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Enhanced Data Gathering For Firefighting Applications

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***Abstract*— In buildings with enough network infrastructure, there is a fire alarm network controlled by a Fire Alarm Control Panel (FACP) and interfaced with the overall building network. When a fire starts in the building, the FACP takes some actions to facilitate evacuation and firefighting procedures. The fire alarm network, already fire protected, continues to operate on batteries. The fire department dispatches fire fighters to the site. Often, fire fighters can suffer from many injuries and fatalities due to the lack of information about the fire site. This paper proposes a fault-tolerant network of robots to be deployed in a building with any number of floors and communicate with the fire alarm network through the FACP. Wi-Fi and LTE interfaces need to be added to the FACP to allow for this functionality. The main purpose of the robots is to scout the region, send live video stream as well as different measurements from the site to the Incident Commander (IC) while other firefighting procedures are carried out in parallel. Throughout the paper, the network is designed and tested for proper functionality, and an Ethernet-based on-board network for robots is proposed and successfully simulated.**

Keywords*— *Search and Rescue; Firefighting; Ethernet; Wi-Fi; LTE; Fault-Tolerance.

I. INTRODUCTION

In our present day, as soon as a fire department receives an alert, it dispatches its crew and equipment to the location of the fire (fire ground). The firefighters then attempt to locate, identify, control and extinguish the fire from a safe distance along with safely rescuing any remaining trapped survivors [1]. This process is managed by the Incident Commander (IC) who is on the scene to monitor and govern the situation [2]. The IC needs to make sure that the firefighting process goes as safely, effectively and efficiently as possible. However, this is an extremely difficult task due the lack of information and rapid change of the situation. The little information received by the IC is neither consistent nor well processed. Some of the firefighting teams inside the building manage to communicate the data they have collected regarding the situation and the actions they have taken to the IC over radio while others fail to do so. The IC is then required to use his/her experience along with the limited information received to try to make a clear picture of the current situation of the fire ground and command the teams accordingly [3]. If the commands are not followed correctly or are executed at the wrong time due to communication failures, it can lead to disastrous consequences, e.g., entrapment of the search and rescue team. Not to mention that it is highly unlikely that the virtual picture created by the IC is identical to the actual situation. Consequently, unfortunate injuries and losses occur too frequently. Even though the fire ground has a lot of information, only very little of this information is communicated and processed properly [2]. As it stands, the real-time data extracted from the firefighting environment is very limited, whether it is from the fire alarm panel, the fire alarm system, or the firefighting command center. Despite the various attempts to use today's technologies to enhance the firefighting process, the state of firefighting today is far from ideal [4]. The losses caused due to fire because of the absence of critical information and real-time data processing of this information are too high.

Therefore, a network of robots is proposed in this research. These robots have an Ethernet connected on-board network and are deployed in the building afire. The robots are designed to gather information about the fire ground through scouting the floors of the building. One robot is deployed in each floor and each robot communicates the information it gathers along with the video stream it captures through sending them wirelessly to the fire alarm control panel on that particular floor and to the robots deployed in the floors above and below the floor of the robot. Fault-tolerance is applied to the entire architecture which is also modular and can be applied to a building with an arbitrary number of floors. Both the network of the robots with the fire alarm control panels and the on-board network of the robot were successfully simulated on Riverbed [5] and tested for functionality.

In Section II, a complete description of the system architecture is given. In Section III, there is a description of the simulation methodology with some detail for each subsystem. It also includes the performance metrics on which simulation results are assessed. Results of simulations, which were carried out on Riverbed Modeler, are presented in Section IV. Section V concludes this research.

II. SYSTEM ARCHITECTURE

The purpose of the network designed is to provide reliable communication between robots deployed in the building and the Cell On Wheels (COW). The system is fault-tolerant such that each stream of data is sent on three paths. Each robot

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sends its information to the adjacent robots (the floors directly above it and below it). Then, each robot in turn sends data received from the adjacent robots along with its collected data to its corresponding panel or to the COW over Wi-Fi. Finally, the panels send data to the COW using a cellular network. Therefore, this system ensures that all information gets delivered eventually to the COW even in the case of any path failure. The on-board network of a robot is proposed to be Ethernet instead of the conventional CAN network so that it can accommodate higher data rates which are needed for the multiple IP video streams carried between robots and to the COW.

