Expanding the Coverage Area of a Formation of Robots Through a Mesh Network and a Real Time Database Middleware

Leandro J. Caetano, Tiago P. Nascimento
LASER - Embedded Systems ans Robotics Lab
Department of Computer Systems
Federal University of Paraiba (UFPB)
Cidade Universitaria - João Pessoa - PB - Brazil
Email: leandrocaetano@ct.ufpb.br, tiagopn@ci.ufpb.br

Márcio Adamec L. Oliveira, Gláucio B. Rocha
Department of Computer Systems
Cidade Universitaria - João Pessoa - PB - Brazil
Email: {marcio.adamec, glauciobr}@gmail.com

Abstract*—The communication between robots is essential and of great interest in the robotics research field. It is from it that robots can discover and pass on information about obstacles in their way, pass on to the other robots information about a target that other robot can not detect, determine together which is the best route to follow, among others, until the goals are achieved. The major difficulty in the context where robot communication exists in an ad hoc network is distancing the robots from each other. So that one of them for example, may migrate to another area leaving their initial formation, completing a specific task and return to the starting point, in addition to distancing the whole formation of robots from a central computer. By distancing a robot from the limits imposed by other means will entail a loss of signal compromising communication between them. The challenge, therefore, is to maintain communication between these same elements even though they are apart. The purpose of this article is to demonstrate the feasibility of expanding the coverage area of a formation of robots that use a Real Time Database (RTDB) under an ad hoc network communication, by including them in a Mesh network. According to the performed experiments, we proved that the inclusion of robots in this type of network, and using the RTDB, has added the ability aforementioned thus allowing robot control from a central point, called the Basestation, and therefore enabling the distancing between its components without loss of communication between them.

I. INTRODUCTION

The use of mobile robots working cooperatively became an essentially important fact in robotics [1]. The division of tasks between various elements simplifies the actions and decrease their performance runtime. This is due to the fact that, by working jointly multiple robots can share information with each other, help each other and share responsibilities [2]. By working together and cooperatively these robots can complete a task faster than working alone. Multi-robot systems formation relies on communication between agents to maintain cooperation between them so the formation can move in any environment helping each other in order to overcome barriers and achieve their goals. This raises several issues due to noise and distancing between robots. This type of cooperation was described by [3] in a communication project for robot soccer game [4]. It is an approach where several robots (agents) can maintain communication with each other through a Wi-Fi network using a TDMA (Time Division Multiple Access) system, described in [3]. The TDMA was called Adaptive TDMA in another study by the same authors [5], which consisted of a modification that allowed a self-supporting configuration of the agents in the case of changes in the number of robots without clock synchronization, as well as self - configuration of the communication channel that interconnects the agents. When an agent wants to provide any information, he places it in a shared memory area, where any of the other agents can get it directly. Each agent transmits information he want other agents to retrieve, at periodic intervals, in a multicast communication. This information can be related to the location of the robot itself or any other information. This storing and information sharing system is called a Real-Time Database (RTDB) middleware for collaborative robotics [3].

In the work done by [6], the authors proposed a change in the synchronization protocol for RTDB, allowing its operation in ad hoc networks. This change also allowed the flow of data to be transmitted, in an effective way, through the ad hoc network, contributing to more accurate measurement of the distance between the mobile operators and providing an improvement in their range. The results showed that there was a reduction of approximately 3.3 times the failure rate of package delivery. Even with the gains achieved, the mobility of agents are still limited to the scope of the ad hoc network. In both analyzed approaches, they suggest a communication between robots which is limited by the maximum distance allowed by the range of the wireless network, i.e., as those involved grow distant communication signal gets weaker and consequently there will be a loss of information exchanged.

To solve this problem, we associated the system described above to a Mesh network [7]. The main objective is to increase the scope communication area between robots that use a RTDB under an ad hoc and between them and a reference center, called *Basestation*. The main question at this point is: Why use this type of network topology and not another? One option to extend the network would be to place multiple access point along the way. One of the disadvantages of this scheme would be the number of cables that have to be launched from a central point to each access point since they work as repeaters. Routers in mesh networks, on the other hand, can communicate wirelessly with other routers, moreover, a robot traveling in this topology can switch between routers transparently without the need for authentication, required in the aforementioned topology. A lineup of robots working in a mesh network can cover any area and receive instructions from the *Basestation*, perform a certain task - by one or more agents - and return to starting position, due to the fact that there is no need for reconfiguration of interfaces network when the agents move from one mesh router to another [7].

