Design of a Wireless Communication System for Unmanned Search and Rescue

SHERIF ABDELLAH*, YOUSEF ABO EL NOUR*, AHMAD BARACAT*, MINA MORGAN*, MOHAB OSAMA*, RAFIK RAEF*, HASSAN HALAWA*, RAMEZ DAOUD*, HASSANEIN AMER*, MAGDY EL-SOUDANI**
*Electronics Engineering Dept., American University in Cairo, AUC Avenue, New Cairo, EGYPT;
**Electronics and Communications Department, Cairo University, Giza, EGYPT
{sherif.abd; yousefaen; baracat; minamfm; mohab.ossama; rafikraef; hassan; rdaoud}@aucegypt.edu

Abstract: - The use of robotics in Search and Rescue operations is a topic that is gaining momentum in the scientific community. One aspect of such operations that has yet to be explored is that of wireless communication between the various robotic elements operating in the disaster area. This paper presents a model consisting of 15 Unmanned Ground Vehicles (UGVs), two Unmanned Aerial Vehicles (UAVs) and one Cell On Wheels (COW). This configuration explores the nature of such communication in the form of a network with payloads of sensor data, video data and telemetry bursts being sent from the UGVs via the UAV to the COW, and with telecommands being sent via the downlink. Another issue explored is that of horizontal handover that occurs when one UGV moves out of its home UAV's coverage and moves into another UAV's coverage. The results of the paper show that the network is fully functional with benchmark compliant video latency and jitter. Moreover, it is shown that the handover that occurs between the two coverage areas experiences no loss of useful information.

Key-Words: - Search and Rescue, 802.11, Handover, Unmanned Vehicles, Latency, Jitter, Robotics.

1 Introduction

Natural and man-made disasters are an ever-present danger that the world has to live with. With the increase in global population and the advancement of technology, it is becoming more and more important that the Search and Rescue (SAR) operations that take place in the aftermath of these disasters make use of this advancement. As such, a lot of research is being undertaken today on the incorporation of robotic intelligence in SAR operations.

However, an often underappreciated aspect in such research is that of communication between robotic intelligences. The existing literature does not delve into the details of such communication and even then, only from a purely theoretical perspective. In this paper, wireless communication between robotic intelligences is explored. The processes of communication between multiple nodes as well as horizontal handover and the effect of altitude on such communication are also investigated.

The paper is organized as follows: some of the works that are relevant and related to the scope of this paper are described in section 2. Section 3 elaborates on the specific problems that this paper aims to solve. The model used for simulation as well as its specific parameters are described in Section 4. Section 5 presents the simulation results and provides an analysis and interpretation. Section 6 concludes this paper.

2 Related Work

In this section, two of the most important SAR projects will be described: ICARUS and CRASAR. Also, other relevant research papers are presented briefly.

2.1 ICARUS

Integrated Components for Assisted Rescue and Unmanned Search operations (ICARUS) is a research project funded by the European Commission's Directorate-General for Enterprise and Industry. It aims at developing robotic tools and mechanisms to help and assist humans in cases of disaster. The project focuses on developing unmanned SAR technologies to assist in detecting, locating and rescuing survivors in disaster areas [1].

SAR is a wide field that includes sub-fields based on terrain surroundings and the disaster area [2]. ICARUS primarily focuses on two sub-fields of SAR, which are Urban Search and Rescue (USAR) and Maritime Search and Rescue (MSAR). In

USAR and MSAR, the focus is on locating, extracting and providing medical support to survivors found in natural and manmade disaster areas, and emergency water landings and shipwreck disasters respectively. MSAR uses seaplanes, submarines, rescue boats and ships [1].

ICARUS has eight main objectives that address the typical needs of SAR operations. These objectives are described in [3]. In SAR operations, the highest priority is given to locating and extracting survivors from a disaster area. Manpower is not sufficient and usually lacking for searching in disaster areas due to their wideness and criticality of causing further collapses inside such areas. That is why developing light human detection sensors is a necessary advantage for SAR robots that they must acquire.