A. Robot On-Board Ethernet Network Architecture

For the on-board network architecture, a many-controllers-many-sensors methodology is used. The architecture is shown in Fig. 1. This architecture consists of many modules and sub-modules connected to a switch in a star topology. When compared to a one-controller-many-sensors architecture, this architecture requires more hardware and a switch with more ports. Accordingly, it requires a higher cost. On the other hand, each link will have much less traffic and thus, the delays will decrease significantly as each sub-module operates on its own and sends its own data to the main controller. This architecture uses a mix of different fault-tolerance techniques to increase the reliability of the system.

The main module/controller essentially receives all packets and data from the other modules and forwards them to the fire alarm control panel on the same floor and the robots on the adjacent floors. Mainly, it forwards the sensor data, camera video streams and location status to the mentioned destinations, along with the telemetry. It also sends a watchdog signal to the navigation module for fault-tolerance purposes.

The on-board network has several sensors that collect data and information to be sent to the main module and then to the COW. Triple Modular Redundancy (TMR) is used for fault-tolerance and therefore, there are three identical sensor modules. Each module resembles a cluster of different sensors. These sensors include flame sensor, smoke sensor, temperature sensor, battery meter and air quality sensor. On each sensor cluster, an ultrasonic sensor is used to report the robot's distance from the surrounding obstacles to the main and navigation module, so that the navigation module can determine the path and the direction that the robot will follow.

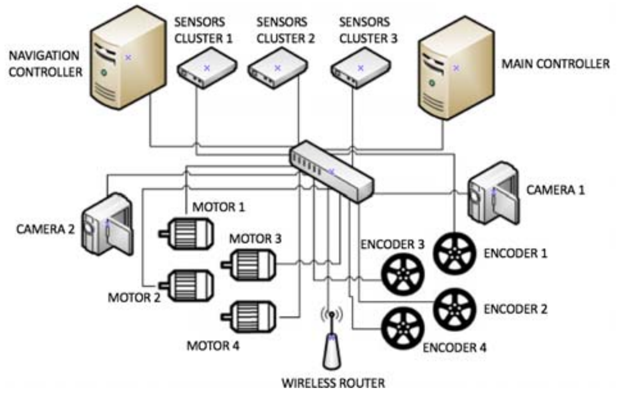

Fig. 1. Robot On-Board Network Architecture

The architecture contains two camera modules for fault-tolerance. The camera module generates the heaviest load on the on-board network. That is mainly because it is responsible for sending thermal video streaming packets to the main module. This video can either be sent in standard quality or high quality. The advantage of sending standard quality video is that it reduces the load on the network. On the other hand, using high quality video increases the traffic on the network, but provides a much better view of the situation to the firefighters.

B. Wireless LAN Archeticturethe

In this section, two approaches are discussed to define Wi-Fi channel allocation among different robots and between robots and panels in the same floor, namely a multi-floor approach and a modular approach. Both approaches follow the following set of assumptions.

First, the model assumes an average-sized office building with one robot per floor. In addition, since the communication occurs indoors, the panel and the COW coverage are each considered to be 100m. This is justified assuming the absence of Reinforced Concrete (RC) walls within individual floors as well as the use of high wireless transmission power. Moreover, the separation between each floor is 6m and floors are made of RC slabs with an average attenuation of 15dB [6]. The area should be covered completely by either the panel or the COW (no blind spots), such that a robot can roam freely in the zone without losing connection with the overall system. Communication is heavily power consuming because of the high transmission power; hence, battery sizes should be increased accordingly. However, the mission time for the robots is only expected to last less than one hour.