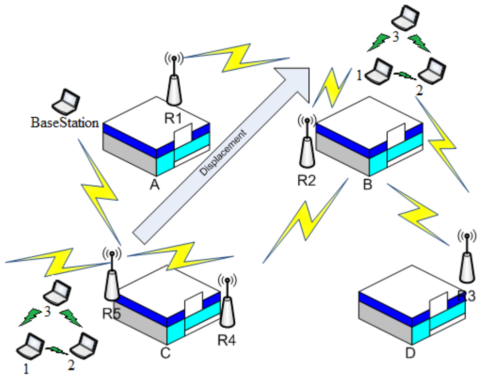


Fig. 1: Displacement of formation: This figure emphasizes the displacement of the group of Agents to another position, but without losing communication with the *Basestation*. Each agent was represented by a laptop.

In this paper we propose a way to expand the coverage area of these robots using a Mesh network and, manage through it, to be able to lead them to any area where their limits are the limits of the area covered by the mesh network. Figure 1 shows the basic structure proposed by this research where it can be seen a formation of robots performing the monitoring of an area which contains four buildings. All the area is within a Mesh network. Note that near one of the buildings there is a component called *Basestation*, a central computer linked by cable to the mesh network that sends and receives the data sent by the laptops of each robot. Figure 1 also shows the displacement of this formation of robots through the area. The purpose of this paper is to enable this robot formation to move around the area allowing the *Basestation* to be able to send instructions to the robots (or to receive data from them) so that they can perform some specific task. Note also that the formation has its own ad hoc network where their RTDB is shared between themselves and part of this data is shared with the *Basestation*. This multi-layer configuration allows the robots to share important information to maintain the formation without sending useless data to the *Basestation*. In fact it would be useful, for example, while surveilling large companies that have various buildings scattered within a large area.

Finally, this article emphasizes the use of a communication in a formation of robots using a RTDB in ad hoc for the communication between robots in each team and a mesh network between the teams, their respective robots and a central computer (*Basestation*). Figure 2 demonstrates another case, the break of a formation where one of the robots in formation must leave its team to do a reconnaissance. This break of formation case was well discussed in [8]. Although this break of formation interrupts the RTDB ad hoc communication between robot 3 and its teammates due to the large distances between them, the Mesh network maintains global communication between robot 3 and all the other robots in this area and the *Basestation* enabling robot 3 to go back to formation if necessary.

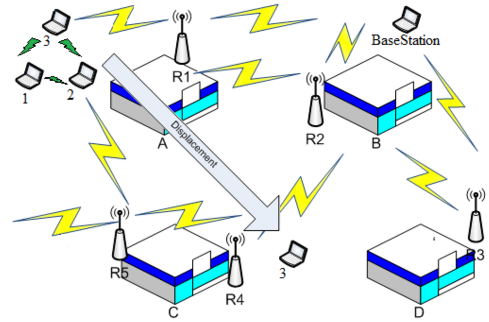


Fig. 2: Station displacement: Communication between all devices that are part of the mesh network. In this example the Agent 3 moves, leaving its position. In this network it will continue communicating with the two other Agents in the group, regardless of distance within the coverage area. In turn, the *Basestation* guards their position and can also send them instructions. Each agent was represented by a laptop.

Therefore, this article is structured so that in the next section (II), the RTDB configuration in ad hoc communication between robots of the same team will be explained. In Section III, the scope of mesh networks will be explained. In Section IV the experiments with the RTDB in ad hoc between robots of the same team and these teams within a Mesh network will be presented. Finally, the conclusion (V) will be presented in the last section.

II. Real Time Database

The growing importance of real-time computing in numerous applications and restrictions related to transaction processing in a timely manner (which the basic models of conventional data considered present when subjected to real-time systems [9]) led to the first studies on the concept of Real Time Database [10]. This type of implementation consists of a database distributed in real time, which allows local data (not persistent) to be accessed and shared between mobile systems. Thus simulating a local access, becoming different from typical implementations, that are based on client-server [11]. For these characteristics, the RTDB is widely used in remote areas of knowledge such as aerospace and defense systems, industrial automation, robotics and nuclear power plants - which is exemplified in the experiments of [10].

