Experimental Study of Data Network in Confined Space of Vessel: Opportunities and Challenges

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***Abstract*—With the advent of ultra-high-speed 5G networks, many industrial sites are introducing digital technologies. The shipbuilding industry is also inevitably changing to a digital shipyard, and many digital technologies are being applied to industrial sites. However, since there are many closed confined spaces made of steel in ships, many communication technologies are facing limitations in application. In this paper, the performance of wired/wireless confined space communication in a ship to apply a remote inspection solution was analyzed. In addition, considerations for methods to overcome the problems occurring here and discussions on what needs to be developed in the future are discussed. Through this, we intend to identify the current limitations of confined space communication and prepare new opportunities by organizing new challenges.**

***Index Terms*—Confined Space, Closed Space, Communication in vessel, Digital Shipbuilding**

I. INTRODUCTION

The combination of high-speed network development and digital conversion technology in the industrial field is changing things that have been done in the industrial field for a long time to be solved in the online world. These changes have evolved into digital twin systems that can be monitored and made decisions in the online world. The digital twin system is a technology that can predict the result in advance and reflect the result in reality by creating a real object in the virtual world as twins and simulating various situations that can occur in the real world in the virtual world. [1]

Shipyards have also increased the number of sensors for collecting various information in order to grasp the site situation at a long distance and are exchanging the information through heterogeneous communication. Based on this information, digital shipyards are used in various ways not only to prevent safety accidents but also to improve process efficiency. In particular, industrial application services using image information are expanding their scope, and efforts have been made to improve productivity by utilizing collected image information and combining it with artificial intelligence. Figure 1 is a conceptual diagram of our proposed 5G network based digital shipbuilding system, which digitizes and collects various on-site information through heterogeneous networks including 5G networks, and shows how decision support and simulation are possible in a virtual shipyard space. [2]

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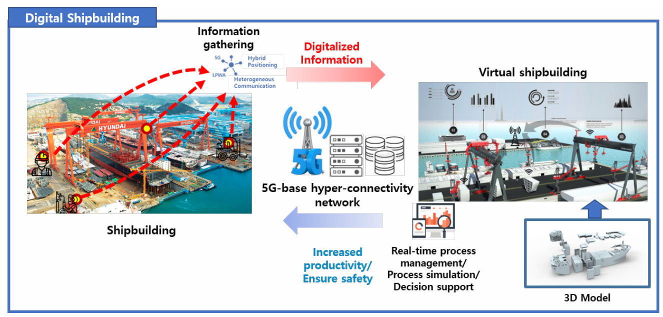

Fig. 1: 5G network based digital shipbuilding [2]

With the combination of 5G and artificial intelligence, the information collected in reality is gradually growing into large-capacity information such as images and videos, beyond simple analog information and digitized information. In addition, not only a blueprint sharing service that simply downloads large amounts of information, but also an ultra-low latency service that can remotely control heavy equipment is gradually spreading. In particular, due to COVID-19, non-face-to-face business processes such as remote video conferences have also increased. These services take advantage of the URLLC(ultra reliable and low latency communication) and MEC (Multi-access Edge Computing) features of 5G networks.

5G Network URLLC [3] utilizes MEC as a 5G network key technology that not only provides a stable network but also provides ultra-low latency services close to real time. As shown in Figure 2, MEC [4] can provide faster response speed compared to more conventional networks by taking charge of computing and its response at the edge server located at the end of the network instead of a distant cloud server. Due to these characteristics, MEC is widely used for real-time control and streaming services. [5] We are using the 5G network to build a digital shipyard by building a shipyard, and in particular, we are using ultra-low latency for remote collaboration services.