Robot-Robot communication refers in this context to the two-way communication between two robots in two adjacent floors. However, Panel-Robot communication refers to the communication between one robot and either the COW or the panel in the same floor. Whenever panel is mentioned as a transmitting or receiving node, it means this node can be either a panel or the COW.

In one direction of Robot-Robot communication, the source robot sends to the destination robot the source's video, sensors and telemetry data and the destination's telecommands. As for Panel-Robot communication, the robot sends a total of three videos, three telemetry data and three sensors data to the panel at a time, while the panel sends to the robot a total of three telecommands. The three videos, three telemetry data and three sensors data sent by the robot correspond to the video, telemetry data and sensors data generated by the sending robot as well as the ones generated by its two adjacent robots. The three telecommands sent by the panel to the robot also correspond to the telecommands intended for the receiving robot and the telecommands for its two adjacent robots.

Since Wi-Fi has only three non-interfering channels (1,6,11), the most intuitive way to divide channels among communicating nodes is to devote one channel to Panel-Robot communication and another channel to Robot-Robot communication. However, the amount of collisions for a robot receiving from two other robots degrades the quality of communication. Therefore, two architectures are proposed to ensure that no node uses the same channel to communicate with two different nodes.

1) Multi-floor Approach: In this architecture shown in Fig. 2, one Wi-Fi channel is dedicated to Panel-Robot communication and the other two non-interfering channels alternate between robots. This implies that a robot will use, in general, three different antennas with distinct channels so that the robot can communicate on the three channels simultaneously without introducing any switching delay. All nodes are assumed to use IEEE 802.11g since it is available in all infrastructures and allows for high data rates. All nodes transmit with a maximum data rate of 54Mbps, with 100mW (20dBm) transmitted power and receive with -95dBm Packet Reception Power Threshold (PRPT).

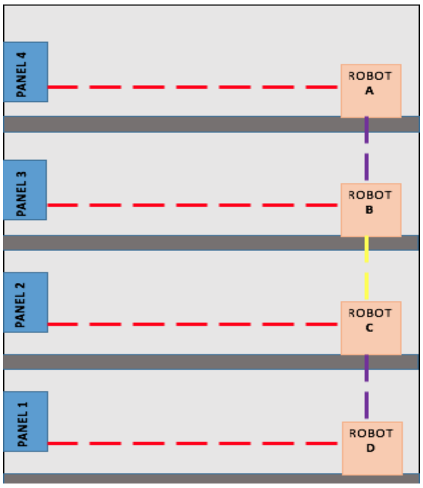

Fig. 2. Multi-floor Approach Architecture. Dashed lines pair two nodes on a Wi-Fi communication channel. Different channels are differentiated by their colors.

2) Modular Approach: Following the previous architecture, a further generic extension is introduced as shown in Fig. 3, thus not limiting the design to be implemented on only two- or three-floor buildings. The building is then divided into clusters; each cluster consists of two consecutive floors. Within each cluster, a channel is dedicated to Panel-Robot communication while another non-interfering channel is dedicated to Robot-Robot communication. The dedicated channels alternate between two consecutive clusters; a channel assigned for Panel-Robot communication in one cluster would then be assigned to Robot-Robot communication in the next cluster and vice versa. The third vacant non-interfering channel is fixed to accommodate the communication between two consecutive clusters through their adjacent robots.

C. Backbone Communication Architecture

Data collected by the panel should then be sent over a 4G cellular network, also known as Long Term Evolution (LTE), to the COW. Instead of using an LTE interface for each floor, floors are again grouped in clusters of two floors each. Each cluster is limited to one LTE interface. All cluster data is aggregated and sent through this interface. Assuming the panel is programmed with the required intelligence and possesses the necessary computational power allowing it to process its received data and to remove duplicates with no significant processing delay, this method reduces traffic on the cellular link as shown in Fig. 4.