Several types of robots are usually involved in SAR operations depending on the type of the surroundings in a disaster area. For disasters that take place in terrain and aquatic areas, Unmanned Ground Vehicles (UGVs) and Unmanned Surface Vehicles (USVs) are being used respectively [2]. Also, an Unmanned Aerial System (UAS) is being used for SAR operations in almost all types of disaster areas due to its importance in mapping the disaster area, target observation and communication relaying [4]. ICARUS aims at developing cooperative tools for UGV, USV and UAS to enhance their SAR capabilities [3].

Operators coordinating SAR operations outside a disaster area handle an extensive number of SAR robots as well as manned teams networked together. This heterogeneous network must be maintained, controlled and monitored at all time. That is why ICARUS seeks to applying a Network Centric Paradigm to achieve a central control unit of different platforms in a disaster area. The control should consist of specific task to certain vehicle types, mission-level planning, and coordination and supervision commands [3].

In SAR operations, a strong communication system is very crucial to sustain real time communication networking in harsh disaster conditions between the human rescue teams as well as the rescue robots. In this sense, ICARUS focuses on ensuring mobile and wireless communication for all the operational platforms including manned teams, individual and group communication with high quality, and high capacity, range and power efficiency in the network communications [3].

SAR robots are not the main operational platform in disaster areas. Human teams are also used extensively. The integration between the unmanned SAR robots and human teams is very essential in their communication network. In fact, the operators outside a disaster area are concerned with monitoring, controlling, collecting and sharing data from all the operational platforms in the area.

2.2 CRASAR

The Center for Robot-Assisted Search and Rescue (CRASAR) is part of the Texas A&M Engineering Experiment Station Center. It aims at improving disaster awareness, anticipation, response, and recovery through the development of robotics tools, techniques and mechanisms as well as related technologies.

The human-robot crew organization and protocols in CRASAR were first developed for UGVs. There are studies that show that the team performance with the aid of UGVs improved nine fold. The organization also extended the use of robots to include small UAVs. One of their most noted deployments was presented in [5] showing the importance and feasibility of robotic SAR in real life crises.

2.3 Other Studies

In addition to ICARUS and CRASAR, there have been several research papers about communication network between UAVs and UGVs outside the context of SAR operations. In [6], the communication between several UGVs has been studied. It conducts several tests on the improvement of this communication network through adding a UAV as a relay node between them. As a final result, it proposes a mobility strategy of the UAV using a certain algorithm to achieve this improvement. In [7], two types of network communications are studied: UGV to UAV communication and UGV to UGV communication via UAV. These types of communication have been modelled under a dynamic behaviour of both the UGVs and the UAVs. The results show that the average speed of the UGVs and the UAVs' trajectories affect the two types of network communications.

Regarding SAR operations, in [8], a network of mobile sensor nodes is developed for SAR operations inside buildings. These sensors collect temperature data and are used to help human beings to navigate in buildings under fire in order to find an exit. The paper discusses algorithms of cooperative localization of the mobile sensor nodes. In [9], robot sensor network is developed through the usage of simple and inexpensive robots and sensors for locating and tracking of survivors in SAR

operations. The paper proves the efficacy of such a network through simulations and empirical results. In [10], the search performance of a team of mobile robots in SAR operations has been compared to another team using a non-cooperative approach. The cooperative search approach has been proven to have faster performance.

3 Problem Definition

SAR operations present a unique set of challenges that rescue teams and operators must face. In fact, disasters come in several forms, and the scale and kinds of destruction are hard to predict accurately. However, if there is to be progress towards the full automation of SAR operations, the following problems must be met with flexible solutions that can cater to the different geographical and topographical needs of the various disaster-prone areas. Wireless communication and lossless handover in time-critical situations are the two main problems that this paper aims to solve.