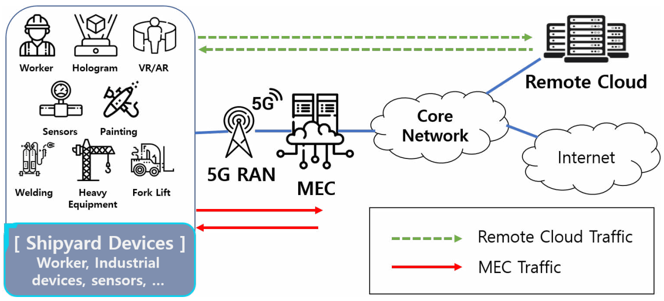

Fig. 2: 5G network architecture

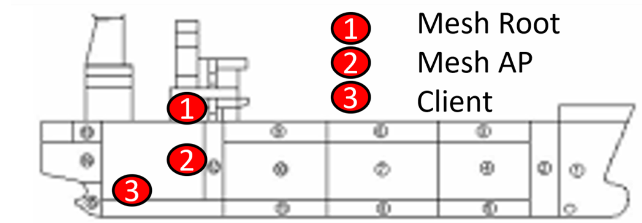

Fig. 3: Location of mesh stations in the first scenario

II. Problem of Confined Space Network

In order for a shipyard to operate a digital shipyard, it is essential to utilize a high-speed, low latency 5G network. In addition, in order to fully utilize the advantages of 5G networks, a good communication environment between the base station and the mobile device must be guaranteed. However, in the case of shipyards with many steel structures, most of the radio waves are blocked, resulting in many communication shadow areas. In particular, stable data transmission and reception is difficult due to a one-hop-based network configuration that must be directly connected to a mobile terminal and a base station in an confined space made of steel structures inside a vessel. To overcome this problem, various communication technologies have tried to solve it using multi-hop technology. However, satisfactory results were not obtained due to interference by reflected waves in an enclosed space.

To solve this problem, we recently used a very reliable wireless RF communication technology such as LoRa, a CSS(Chirp Spread Spectrum)-based communication method In addition to 1-hop communication presented in the existing LoRaWAN standard [6], LoRa Mesh [7] and two-hop based LoRa communication technology [8] have been proposed as technologies to overcome communication shadow space. This technology has been presented as a communication technology applicable to confined spaces that is far superior to existing Wi-Fi. However, it is not applied to services requiring high traffic such as remote inspection due to traffic duplication problem by relay [9], high network control overhead and low data transmission/reception speed.

In this paper, we built a broadband wireless communication technology with multi-antenna that can handle high traffic for communication in an confined space of a ship in a shipyard and discussed its limitations. To analyze the problem, a confined space communication network was established using Wi-Fi 6 (IEEE 802.11ax [10]), which has improved multi-antenna utilization technology compared to the existing technology [11]. Technologies such as Wi-Fi 6's Spatial Reuse and Multi-user MIMO are used to reduce the effect of interference compared to the existing ones. Based on the experimental results, the limitations of the current wireless Wi-Fi multi-hop network are analyzed, and solutions for limited space communication through convergence with heterogeneous communication technologies are discussed to expand the 5G network.

III. Experimental Study

In order to analyze the performance of confined space communication inside a ship, experiments were conducted in two scenarios. In the first scenario, the performance of the wireless network in a confined space was verified by measuring the throughput of the network and transmitting video. In the second scenario, the usability of the remote inspection application service and the signal strength of wireless communication were measured using a head-mounted display device for remote inspection. A wireless multi-hop network performance test for remote inspection inside a ship was conducted at a shipyard located in Ulsan, South Korea. For connection with external networks, cellular networks such as 5G/LTE are connected to the gateway. Since cellular network communication is difficult inside the ship, a Wi-Fi-based wireless network was established to provide network connectivity.

The wireless network protocol used IEEE802.11ax and 802.11s. As network equipment, a router using both 2.4GHz and 5.8GHz simultaneously was used. Multi-user MIMO function is supported by using two antennas per each frequency, and each antenna has a 5dBi gain. The wireless backbone network and the wireless AP are configured to use both 2.4GHz and 5.8 GHz simultaneously. For one channel bandwidth, 40 MHz in 2.4 GHz and 80 MHz in 5.8 GHz were allocated through channel aggregation.