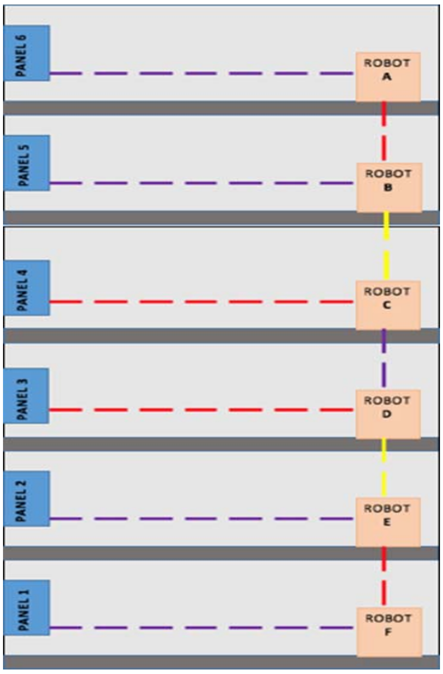

Fig. 3. Modular Approach applied to 6 floors. Dashed lines pair two nodes on a Wi-Fi communication channel. Different channels are differentiated by their colors.

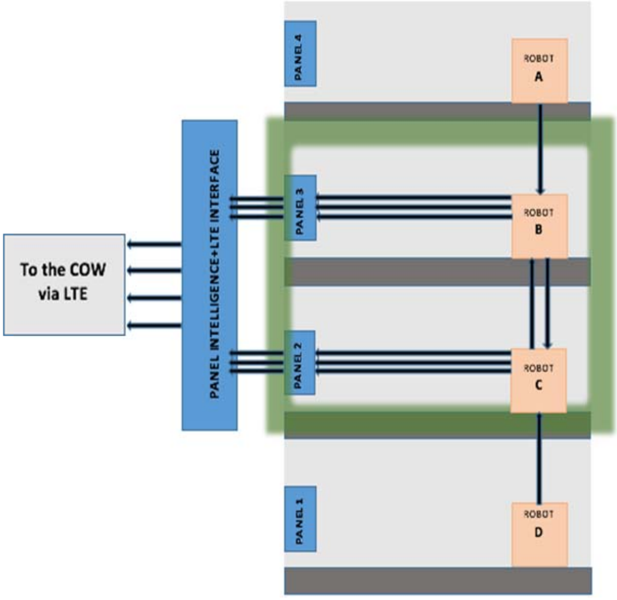

Fig. 4. Backbone Communication

III. SIMULATION METHODOLOGY AND PERFORMANCE METRICS

A. Robot On-Board Ethernet Network

When simulating the on-board network on Riverbed Modeler, Ethernet workstation node is used to represent all modules. Different applications are then used to differentiate between those modules depending on their functionalities. A 32-port switch represents the main switch. The nodes are connected to the switch using a 1000BaseX Ethernet cable. The fire alarm control panel Wi-Fi interface and the two robots Wi-Fi interfaces are represented with three extra Ethernet workstations to study the wired link only.

In the on-board network simulations, data was sent using UDP protocol. The sensor data is defined as the summation of the data of sensors available in the market and the sampling rate of the cluster was defined as the lowest sampling period of the sensors which is 32msec [7-12]. Each encoder sends to both the main and navigation modules at a rate of 140Bps [13]; in addition, the ultrasonic sensor sends to both the main and navigation modules at a rate of 1200Bps [14]. On the other hand, the motor receives from the navigation module at a rate of 380Bps [13]. Video data rate is from the Amazon video on demand standard definition [15], the telemetry and telecommands are from NASA [16]. A watchdog, between the main module and the navigation module, is represented by the summation of three times the sensor data, telemetry and telecommand and its sampling rate is half that of the lowest sensor or 18msec to avoid any loss of data. The rates are shown in Table I. The main module sends to the panel telemetry, sensor data and video of three robots which are the two adjacent robots' data as well as its own data. It also receives from the panel three times the telecommands. Each robot sends to the adjacent robots its telemetry, telecommands video and sensor data.

