the transmissions of nodes O1 to O4 as well as nodes P1 to P4, though, not consistently as a result of the movement described above. The initial power transmission value of nodes was chosen in the same way as that in the FIXED scenarios.

The signal received in the sensory node position is pr, and, it is already attenuated according to the propagation model. However, in the sensory node we have to guarantee that $(\sum pr_O \ \leq \ I')$ at a certain instant of time (snapshot).

In the same way as in FIXED scenarios, the problem is approached such that in case of a packet collision at S1 receiver, the measurement is discarded and new detection is awaited. As the node's speed is low, for the purpose of calculations we assumed that the reserved medium circle centered on the nodes [2].

Sensory node measurements are performed the same way as for the FIXED scenarios, but the increased mobility creates complications, mainly for the primary location mechanism that needs to establish a position line in a short time interval (location window $\leq$ snapshot).

For the simulation, we used an obstacle-free square area with side D where we positioned the nodes for each scenario. The variables employed, as well as their values are summarized in Table 1.

Name	Value	Obs.
D	100m-3000m	square area side
f	1GHz	utilized frequency
η	-100.9dBm	*noise floor*
X	$N(0; 5^2)$	log distance path loss
Y	$N(0.01d; 0.05d^2)$	range error (RSS)
ϵ	1%	positioning error
ϕ	1%	AoA error

Table 1: Used variables.

For the calculation, we have assumed that transmission medium is the atmosphere, at sea level, with unit refractive index and that the propagation speed of radio frequency waves is the same as that of light in vacuum. Transmission power (EIRP) is 0 dBm and it corresponds to the standard range.

[2]However, as the nodes are in movement, the reserved circle cannot assume a circular shape centered on the sensors themselves. It can assume any form.

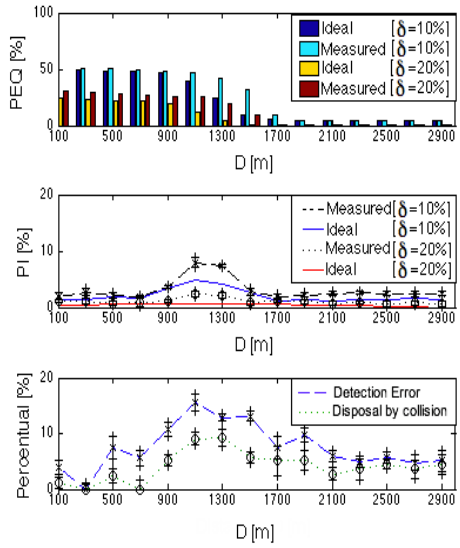

Figure 4: Scenario 1.

We represented the shadowing effects on log-normal shadowing propagation model as a normal random variable $X \sim N(\mu, \sigma^2)$. The maximum exchange time of messages (RTT) is on the order of hundreds of μseconds, for the largest distances between the nodes.

In relation to the location of primary node transceivers, we considered only one error in estimated distance d, that takes into account the variable and static errors dependent on the scenario, and which has been modeled as a normal random variable $Y \sim N(\mu, \sigma^2)$ [17]. The angle of arrival determination error (ϕ) and the error due to positioning system (ϵ) are both fixed.

In the MOBILE scenario, the nodes have maximum speeds of 1.8 m/s, equivalent to a common walk. With that in mind, the displacement of nodes during the exchange time of messages plus time spent by the location mechanism to obtain a P node estimated position maximum of 6.5 m.

We considered an interference on the primary node when interference level I is surpassed. As adjustment methods for power control mechanism, we employed 10% and 20% values for the adjustment factor δ [3] in the calculation of I (interference limit projected onto the sensory node position).

For the value of I we used -90 dBm, similar to that used as the detection limit of the commercial carrier interfaces that follow the IEEE 802.11b standard. The value of I is referred to the (fixed) limit of interference tolerated by primary nodes, which is released at the beginning of the oper-

[3]The use of an adjustment factor aims to minimize the effects of errors during detection of transmissions of primary nodes as well as the collision effects in sensory nodes among packages from operational and primary nodes, which can be observed for the scenario 1 (Figure 4). These errors are not deterministic, since their causes are not deterministic either.

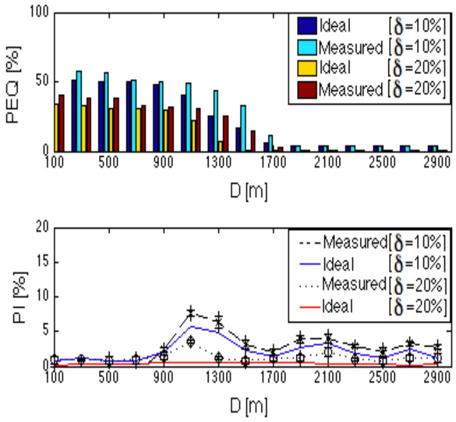

Figure 5: Scenario 2.

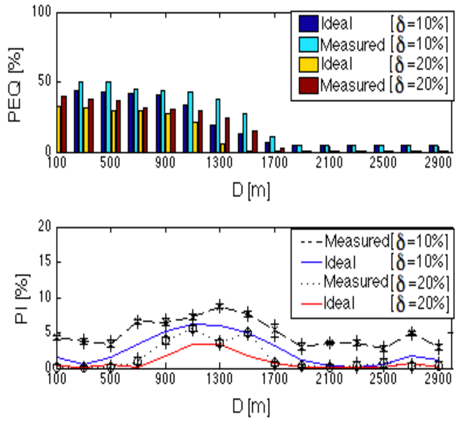

Figure 6: Scenario 3.

ation of the primary network.