As shown in Figure 3, in first scenario, a multi-hop network was built from the deck house entrance(location 1 in figure 3) on the container ship to the bottom of the engine room(location 3 in figure 3). To check the network performance,the iperf tool was used to measure the network throughput. In order to see the possibility of video transmission, the results were checked for video streaming performance through RTMP server. The RTMP server transmits 360p, 720p, and 1,080p videos and measures their quality. As a client, an Android-based mobile phone which support IEEE 802.11ac was used for the experiment.

Figure 4 shows the results of network throughput measurements using iperf tool. A total of 100MB of TCP-based data was transmitted through a 2-hop wireless network. It can be seen that the network environment changes frequently as workers open or close the door as they enter and exit the engine room of the container ship over time. Experimental

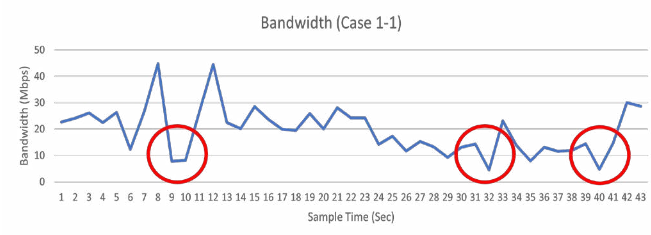

Fig. 4: Network throughput result using iperf

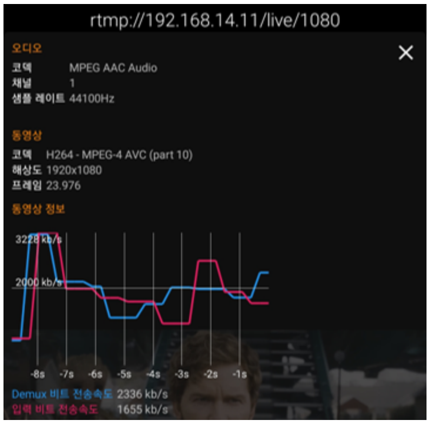

Fig. 5: Video streaming bitrate information via VLC (1,080p)

results in the deepest engine room showed an average data throughput of 19.2 Mbps, with a maximum speed of 44.8 Mbps and a minimum speed of 4.53 Mbps. In some time periods with red circles(9-10 seconds, 32 seconds, 40 seconds), real-time video with high quality, such as 1,080p, may be partially frozen due to slow network speeds. However, medium and low quality videos such as 720p and 360p could be played without any major problems. According to the CISCO webex information, the sender side generates traffic of 1,750 kbps to 2,380 kbps and the receiver side generates traffic of 1,260 kbps to 1,820 kbps in a 720p quality video conference.

The same experiment was conducted on a ship under construction instead of a completed ship. Experimental results showed the average data throughput was 49.9 Mbps, the maximum speed was 64.6 Mbps and the minimum was 29.7 Mbps. Figure 5 shows the playback information of a 1080p video streamed over a wireless multi-hop network viewed through VLC. We can see that 24 frame images and 44.1KHz audio information of the video are received without omission. The reason why the network shows higher performance on a ship under construction than on a ship that has already been completed is that the doors are always open to supply electricity and various utilities to various cables during the construction stage. As a result, since the iron door is always open, the phenomenon that radio waves are blocked is reduced, resulting in better results than previous experiments. However, it was confirmed in the same way as in the previous experiment that the performance of the network was partially degraded according to the entry and exit of the worker.