TABLE I. APPLICATION DATA RATES

Application	Data Rate
Sensor data [7-12]	1582.0625Bps
Telecommands [16]	31.25Bps
Telemetry [16]	500Bps
Camera [15]	112.5kBps
Watchdog	5277.44Bps
Main -Robot ½	114.613kBps
Main - Panel	343.746kBps
Panel - Main	93.75Bps

B. *Wireless LAN Architecture*

Over any wireless link, video traffic is sent over UDP with a video conferencing application, while telemetry and sensor data as well as telecommands are sent over TCP using FTP applications. The sampling rate is chosen to be 40ms for video conferencing and 1s for TCP.

In Panel-Robot communication, the incoming stream frame size for video is 13500B (3*112.5kBps*0.04s), while the file size is 6246.1875B ((1582.0625B + 500B) *3*1s) for telemetry and sensor data and 93.75B for telecommands. Further, in Robot-Robot communication, the incoming stream frame size for video is 4500B (112.5kBps*0.04s); the file size is 2113.3125B (1582.0625B+500B+31.25B) for telemetry, sensor data and telecommands.

The panel is represented by an Ethernet workstation node (to represent intelligence) connected to a WLAN-Ethernet bridge via a 1000Mbps Ethernet cable. Robots have a distinct antenna for each Wi-Fi channel. Each radio antenna is a mobile WLAN workstation, and all of them are put at the same location to represent a single robot.

To model the floor attenuation, the receiver sensitivity is adjusted to account for the 15dB loss in the floor. Therefore, if the nodes used to receive with -95dBm PRPT, they are adjusted to receive with -80dBm PRPT instead. In simulation, the panels were separated from robots in the same floor by 2m vertically and 100m horizontally. Channel 1 is dedicated to Panel-Robot Wi-Fi links, while channel 6 is used between robots 1 and 2, and channel 11 is used for robots 2 and 3.

To test the functionality of the multi-floor approach, two scenarios were simulated to model the cases of two and three floors. Channel 1 is fixed for Panel-Robot communication, channel 6 is dedicated to communication between robots 1 and 2 and channel 11 is used for communication between robots 2 and 3. On the other hand, four floors were simulated to represent 2 clusters in the modular approach. Results from the last simulation are then generalized to more clusters. In floors 1 and 2, channel 1 is fixed for Panel-Robot communication and channel 6 for communication between robots 1 and 2. The channels are interchanged in the next two floors. Channel 11 is then used between robots 2 and 3.

C. *Backbone Communication Architecture*

As discussed above, a cluster LTE interface sends 4 videos to the COW with a total of 18kB sent every 40ms, and 4 telemetry and sensor data files with a total of 8328.25B every 1s. The COW, in return, sends 4 telecommands files to a cluster LTE interface with a total of 125B every second. Again, only video is sent over UDP while the rest is sent over TCP.

To simulate this scenario, two LTE workstations were used to represent interfaces for two clusters, and a third workstation for the COW. To establish the connection, there needs to be an eNodeB connected to Evolved Packet Core (EPC) via a Point-to-Point Protocol (PPP) link. Results for this scenario apply to both WLAN approaches.

D. *Performance Metrics & Application Benchmarks*

For video traffic, three performance metrics are computed. The first is the *delay* which is defined as the average of end-to-end delay of all packets at the recipient node. The standard deviation of those delays defines the second metric, namely *jitter*. The last metric is *packet loss* which is defined as the percentage of dropped packets to the total number of transmitted packets. In FTP traffic, only delay and jitter are important since files are guaranteed to be delivered by TCP. All results are based on a 95% confidence analysis. The benchmarks for video traffic are 100ms delay, 40ms jitter and 0.1% packet loss [17]. For FTP traffic, delay and jitter need to fall within the sampling period, which is 1s.

IV. SIMULATION RESULTS

Throughout this section, all simulations are carried out on Riverbed modeler. Reported results are 95%-confidence intervals for 33 runs with different seeds each.