3.1 Wireless Communication

The problem this paper aims to tackle is that of supporting wireless communication between the various UnManned Vehicles (UMV's) navigating through a disaster area. It is important to note that battery power and mission times vary widely from minutes to several hours depending on the type of vehicle used and on the medium the vehicle moves through; land, air or water [11].

UMV's deployed in SAR missions are typically equipped with arrays of sensors and imaging equipment, all of which ideally transmit real-time data. It is vital in such situations that data drops and video-jitter be kept to a minimum, as any large delay may potentially lead to the overlooking of vital signs that can lead to the loss of human life. Data rates vary widely, reaching up to several Megabits per second (Mbps) depending on the type of sensor used and the quality of data required. While one UMV may not produce a strain on the available bandwidth, having several UMV's in the area all communicating data simultaneously while at the same time receiving commands to move to areas of interest, all with no loss of useful data, is a challenge. This paper proposes that instead of having all UMV's send all of their raw data to the data sink, one UMV will aggregate the data and subsequently forward it.

3.2 Time-Critical Operations

The main purpose of SAR operations is to scan the area for any signs of human life and to respond accordingly. As such, whenever vital signs are detected, the top priority is to immediately extract them and perform emergency medical procedures; this is no different when using UMV's.

The scanning process usually involves the splitting of UMV's into cells or groups [11], with the cell leader usually being an Unmanned Air Vehicle observing the terrain from a higher vantage point. The other cell members are usually made up of Unmanned Ground Vehicles (UGV) with sensors and other life detecting equipment.

Due to the fact that such responses must be swift, it is expected that a UMV, usually a UGV that has medical or rubble-removing capabilities, should break formation and along with a UAV acting as a supervisor, start moving towards the special emergency area. The underlying assumption here is that the UAV serves as a router that transmits the UGV's sensor data to the data sink or command center. Regardless of the protocol used, when the UGV breaks away from formation and its old supervisor and establishes communication with the new one, some form of handover is required. This handover must be carried out in such a way that data loss is minimal while preserving the telemetry and telecommands that allow for the monitoring of the rover's state and for controlling the rover remotely respectively. Telemetry information includes configurations status, identification, battery levels, and coordinates, ON/OFF status of all commandable equipment [17]. This arrangement allows for a focused rescue effort, with the new UAV having a fresh battery and as such a longer mission time than the one currently operating.

This paper proposes a solution to the above challenges using wireless communication protocols while further exploring the outlined handover scenario in a lightly populated urban environment or a rural area. The next sections provides a more specific look at the studied scenario, providing data rates, areas and the UMV trajectories, along with information on the communication protocol used.

4 Model Description

The model is based on units each covering a certain area, hereon referred to as cells. Each cell is populated by a group of 15 UGV's and one UAV [7]. Ground rovers were used as a type of UGV while quadrotors were used as a kind of UAV as in [12,13]. The quadrotor has the job of aggregating and relaying the information back to the backbone

while the rovers have the job of locating survivors. The quadrotors were chosen to act as the relaying nodes for four reasons: the quadrotors' altitude, the rovers' batteries, the ease of replacement of quadrotors and the quadrotors' wider field of view.

First and most importantly, the altitude of the quadrotors allows their use as access points since it ensures a Line of Sight (LOS) with all rovers. Second, the rovers' batteries need to be conserved in order to maximize their mission time; having a rover take on the burden of acting as a router increases its power consumption due to the overhead of relaying and aggregating data, which is not their primary purpose in the mission. Third, due to the fact that quadrotors move at higher speeds relative to the rovers, as well as the fact that quadrotors have altitude, they are much easier to swap in and out when their batteries are low. Additionally, quadrotors do not have to deal with the many obstructions a rover may have to deal with in a disaster area. Finally, quadrotors can provide a bird's-eye view of the disaster area, allowing for a much faster initial scan of the location as well as more rapid identification of areas of interest and emergency areas, which in turn enables a faster response [2].