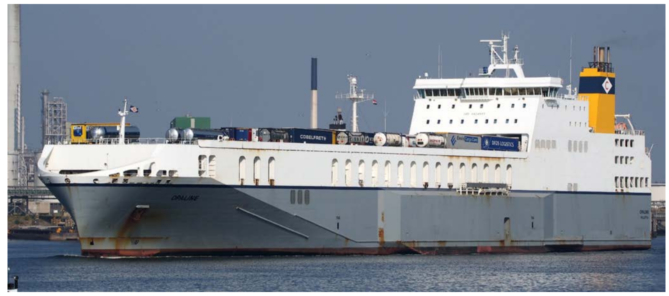

Fig. 6: Example of ConRo ship

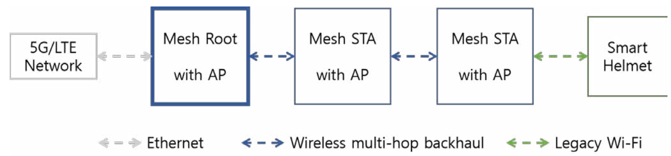

Fig. 7: Multi-hop network connection in the confined space (second scenario)

The considerations for performance improvement that can be confirmed through this experiment are as follows.

- Network terminals that are connected to the outside, such as mesh root terminals, should make a good communication link with the inside as much as possible. One option is to place the wireless network's gateway inside the deck house where external network connectivity (5G, P-LTE, etc.) is available. Or we can utilize other wired infrastructure, such as powerline communications, to provide a connectable network between internal wireless networks and external wireless networks.
- Wireless network terminals should be arranged so that the bottleneck of each wireless section can be minimized. Because, it was confirmed that the wireless section with the lowest speed would limit the performance of the entire network, and that part occurred mostly in the part made up of iron doors.
- If the ship's iron door is closed, that part may become a bottleneck due to the performance degradation of the communication link. Improving the wireless experience by adding intermediate mesh stations to either side of the door can help improve overall performance. However, the configuration of too many relays is the main cause of overall performance reduction.

In the second scenario, the experiment was conducted by moving to a large-sized ship, and the effect on multi-hop and the radio signal propagation environment were analyzed. Figure 6 is a vessel used in the experiment called ConRo. It is a ship that can transport containers and cars at the same time, and provides a higher and wider space than first scenario. Figure 7 is a diagram of the network connection used in second scenario. A mesh root terminal was installed together with an 5G/LTE router in a place where power was supplied, and the network was expanded through two wireless mesh stations. A smart helmet capable of remote video meetings was used

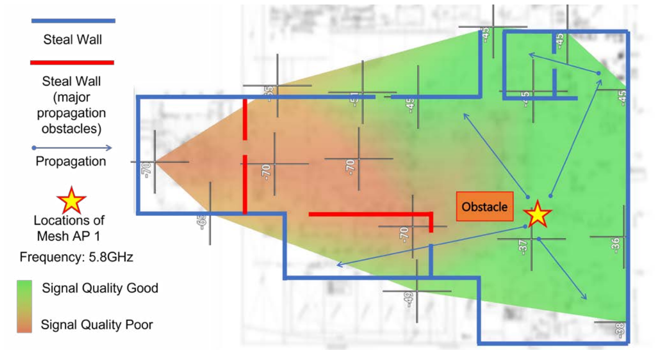

Fig. 8: Wi-Fi RSSI Heatmap of Mesh Root Station(AP1) (5.8GHz)

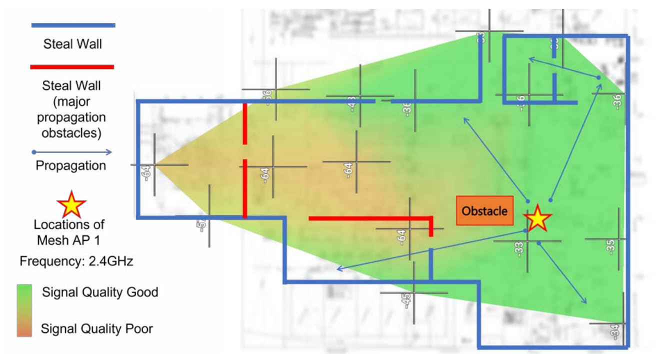

Fig. 9: Wi-Fi RSSI Heatmap of Mesh Root Station(AP1) (2.4GHz)