A. *Robot On-Board Ethernet Network Architecture*

The maximum incoming delay to the main module is 25.662μs while the maximum outgoing delay is 176.206μs. Therefore, the total delay through the on-board network is 201.868μs. In addition, there is no packet loss observed in the onboard network. These results are expectable because in an Ethernet network managed by a switch, the only none deterministic delay is the queuing delay. Usually, there is no queuing on the ports of the switch; however, when the queuing is high, there is an increasing variation. The variations are too small though and can be neglected.

B. *Wireless LAN Architecture*

1) Multi-floor Approach: According to the simulation results for two floors, the output shows that, for the Panel-Robot video traffic, the average delay reaches a maximum of 6.96ms and a jitter of 1.17ms with a packet loss of 0.012%. Regarding the telecommands traffic, the average delay reaches a maximum of 208.95ms with a jitter of 1.45ms and no packet drop. The telemetry and sensor data traffic result in a delay of 21.34ms and a jitter of 2.22ms. On the other hand, for Robot-Robot video traffic, the average delay is 1.72ms maximum and a jitter of 0.61ms while the packet loss is 0.012 %. For the same link, telecommands and telemetry traffic, the maximum average delay is 204.67ms with a jitter of 0.64ms and no packet loss. Therefore, all video and TCP traffic pass benchmarks for this scenario. Similar results for three floors are shown in Table III.

TABLE II. TWO FLOORS SIMULATION RESULTS

Two Floors	**Panel-Robot Communication**		
Traffic Type	***Delay (ms)***	***Jitter (ms)***	***Packet Loss (%)***
Video	[6.95-6.96]	[1.16-1.17]	[0.012-0.012]
Telemetry & Sensor Data	[21.23-21.34]	[2.16-2.22]	0
Telecommands	[208.91-208.95]	[1.38-1.42]	0
	Robot-Robot Communication		
Traffic Type	***Delay (ms)***	***Jitter (ms)***	***Packet Loss (%)***
Video	[1.38-1.72]	[0.41-0.61]	[0-0.012]
Telemetry, Telecommands & Sensor Data	[204.65-204.68]	[0.61-0.64]	0

TABLE III. THREE FLOORS SIMULATIONS RESULTS

Three Floors	**Panel-Robot Communication**		
Traffic Type	***Delay (ms)***	***Jitter (ms)***	***Packet Loss (%)***
Video	[9.88-9.92]	[2-2.04]	[0.013-0.013]
Telemetry & Sensor Data	[26.73-27.19]	[3.4-3.55]	0
Telecommands	[212.98-213.33]	[2.33-2.48]	0
	Robot-Robot Communication		
Traffic Type	***Delay (ms)***	***Jitter (ms)***	***Packet Loss (%)***
Video	[1.25-1.72]	[0.41-0.61]	[0-0.013]
Telemetry, Telecommands & Sensor Data	[204.61-204.73]	[0.62-0.72]	0

TABLE IV. MODULAR APPROACH SIMULATION RESULTS

2 clusters of 2 floors	**Panel-Robot Communication**		
Traffic Type	***Delay (ms)***	***Jitter (ms)***	***Packet Loss (%)***
Video	[7.49-9.01]	[1.73-1.92]	[0.026-0.026]
Telemetry & Sensor Data	[23.57-25.83]	[2.78-3.34]	0
Telecommands	[211.82-213.37]	[2.35-3.74]	0
	Robot-Robot Communication		
Traffic Type	***Delay (ms)***	***Jitter (ms)***	***Packet Loss (%)***
Video	[1.38-3.96]	[0.41-2.27]	[0-0.026]
Telemetry, Telecommands & Sensor Data	[204.63-213.06]	[0.62-3.19]	0

2) Modular Approach: According to the simulation results for the '2by2' scenario in Table IV, the maximum delay of Panel-Robot video traffic is 9ms and a jitter of 1.92ms with a packet loss of 0.026 %. For the telecommands traffic, it results in a delay of 218.8ms with a jitter of 3.73ms and no packet loss. The telemetry and sensor data traffic have a maximum delay of 25.82ms, jitter of 3.34ms and zero packet loss. For Robot-Robot video traffic, the average delay is 3.96ms maximum with a jitter of 2.73ms while the packet loss is 0.026%. The telecommands and telemetry traffic delay is 212.98ms, jitter is 3.19ms, and packet loss is 0%. Therefore, it is clear that all video conferencing traffic and FTP statistics fall within the deadlines mentioned earlier.