The backbone consists of a Cell On Wheels (COW) and operators that receive the video streams along with sensor data and telemetry information while responding with telecommand signals. The quadrotors act as the link between the backbone and the individual rover cells.

The telecommand signals and the telemetry information are sent using a burst communication technique as described in [14]. This insures that the operators do not lose control of any of the rovers at any point in time, particularly during the case of handover, where a loss of connectivity results in a total loss of communication with the rover, meaning that the rover is essentially unreachable.

All rovers communicate sensor data and telemetry information to the their respective quadrotor at a rate of 20KBps [15, 16] and 0.5KBps respectively [17] to the COW. One rover per cell transmits high definition video at a rate of 0.5MBps [18]. Rovers receive telecommands from the COW at a rate of 31.25Bps via the quadrotors [17]. Quadrotors, on the other hand, communicate high definition video and sensor data to the COW at a rate of 0.5MBps [18] and 20KBps respectively [15, 16]. This sensor data is in the form of temperature and gas pressure information. The combination of these two sensors, along with visual feedback, is essential for detecting potential human survivors as in [15, 16, 19].

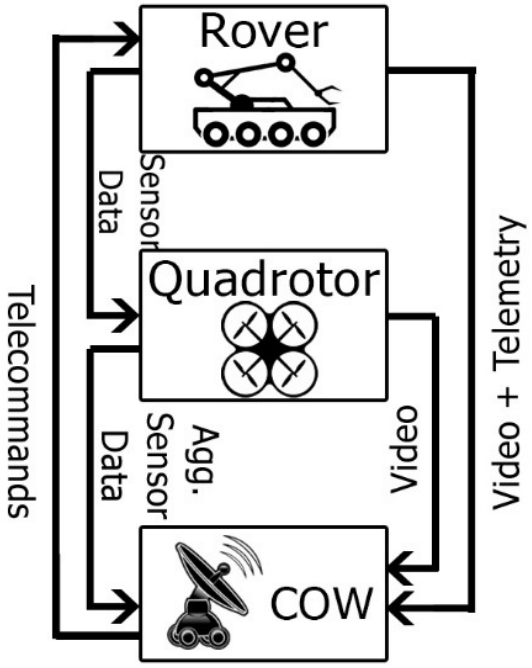

Fig.1 Model of network traffic flow

The quadrotor and one rover of each cell are equipped with cameras to provide the rescue team with a ground-level view in addition to the bird's-eye view. A simple network traffic flow diagram can be seen in Fig.1.

4.1 Case Study

OPNET Modeler Suite [20] was used as the network simulation platform. Quadrotors were modeled as mobile WLAN nodes with an altitude of 60m. 1mW is used for both the rovers and quadrotors transmission power as in [21]. The simulation area is considered a radius of 65m. In order to focus on studying the effect of horizontal handover, the 14 nodes (rovers) of the first cell were kept stationary.

The horizontal handover scenario involves a mobile node, representing a rover, moving at a speed of 10Km/h [22] along a straight line migrating to another cell. As the rover starts losing communication with its respective quadrotor, the mobile node gets in the range of another quadrotor moving at a speed of 25Km/h with an altitude of 80m [23]. At this point, the quadrotor descends to an altitude of 60m and horizontal handover is established. Finally, both the mobile node and the moving quadrotor move together at a speed of 10Km/h. The two dimensional (2D) scenario can be seen in Fig.2.

The theoretical radius of the quadrotor's coverage is determined using the free space path loss equation obtained from [24] as follows:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R}\right)^n \quad (1)$$

where P_r is the power at the receiver, P_t is the transmitted power, G_t is the gain of the transmitting antenna, G_r is the gain of the receiver antenna. λ is the wavelength of the signal and is equivalent to 0.121m for IEEE 802.11g (link between rovers and quadrotor) and 0.05996m for IEEE 802.11n [21] (link between quadrotor and COW). R is the distance between the transmitter and receiver antennas and n is the path loss exponent.