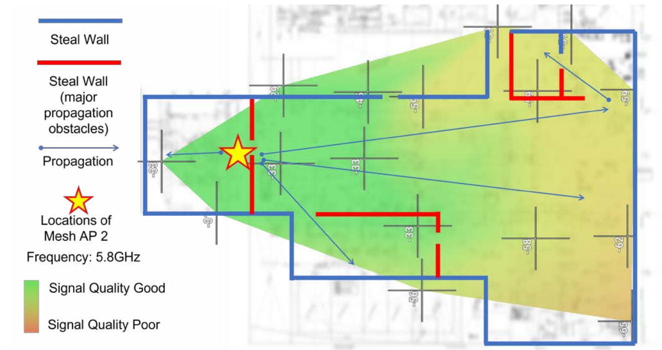

Fig. 10: Wi-Fi RSSI Heatmap of intermediate Mesh Station(AP2) (5.8GHz)

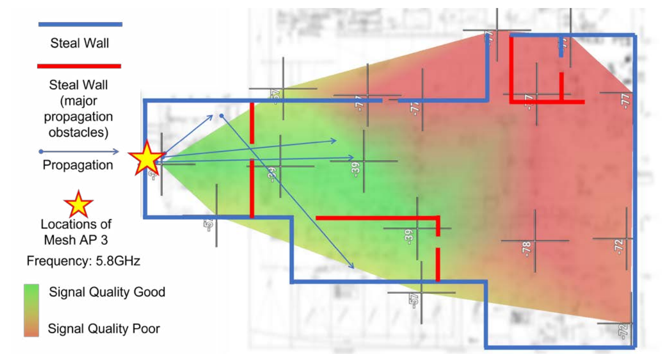

Fig. 11: Wi-Fi RSSI Heatmap of intermediate Mesh Station(AP3) (5.8GHz)

as a client. The voice and video signals of the smart helmet are delivered to the mesh root gateway through the wireless mesh network and transmitted to the outside through cellular network. Other video conference terminals participating in the video conference meeting directly accessed through the internet, and four conference participants shared their screens. For network quality measurement, the received signal for each AP and frequency was measured and displayed through an Andorid-based smart phone.

Figure 8 and Figure 9 show the result of specifying the received signal of the mesh root terminal as a heat map picture. The blue steel wall means the bulkhead inside the ship, and the red steel wall is the bulkhead inside the ship that is the main cause of obstruction to communication. The engine is located in the middle space, and in particular, a large distribution panel and engine are located next to where the Mesh Root equipment is installed, which presents a major obstacle to communication. Received signals of good quality are shown in green, and the poor signal quality is shown in red. In an environment where the door in the bulkhead is open, the applicability of the service was tested using an HMD(head mounted display) capable of remote video conferencing. In places where the signal of the network is poor, some video was cut off, but the voice connection was smooth, and the service continued without significant impact even when moving between mesh APs. Comparing two figures, Figure 8 uses a higher frequency band and a wider channel width than Figure 9. Since a wider bandwidth and a higher frequency are used, the degree of signal attenuation according to distance and obstacles is judged to be large. However, as shown in Figure 8, in areas where a line of sight (LoS) with low signal attenuation is secured, it is judged to be advantageous to use a channel that can support higher frequencies and faster speeds.

Figure 8 and figure 10 show the strength of signal reception between the Mesh Root Station (AP 1) and the Mesh Station (AP 2) 1-hop away from each other in an environment using the same 5.8GHz frequency. In the case of Figure 8, an obstacle was placed nearby and the signal decreased rapidly in the corresponding direction, but in the case of figure 10, there was no obstacle in the direction toward the engine (to the right), indicating a generally good received signal. The deterioration of signal quality at major propagation obstacles is the same symptom for both sides.