C. Backbone Communication Architecture

According to the simulation results shown in Table V, video traffic has a maximum delay of 19.29ms, jitter of 1.6ms, and packet loss of 0.06%. For telemetry and sensor data traffic, their delay is 182. 84ms, jitter is 5.34ms, and packet loss is 0%. Lastly, the delay for telecommands traffic is 252.1ms, jitter is 5.68ms and 0% packet loss. Similarly, the system ensures meeting the benchmarks. A graph of video delay at the COW from cluster 1 simulated over 33 seeds is shown in Fig. 5.

TABLE V. BACKBONE SIMULATION RESULTS

Backbone	**Panel-COW Communication**		
Traffic Type	***Delay (ms)***	***Jitter (ms)***	***Packet Loss (%)***
Video	[18.48-19.29]	[1.32-1.6]	[0-0.059]
Telemetry & Sensor Data	[166.54-182.84]	[2.73-5.34]	0
Telecommands	[245.23-255.18]	[3.4-5.68]	0

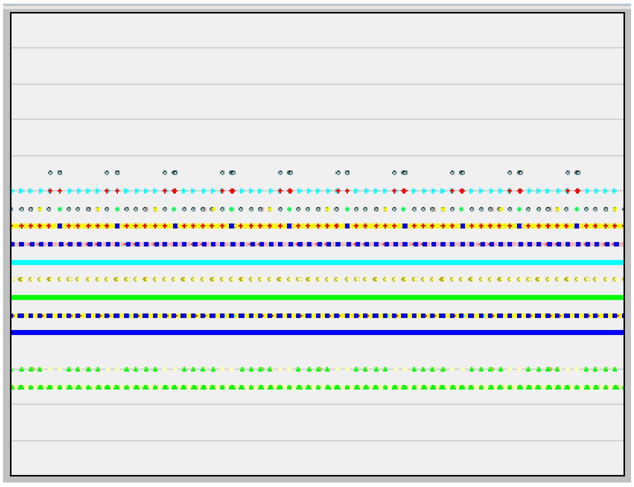

Fig. 5. Video delay from cluster 1 to COW where the x-axis represents the simulation time in seconds (s) while the y-axis represents the delay in seconds (s). The y-axis scale is in milliseconds.

D. Analysis and Discussion

The worst case path for delay is when the information needs to move from one robot to another, then to a panel before it finally reaches the COW. This path includes any other paths as a subset. The total delay on this path is the sum of twice the delay of the on-board network, Robot-Robot delay, Panel-Robot delay, and LTE delay. For video traffic, this total delay is 33.57ms which is below the sampling period (40ms) and the deadline (100ms). For the FTP traffic, this delay is 682.01ms which is below 1s. The maximum video jitter is 2.27ms which is below the 40ms benchmark. The maximum packet loss is 0.059% which is below 0.1%. Finally, the maximum jitter for any FTP traffic is 5.68ms which is below the sampling period (1s). From all the results mentioned so far, it is safe to conclude that the whole system has passed the deadlines with a high safety margin.

V. CONCLUSION

Fire fighters face a lot of difficulties during firefighting due to the lack of information. At the fire ground, the incident commander gathers the information and tries his best to safely end the fire; however, sometimes the incident commander fails and people die. In this paper, a complete fault-tolerant network architecture is proposed starting with the Ethernet robot which can accommodate high data rates needed for video transmission; then a wireless architecture is proposed to allow communication between the robots of different floors (using Wi-Fi) and allow the robot panel communication. Last, the backbone communication (using LTE) is used to guarantee that the collected data is sent to the COW in the required time. All Riverbed simulations proved that the system was able to meet required benchmarks.

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