Most often, the RTDB consists of two parts: the upper layer formed by RTDB itself, which is replicated among all members of the system and includes interfaces for the data which is shared and for the communication layer; and a wireless communication protocol, which keeps multiple replicas of RTDB synchronized [3]. In this article's experiments was used The CAMBADA Project [11], from the University of Aveiro - Portugal, where the top layer is represented by a open source middleware, consisting of a block of distributed shared memory, called blackboard, which in turn serves as the basis of data to each member of the RTDB system, called agents. Which makes possible the sharing of desired information, generated internally, and enabling the access of other participants [11]. The concept of blackboard makes similar assessments as the ones presented in [12] which holds the data of the state of each agent, along with local images and the relevant data of the state of other team members.

This RTDB was developed in such a fashion that the blackboard of each agent is divided into blocks. One of the blocks is a private area reserved for local information, i.e., not shared with other participants in the RTDB, while other blocks are in a shared area [3], as illustrated in Figure 3.

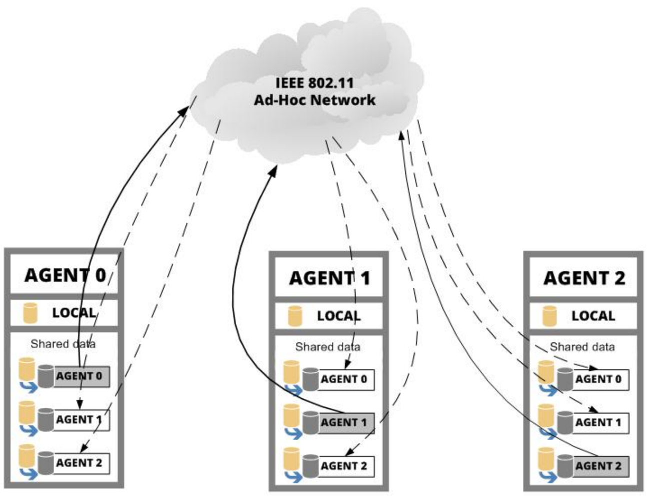


Fig. 3: Each agent transmits its data subset that is allocated in the shared memory.

The communication protocol used between agents is an ad hoc IEEE 802.11, shared in one channel and transmitting its variables with other members of the RTDB. In this case the available bandwidth is divided among all agents. In order to reduce the number of potential collisions, we used the environment access control TDMA (Time Division Multiple Access) adaptive that works by dividing the transmission channel in different time intervals [13], which allows, in a synchronous manner, the agents to start to listen to each other without a centralized marked time. The delivery of information is done using the multicast networks technology, which is the basis of a service network in which a single stream of data from a given source can be sent simultaneously to several interested receivers.

Regarding robotics communications, among related work we highlight the work done by [14] which presents the use of a RTDB in multi-robot communications applied to robot soccer competitions. In other presented works, the authors in [15] and [16] use the same RTDB configuration where an access point is used to share the information among the robots in the same group and to prevent the abovementioned problem, we quote [6]. Furthermore, the authors in [17] used the same RTDB configuration proposed by [6] to develop an anchor-less relative localization algorithm aimed to be used in multi-robot teams. Finally, many studies have contributed to the mobility of autonomous agents, however none made reference to the experiment proposed in this paper. Section IV will present the results intended to analyze the expansion of the coverage area of a formation of robots through a Mesh Network.