Our intention is to show that it is possible for a secondary network to operate without interfering with the licensed network, since that network itself communicated the allowable interference limit by way of its transceiver position. Therefore, we have evaluated individually in each scenario the *interference percentage (PI)* larger than I, in the P node transceiver while observing communication among operational nodes.

We also show that the communication quality can be maintained in the secondary network despite restricting the interference generated by evaluating the connectivity of our operational nodes. In that case, we evaluate the *percentage of broken links (PEQ)* in the secondary network through power control performed by the operational node.

To compare, we created an external network entity that acts acted as a reference, providing ideal, error-free measurements for position, location and transmission of the primary node. That entity provided *ideal* values for PI and PEQ.

In order to observe the behavior of the nodes we varied the available square area altering the value of D that corresponds to square's side length. For the simulation, we varied D from 100 m to 3000 m using a 100 m scale and for each scenario, we did 30 simulation rounds for each value of D for a total of 900 rounds.

Data traffic in the primary network was modeled as an ON/OFF exponential source, with the ON and OFF period averages, respectively, equal to 700 ms and 300 ms. Data was generated at the rate of 64 kbps during ON period. With this information we started to analyze the results.

For $\delta = 10\%$, in the FIXED scenario 1 (Figure 4), it is interesting to note that the *measured value PI* is always larger than zero on the primary node, but for D of 100m-800m and for D between 1600m-3000m, the value of PI is lower, less than 4%.

For values of D between 800 m and 1600 m, the value of PI has a maximum value of 9%. Analyzing the causes of this increase, we see that the sensory nodes have a high number of message collisions transmitted simultaneously by operational and primary nodes in the same intervals of D values. During such message collisions we observed that the sensory nodes discard the measurements, causing PI to increase.

Another contributing factor to the interference is the time window needed for the location mechanism to obtain the estimated primary node position. During that period, operational nodes continue transmitting and causing interference. Additionally, the signal from the primary node fades as the distance from the sensory nodes increases resulting in poor detections.

Behavior similar to the FIXED scenario 1 can be observed in other FIXED scenarios (Figures 5, 6 e 7) and can be attributed to the explanation given above.

In the MOBILE scenario (Figure 7), we have observed that an increase in PI does not occur as it does in the FIXED scenarios, due to variation of node position.

The low speed of nodes along with the restriction of their movement to defined areas and with little intersection among them, produce a value of PI that remains lower than 10% throughout the all simulation.

In relation to the *value of PEQ* as measured in the secondary network (Figures 4, 5, 6 e 7), we see that in all scenarios, PEQ values are high for small values of D and decrease as D increases.

This behavior can be attributed to the small distances among nodes and several intervals of silence in the primary nodes causing a great need to control the transmission power in the secondary nodes, as they can cause high values for PEQ. Even in such unfavorable conditions, it is possible to maintain the connectivity of links (100%-PEQ) to within about 40% to 50%, according to the scenario.

Up to a certain value of D, due to the propagation effects, the signals have a smaller reach, and thus turn-on the power control less frequently causing a more accentuated decrease in PEQ curve.

Increasing δ to 20% and observing, firstly, the FIXED scenarios, we have noticed that measured PI is approximately zero, assuming values of up to 6% for the values of D between 800 m and 1600 m, where the incidence of detection and collision errors is high. The value of measured PEQ also presents a reduction and, consequently, the connectivity of links (100%-PEQ) increases to 60% to 70%, according to the scenario. In the MOBILE scenario, we observed that the measured PI maintains a value below 7% for the whole range of values of D, and the measured connectivity is 60%.

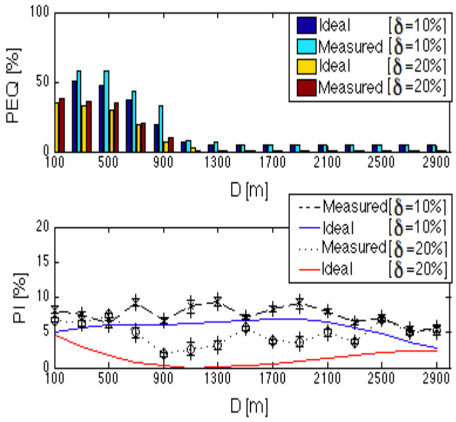

Figure 7: Scenario 4.

4. CONCLUSIONS

As a result of the goal of network and service convergence, the need for spectrum reuse and increasing inclusion and popularization of broadband access among other factors, we conclude that it is only a matter of time that we will see large numbers of secondary networks in operation.

Varying the model of a primary network where there is a transmitter with multiple passive receivers, our results, with two *ad hoc* networks and FIXED and MOBILE nodes, show that we can implement a (simple) interference control on primary nodes with only a mechanism of individual positioning and a signal source detection system (goniometer). At the same time maintaining an acceptable connectivity level among secondary network nodes, a simple indicator of quality in the communications.

For future study, we hope to adjust the location/positioning mechanism for greater effectiveness, implement a mechanism for collision reduction and establish other metrics and more "populated" scenarios for evaluation.

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