Lastly, the Mesh Station (AP 3) was installed in an area that could be connected to the Mesh Station (AP 2), and it was installed on another floor climbing up the ladder. Unlike previously installed network terminals, since they exist on different floors, signals are transmitted only through the ladder passage connected to the upper floor. Because of this, it is possible to provide a network only in a narrow area as shown in Figure 11. Like the previous two cases, the 2.4GHz case was able to cover a wider area.

The considerations for performance improvement that can be confirmed through this experiment are as follows.

- Current technology allows simultaneous use of both 2.4 GHz and 5.8 GHz channels. In order to obtain better results between the communication distance and data rate, it is necessary to select a method for data transmission in which combination of both channels is used. It is also necessary to further analyze whether it is advantageous to use both links or one specific link using metrics such as HWMP (Hybrid Wireless Mesh Protocol) of the existing IEEE802.11s standard.
- Depending on the location of the surrounding obstacles, the difference in size of the shaded area is clearly visible. Research on how to find an installation location that can be less affected by obstacles is needed to provide a smooth network to the area where communication is required.
- In order to use application services such as remote video conferencing, multi-hop networks have many difficulties in terms of latency. In particular, the generation of continuous packets such as streaming is very disadvantageous to networks that use stochastic back-off methods such as basic IEEE 802.11 MAC. To overcome this, research on QoS support methods is needed.

IV. Conclusion and Discussion

In this paper, experiments on wireless network expansion for the application of remote inspection services for confined spaces in vessel and the results were analyzed and problems to be additionally addressed were mentioned. The issues and considerations mentioned above are summarized below.

- In terms of network connectivity, router placement remains an important issue. In particular, the issue of how to adapt to the changing environment in building a multi-hop network is still an unresolved issue in the industrial field. In the case of shipbuilding, environmental changes occur greatly. However, the shipbuilding process proceeds according to certain stages, and a similar network environment is formed for each ship type. Therefore, research is needed to minimize network shaded areas in the shipbuilding process that changes in real time.
- In the case of confined spaces, radio waves are highly reflected, so technologies such as noise canceling were used. However, in the past, the method of transmitting radio waves in all directions using one omni antenna has changed to a technology that can transmit and receive signals in a specific direction using multiple antennas. As a result, the effect of interference caused by reflection of radio waves in the room shows a completely different aspect. Environmental analysis and channel models for this should be additionally considered. Additionally, the confined space made of iron is an environment in which the terminals participating in the wireless network can operate independently without interference from external signals. Therefore, it is necessary to consider interference between internal network terminals, antenna selection, and reflected waves rather than external network interference.
- Depending on the utilization of multiple channels and the various bandwidths of the channels, the appearance of the network to be built will be different. Depending on the nature of the network required by the application service, a technique that can be used selectively or simultaneously in the 2.4GHz and 5GHz bands can be utilized.
- To support delay-sensitive services, a more enhanced QoS support technology that can guarantee real-time is required. Research that can apply cellular network channel slicing technology and medium access control technology to multi-hop wireless networks will be possible. In addition, due to the nature of multi-hop networks, it is necessary to develop a technology that can minimize latency by reducing the number of hops.
- Wireless network technology alone cannot solve the problem of communication loss in completely enclosed spaces. However, there are various confined space communication technologies to overcome the limitations of wireless networks. For example, in addition to wireless signal-based confined space communication, we are conducting research on power line communication technology and metal surface wave-based communication technology. In particular, in the case of metal surface waves, it is judged to be a solution that can alleviate the communication problem for completely enclosed spaces. [12], [13] Research on how these wireless alternative communication technologies can be utilized in ships is also needed.

In future research, we plan to conduct research on a complex network environment in which confined space communications are interconnected to expand the network to wireless communications in an environment where metal body surface waves and power line communications become the backbone.

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