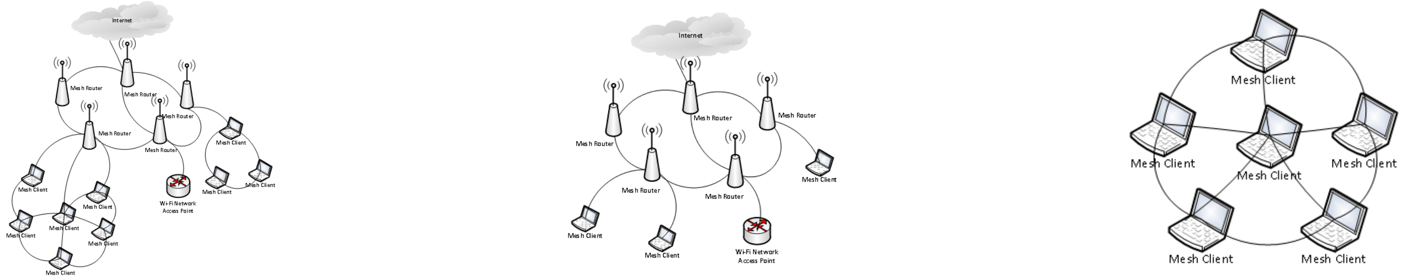
III. Mesh Networks

Wireless Mesh Networks (WMNs) is a technology that is emerging [18] and are becoming an alternative for extending local wireless area networks (WLANs) currently used. The local wireless area networks (WLANs) are based on the presence of an infrastructure for wired connectivity that allows the connection of wireless terminals. Moreover Mesh networks do not depend on the presence of wired infrastructure, i.e., there is no need for cabling, because wireless nodes communicate with other nodes wirelessly without the need for the cabling infrastructure, automatically creating an ad hoc network and maintaining the connectivity of the mesh [19] [18]. Thus, Mesh networks are used in various applications, such as enterprises, building automation, increased coverage of service, community wireless networks, among others [20].

The efficiency of WMNs depends on some aspects of the same projects and settings, such as number of hops, channel number, location of antenna requirements, throughput and latency, among others. Furthermore, several companies have realized the potential of this new paradigm and have available products for Mesh networks. In order for these networks to enjoy all proposed potential there is the need to allocate efforts to investigate some points, for example the not scalable MAC and routing protocols wherein the yield drops significantly with increase in number of nodes or hops [20] [7]. In [7] and [18] it is possible to classify Mesh Networks architectures in three groups, as presented in Fig. 4: Infrastructure/Backbone WMN, Client WMN, and Hybrid WMN.

Mobile multi-robot systems are useful in many critical applications such as search and rescue, environment monitoring and multi-objective environments. Efficient communication among robots in such mobile multi-robot systems is useful for the coordination of such teams as well as exchanging data. Since many applications for mobile robots involve scenarios in which communication infrastructure may be damaged or unavailable, mobile robot teams frequently need to communicate with each other via ad hoc networking. In such scenarios, low-overhead and energy efficient routing protocols for delivering messages among robots are a key requirement. Among related work on Mesh networks we highlight the article from [21], the authors first proposed and evaluated two unicast routing protocols tailored for use in ad hoc networks formed by mobile multi-robot teams: Mobile robot distance vector (MRDV) and mobile robot source routing (MRSR). Both protocols exploit the unique mobility characteristics of mobile robot networks to perform efficient routing. Later, in [21], the authors also proposed and evaluated an efficient multicast protocol mobile robot mesh multicast (MRMM) for deployment in mobile robot networks. MRMM exploits the fact that mobile robots know what velocity they are instructed to move at and for what distance in building a long lifetime sparse mesh for group communication that is more efficient. Their results showed that MRMM provided an efficient group communication mechanism that could potentially be used in many mobile robot application scenarios.

Finally, it is important to mention that, in multi-robot systems, the pure use of a wireless mesh network in ad hoc



(a) Hybrid WMN (b) Infrastructure WMN (c) Client WMN

Fig. 4: Classification of Mesh Networks architectures

mode is not advantageous due to the fact that not all data exchanged between robots are necessary to be seen by the *Basestation* or by other robot teams. In formation control for example, it is common to share observation covariance matrix of a determined target, data which is useless to the *Basestation* [2]. In this case, only the final target position is necessary to be transmitted to the *Basestation*, allowing the Mesh Network to be free of useless data necessary only to the robots in formation. Another problem lies in the synchronism of data flow. In Mesh networks there is no guarantee that the data received and sent by the nodes are synchronous. In this case, the implementation of the RTDB guarantees that.

IV. Experiments

In order to analyze the implementation of the RTDB in ad hoc within a Mesh Network described in the previous sections, some experiments were conducted. In these experiments, the RDTB was inserted in an environment of mesh networks in order to ensure its mobility in spaces with greater distances, ensuring the communication of the teams with a *Basestation*, as well as attesting flexibility of agent strength among different teams of robots. In our proposed work presented in this paper the WMN Infrastructure/Backbone architecture is used, where robots are clients and are only associate to Mesh routers, thus allowing their mobility throughout the network coverage area, making its expansion possible with the installation of new mesh routers.