The simulated model considers Line Of Sight (LOS) communication between the rovers and the quadrotor, which is guaranteed by the quadrotor's altitude. Thus, a path loss exponent of two is used.

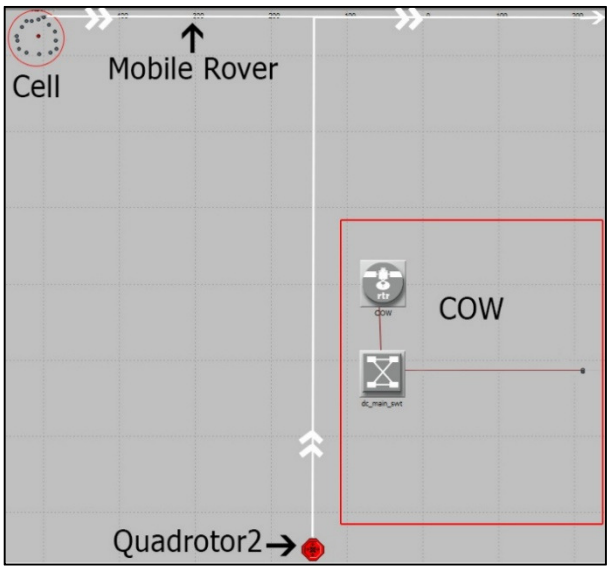

Fig.2 The model with the moving nodes

5 Simulation and Results

In the simulated model, the individual cells were implemented using IEEE 802.11g because its maximum bandwidth (54Mbps) is sufficient according to the chosen transmission bandwidths for the individual nodes. Within each cell, the rovers transmit their data using IEEE 802.11g to their respective quadrotor, which then routes the data to the backbone. The backbone, which connects the cells to each other, was implemented using IEEE 802.11n; this is to ensure connectivity for the larger ranges needed in the backbone. 802.11n is also optimum from a bandwidth perspective since the backbone is typically responsible for handling larger loads originating at different quadrotors. Since there are two different subnets in use within this system, quadrotors need to act as interfaces between the two IEEE 802.11 subnets and thus must have two Wi-Fi radios.

A simulation was performed on a single cell where all rovers were assumed to be stationary at random locations and are transmitting data to the COW. The simulation proved the single cell to be fully operational with 15 rovers with one of the rovers transmitting video.

One of the main factors considered in the simulated model is the handover scenario when a rover moves out of a cell. This would happen when the services of this rover are needed somewhere else. In the model, Mobile Rover moves from its home cell to an unexplored area and a quadrotor is sent to support it. The rover must be able to perform handover without losing any full data set of burst duplicates of the telemetry or telecommand signals so as not to lose control over the rover during handover. The two dimensional (2D) scenario can be seen in Fig.2; the white lines denote trajectory.

Since the Telemetry and Telecommand signals are implemented using burst communication techniques, the durations of each burst and between bursts must be determined. Burst communication is defined as sending successive identical packets within a certain time period and separated by a defined amount of time. In this sense, if one of the packets is lost, the others will still carry the same information to and from the desired destination. In [14], there are three parameters that define the burst communication. t_{F2L} is the time between the first and last packet in the same burst, t_{burst} is the time between the first packets of two successive bursts, and t_{packet} is the time between two successive packets in the same burst. These three parameters must satisfy the following constraints: t_{F2L} must be greater than the longest time spent in a no-connection area between two access points [14]. This is to ensure that at least one of the identical packets that are sent reaches the destination. The speed of the slowest rover must be taken into account while calculating t_{F2L}. Since the rover used in the model has a fixed speed of 10Km/h, the time t_{F2L} is calculated based on this speed. The shadow distance (SD) corresponds to the longest time spent in a no-connection area, which is 0.47Km.