In this scenario, two NIC (Network Interface Cards) were installed in the agents, thus allowing them join in a two networks, the ad hoc and the Mesh network parallel to the ad hoc. In the second network, we used the concept of mesh networking, specifically using the Infrastructure/Backbone WMN model, where two routers were used, Router1 and Router2, serving as the network Backbone. For the implementation of the Mesh network, the routers used needed to have their firmwares updated with an open source project, which uses a Linux system based on firmware for wireless routers and wireless access points, called DD - WRT [22].

The main goal was to evaluate the behavior of agents and RTDB when connected simultaneously to two distinct computer networks, making it possible to send different information for each network by RTDB. The layout of the environment can be seen assembled in Figure 5 where all elements of the environment are described. In addition to Figure 5, Table I describes the environment for this scenario, listing the setting information and their respective network addresses.

Network Element	NIC-1	NIC-2	Agent NIC-1	Agent NIC-2
Basestation	192.168.1.10	X	AGENT=0	X
Router 1	192.168.1.1	X	X	X
Router 2	192.168.1.2	X	X	X
Station 01	192.168.1.12	10.10.1.12	AGENT=1	AGENT=4
Station 02	192.168.1.11	10.10.1.11	AGENT=2	AGENT=3
Station 03	X	10.10.1.13	X	AGENT=5

TABLE I: Physical Description of the Environment

After preparing the network environment, tests were initiated with the RTDB. For the goal of sending different information through the RTDB to be achieved, we conclude that more than one instance of this component needed to run simultaneously, which was a problem because multiple instances of a RTDB on one computer were not supported, according to a study conducted by [23].

In the first test, the two RTDB's were initialized with the same shared memory key for both NICs. This shared memory key is defined by the environment variable called "AGENT", which receives as a parameter an identification number from the agent. With this configuration, the information was distributed to both networks, causing redundancy and conflict in the delivery of the data stream, which moves away from our main objective. This configuration becomes interesting in some instances where there is the need for duplication of transferred information between every agent involved.

Given the above, the main challenge of this step was to make alterations to the RTDB code so that multiple instances were initialized in the system. Based on the study described by [23], the solution found was to ensure that the shared memory key for each instance RTDB were to be different. The solution to this problem was given by a change in the manner in which the RTDB communicated. We began to use different environment variables for each communication established, and with that, reached an isolation of the flow of data between the NICs. Thus, each NIC starts to receive a different data context. The experiments performed are described below, which can be divided into three stages.

A. First Instance - RTDB in Ad Hoc network and MESH network:

According to Figure 5, as previously explained the stations connected to two different wireless networks - ad hoc and mesh - can be seen. The *Basestation*, on the other hand, was connected via a standard Ethernet cable to Router 1, which in turn was connected to Router 2 via wireless network, forming, in fact, the Mesh network.

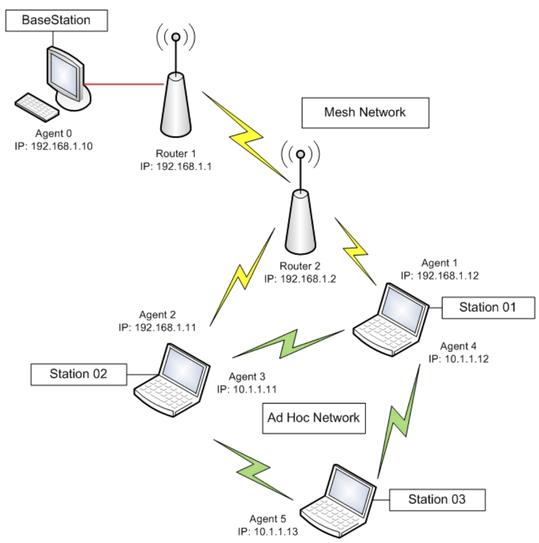


Fig. 5: First Instance - RTDB in ad hoc network and MESH network

This example makes it possible for the *Basestation* to read data of a possible location from the agents which have communication with the mesh network. This enables the *Basestation* to interfere with the action of these agents through information from the RTDB, even if they are geographically distant. However the information in the communication transmitted through members of the ad hoc network are only available to its members. In this case, these messages do not reach the *Basestation* (only a small part of it) which, in a way, is an advantageous factor because it does not burden the data flow in the Mesh network.

B. Second Instance - RTDB in Ad Hoc network and MESH network, with displacement of one of the agents between routers:

At this time, we analyzed the behavior of RTDB when subjected to an offset of the agents between the routers that formed the Mesh network. To do so, we moved Station 02 which was connected to Router 2, and the ad hoc network, towards the Router 1.

The communication with Router 2 was lost when we reached about 50 meters of spacing. However, as expected, approximately 10 transmission packets were lost and the communication was reestablished to the Mesh network with the assistance of Router 1 in a short time (approximately 5 seconds), a fact that did not interfere on the efficiency of RTDB use, which becomes justifiable due to the high synchronization capability of this kind of database. The configuration of this scenario can be found in Figure 6.

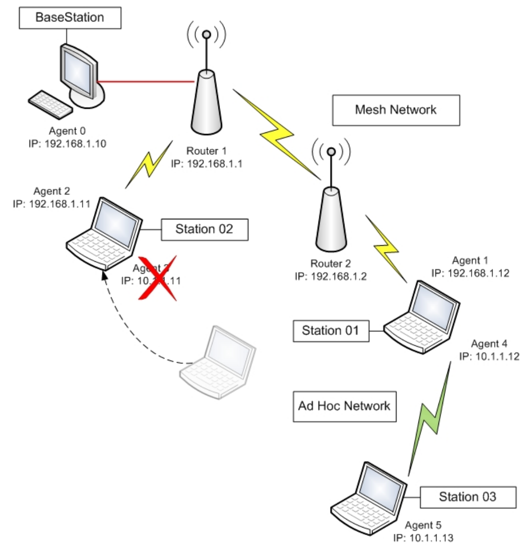


Fig. 6: Second Instance - RTDB in ad hoc network and MESH network, with displacement of one of the agents between routers

C. Third Instance - RTDB in Ad Hoc network and MESH network, with a distancing of one of the agents and loss of connection with the MESH network:

In this last instance, as shown in Figure 7, we distanced the agent, called Station 02, from the Mesh network routers in order to cause total loss of signal. As described in the second instance, the connection previously established with Router 2 was lost at about 50 meters away due to differences in environmental barriers.

Therefore, Station 02 could not establish direct communication with the *Basestation*, thus it was only able to detect agents members of the ad hoc network. Initially, this would not be an ideal scenario, since the *Basestation* would lose its ability to control this specific agent. However, the formed structure enables the stations which sustain both parallel communications, ad hoc and Mesh, in parallel, such as Station 01, that allow the data to arrive at the *Basestation*, and vice versa, transforming these stations into communication bridges.

V. Conclusion

The collected results showed that the use of a formation of robots in a Mesh network enables a wider range of reach of that formation. Thus allowing participant agents to distance themselves from each other and still return to their initial form, even with loss of signal between the agent who distanced themselves to carry out a task for example, and other robots members of its formation. Moreover, one can multiply the functions of operation of robots without the fear that they are lost from its formation because of communication break.

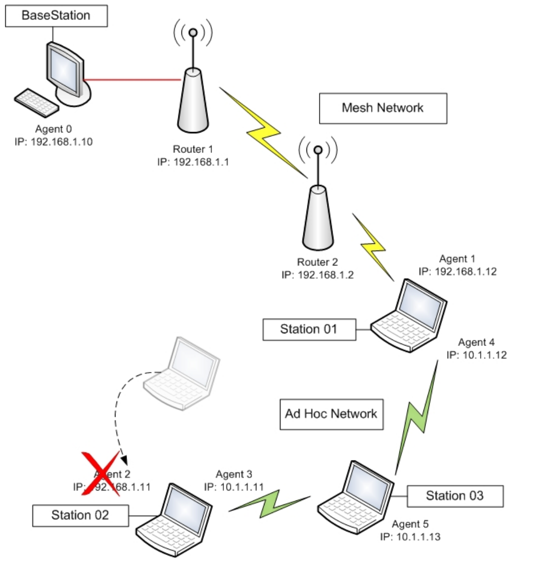


Fig. 7: Third Instance - RTDB in ad hoc network and MESH network, with a distancing of one of the agents and loss of connection with the MESH network

However, despite this great benefit, we point out that all this was possible because of this junction network topologies that used the RTDB in local ad hoc and global Mesh network. This two layer network allowed the expansion of the range of the agents while creating other opportunities for communication, where a RTDB is shared between agents through ad hoc and another with *Basestation* through Mesh network, allowing a same station to represent two distinct agents.

Finally, it is important to mention that using RTDB allowed the synchronism of data both between the robots in ad hoc and between the groups of robots and the *Basestation*.

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