$$t_{F2L} > \left(\frac{SD\ (Km)}{Speed\ (^{Km}/_{h})}\right) \times\ 3600\ sec$$

$$t_{F2L} > \left(\frac{0.47\ (Km)}{10\ (^{Km}/_{h})}\right) \times\ 3600\ sec$$

$$t_{F2L} > 169.2\ sec \quad (2)$$

t_{burst} must be less than or equal the shortest time taken to travel between two access points [14]. This is to ensure that the rovers receive new telecommands at all time. The speed of the fastest rover must be taken into account while calculating the t_{burst}. The AP distance corresponds to the shortest time taken to travel between two access points (APD), which is 0.56Km.

$$t_{F2L} > \left(\frac{APD\ (Km)}{Speed\ (h)}\right) \times\ 3600\ sec$$

$$t_{burst} \leq \left(\frac{0.56\ (Km)}{10\ (Km/_h)}\right) \times\ 3600\ sec$$

$$t_{burst} \leq 201.6\ sec \qquad (3)$$

t_{packet} depends on the number of packets used in one burst. The lowest number of packets that can be used in one burst is two. In [14], the speed of the vehicle was assumed to be 33Km/h and after experimentation, it was determined that 3 packets were needed to ensure connectivity. Since the speed of the rover is 10Km/h in this model, the rover spends more time in the shadow zone than in [14]. As such, the number of packets therefore had to be either 3 or more. It was shown by experimentation that 3 packets ensured appropriate burst communication in this scenario.

$$t_{packet} = \frac{t_{F2L}\ (sec)}{№\ of\ packets\ in\ a\ burst - 1}$$

$$t_{packet} = \frac{169.2}{2}\ sec$$

$$t_{packet} = 84.6\ sec \qquad (4)$$

Fig.3 shows a typical burst communication would with one of the rovers.

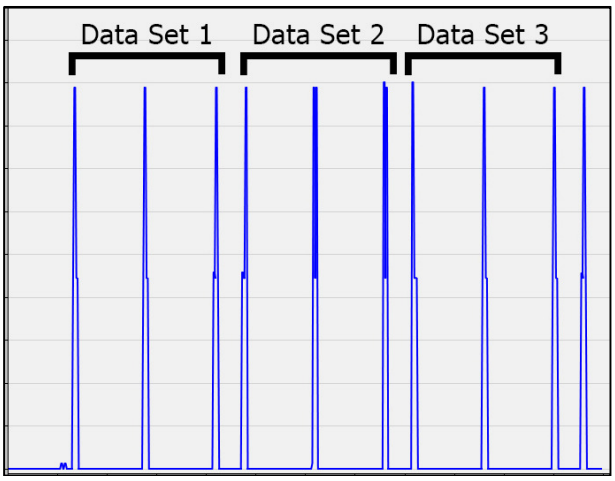

Fig.3 A typical telecommand signal.

5.1 Simulation Results:

Fig.4 shows the received telecommands for the Mobile Rover; the mobile node which has to perform handover from one cell to the other. The lower graph in the figure shows the access point connectivity which changes when the handover is complete. The upper graph shows the telecommand data received. During the handover period, it is clear that there are two replicas (the terms replicas and packets are used interchangeably) lost from the third data set, however the third replica arrives which indicates that no actual telecommand data was lost during the handover.

Fig.5 shows the total telemetry received at the telemetry server in the COW from all rovers. As seen, the amount of telemetry data received decreases for the two replicas at the handover region. This is because one of the rovers (the one in the handover region) is temporarily not communicating. However the third replica from the same data set arrives with the total amount for 15 rovers and thus no telemetry data is lost.

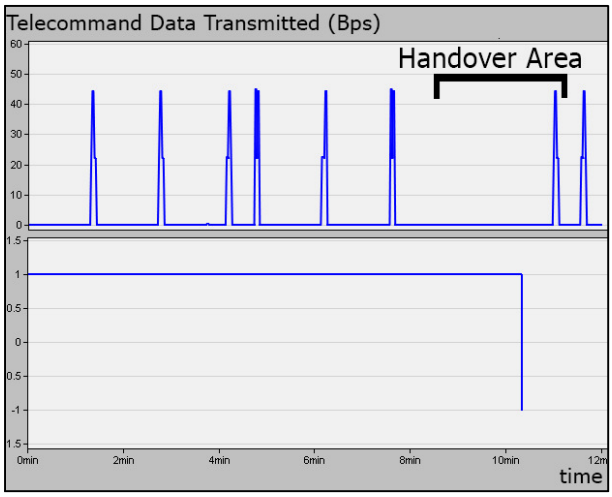

Fig.4 Telecommands and AP connectivity of mobile node

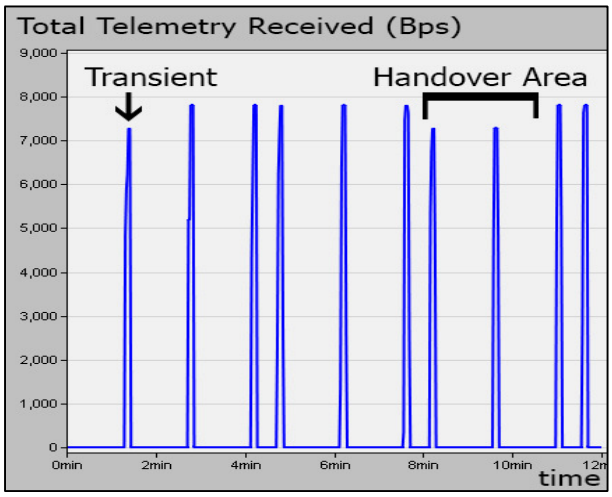

Fig.5 Total telemetry received at COW

Fig.6 shows video transmission from Video Rover. Video Rover is the only rover that transmits video within the cell. The rover transmits video as well as sensor data at 0.5MBps and 20KBps respectively resulting in a total bandwidth of 544768Bps.

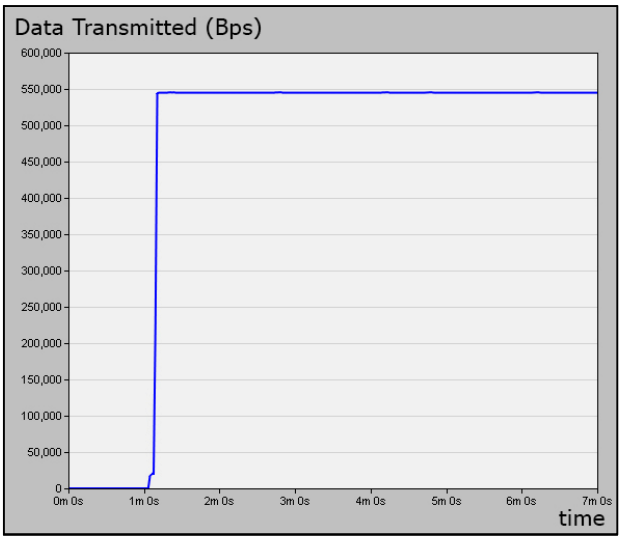

Fig.6 Total Traffic sent from Video Rover

5.3 Interpretation of Results

All presented delays in this paper include packet propagation, transmission, encapsulation, de-capsulation and queuing delays for different nodes within the network.

The following results were collected based on 95% confidence level analysis for latency, jitter and maximum delay. All tabulated numbers stated are in milliseconds (ms). Table 1 shows the studied metrics regarding packet end-to-end delay for telemetry and telecommands. Telemetry and telecommands are transmitted to and from the COW, respectively.

	Telemetry	Telecommands
Latency	[6.00; 6.28]	[12.01; 13.45]
Jitter	[5.54; 5.98]	[18.94; 21.22]
Max. Delay	[22.19; 24.52]	[65.72; 74.40]

Table 1 Telemetry and Telecommands end-to-end delay

Table 2 shows relevant statistics about the packet end-to-end delay for the video that is sent from the quadrotors to the COW and the video that is sent from Video Rover to the COW respectively. Since the rover's video is sent over two hops, it is clear that it has notably greater delay when compared to the video sent directly from the quadrotors.

According to [25], acceptable values for IP video surveillance camera video latency range from 20-40ms with jitter of 1-2ms. The maximum video latency monitored in this model is 7.30ms, while the maximum jitter is 0.33ms. These numbers all comply with the stated benchmark and thus the video quality is considered to be satisfactory.

	Quadrotor video	Rover video
Latency	[2.63; 2.98]	[3.72; 4.36]
Jitter	[0.10; 0.14]	[0.30; 0.33]
Max Delay	[3.68; 4.03]	[6.54; 7.30]

Table 2 Rover Video and Quadrotor Video end-to-end-delay

Table 3 shows relevant statistics about the packet end-to-end delay for the sensor data that is sent first from the rovers to the quadrotor. The quadrotor then aggregates and forwards the aggregated data to the COW. The delay presented in Table 3 was calculated by adding the end-to-end delay from the rovers to the quadrotor and the end-to-end delays from the quadrotor to the COW.

Latency	Jitter	Max Delay
[2.93; 3.42]	[0.45; 0.53]	[6.06; 6.81]

Table 3 Sensor data end-to-end delay

When considering packet drops in a network, there are two important types of drops: drops due to buffer overflow and drops due to an exceeded retry threshold. The simulation results show that there are no packet drops in the system due to buffer overflow. However, as seen in Fig.7, there are some packet drops due to exceeded retry threshold. These retry threshold drops are mainly concerned with telecommand packet drops around the handover area. Nevertheless, as long as a burst replica is always received as in Fig.5, this is not considered to be a problem.

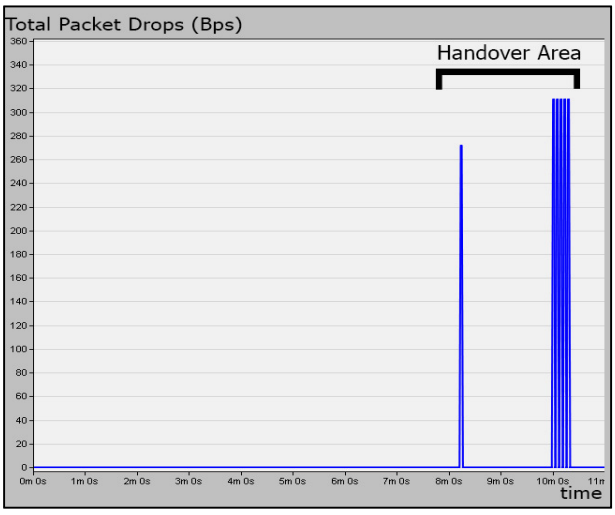

Fig.7 Packet Drops due to Retry Threshold Exceeded

6 Conclusion

This paper highlighted the importance of communication between intelligent robots in the context of Search and Rescue (SAR) operations. Fast response and deployment times are crucial to the success of these operations. A brief overview of existing work in the field was provided. Wireless communication and lossless handover in time-critical situations were defined as the two main problems that this paper aimed to solve.

A model incorporating 15 rovers, 2 quadrotors and a Cell on Wheel (COW) was simulated using OPNET. The scenario studied the traffic between the rovers and the quadrotor acting as a relaying node with the purpose of aggregating information to the COW. A combination of IEEE 802.11g and IEEE 802.11n are used as communication protocols. The communicated data was in the form of telemetry, video and sensor data from rovers to the COW via the quadrotors. The combination of this data allows for detecting potential human survivors. Telecommands were sent from the COW to the rovers via the quadrotors. Additionally, a bird's-eye view video was sent from the quadrotors to the COW. Horizontal handover of one rover migrating from the coverage of a quadrotor to the other was investigated.

Simulation results showed that the model is fully functional, with no loss of useful data even during the handover process. For the most critical application, which is the video communication, a comparison with an IP video surveillance benchmark showed that the values obtained for jitter and latency were compliant with the standard.

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