The Efficient Distribution Method of Limited Wireless Communication Frequency Resources for the Multi-robot Teaming

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Abstract: In the situation where various defense robot systems are developed and operated, wireless network is an indispensable element to remotely control unmanned robots. However, when each defense robot is operated on the basis of wireless communication, the available frequency resources per robot are limited. At this point, if multiple robot operations are increased and the number of robots participating in them increased exponentially, a serious shortage of available frequencies is expected. Therefore, we propose a dynamic allocation of frequency resources as the bottom-up type approach to overcome this problem. More specifically, we implemented a bandwidth allocation scheme according to the priority change of each end node. We also show the validity and efficiency of this method through the related experimental results.

1 INTRODUCTION

When an unmanned robot is operated at a remote control station in real field as a defense use, a wireless communication environment should be established basically irrespective of whether the robot is a ground vehicle or an aerial vehicle. However, the available bandwidth of the communication frequency is limited, and the number of the robot for the military purpose is steadily increasing (Alberts, David S., et al., 2000). In such a situation, when a plurality of robots are operated by a single control system or heterogeneous robots are operated together, a serious shortage of wireless network frequency is expected. Especially, military frequency is strictly controlled due to security problems in military operation environment (Heeseo Chae, et al., 2017). The unmanned robot we are developing currently needs to be allocated a communication frequency from the government in order to use it in the actual field. However, there are many difficulties. Because not only new unmanned robots but also existing systems use similar communication equipment, the available frequency bands are similar. Thus, users should pre-check and avoid the preferred communication frequency band. Depending on the area, they have to be preoccupy the available frequencies and use it selectively. (Jae Hyuk Ju, 2014). Therefore, multi-robot operation method and frequency utilization approach are being researched to overcome this limited environment (D. Gesbert, et al., 2003).

In this paper, we describe a case where heterogeneous robots operating in a limited wireless communication environment are teaming through multiple robot control methods. In order to use allocated frequencies effectively, we will distribute them in accordance with each mission and suggest a way to reallocate the network channels in a bottom-up manner. We also show the system design and the software architecture that will enable such mechanism, and explain the implementations. Finally, we analyse the experimental results applied to the actual multi-robots and confirm the feasibility and expandability of our approach.

2 CONFIGURATRION OF THE DEFENSE ROBOT

There are three types of defense robots that we develop. Size and weight are the criteria, and as

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shown in Figure1, it is classified into large-class, medium-class, and small-class unmanned robots. Even if the types of robots are different, each network device used for wireless communication has a common functions. There is some performance difference depending on the operating range of the robot (Hyo Keun Lee, et al., 2017). In the actual field, the robot is remotely operated using the legitimate network frequency assigned by each military unit. In order to do teaming among the robots of different classes, it is necessary to separate the channel within the provided communication frequency range, allocate them to the respective robots, and operate them appropriately (Heeseo Chae, et al., 2016).

EOD robot	Multi-purpose UGV	Unmanned Combat Vehicle
- Weight: **100kg**	- Weight: **1ton**	- Weight: **5ton**
- Power Unit : **EV**	- Power Unit : **EV**	- Power Unit : **HEV**
- Drive : **Track/Flippers**	- Drive : **6x6/In-hull**	- Drive : **6x6/In-hub**
- Max Speed : **12km/h**	- Max Speed : **20km/h**	- Max Speed : **60km/h**

Figure 1: Multi-robot teaming concept and each robot spec.

The above figure shows the concept that each robot operates remotely around the control station. Although it operates in a top-down approach with in the allocated frequency, it may also perform direct communication between robots through the ad-hoc network if necessary (Heeseo Chae, et al., 2018). In addition, according to the driving ability and the role of each robot, there is a difference in priority in using network resources.

2.1 The Common Network Device Design

For multi-robot teaming, hardware and software of communication devices should be provided as the same common platform for each robot.

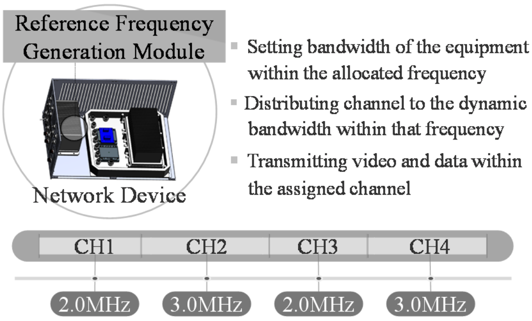

Figure 2: The Network device to set the dynamic bandwidth.

In the past, when the frequency was allocated to each device, the channel was distributed as the same bandwidth (Albus, J. S. et al., 2006). This is a top-down approach, and we use the dynamic bandwidth configuration scheme shown in Figure 2 to improve it. This method is the common design of the hardware side, and in terms of software, the common communication architecture is required to implement it.

2.2 The Common Network Architecture

The runtime view of the network architecture, which is mainly performed by the control station, is as follows.

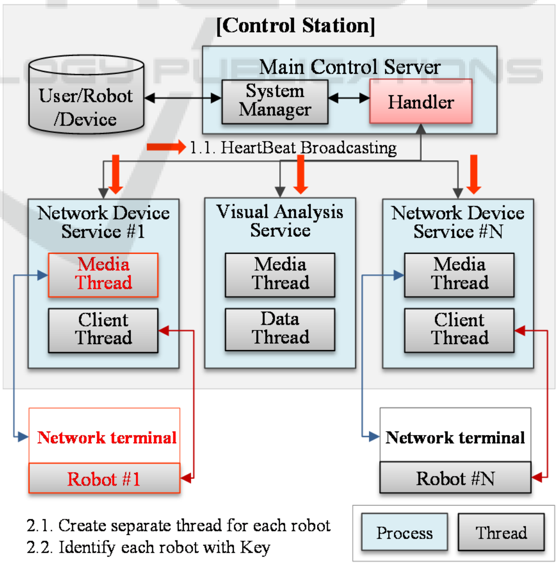

Figure 3: The Network architecture for server process.

The operator's command are transmitted through the process that is dedicated to each robot. Utilizing this multi-thread structure, N robots for teaming can be remotely controlled as long as communication resources are provided. The heartbeat is periodically transmitted to prevent the network disconnection between the control station and the robot. In order to cope with dynamic bandwidth change, it is possible to continuously identify the robot that was being controlled by using a key for each robot.

3 FREQUENCY DIFFERENTIAL DISTRIBUTION SCHEME

If a large number of unmanned robots are operated according to the conventional method within a limited frequency, it is inevitable to provide insufficient bandwidth to all robots. That is, the legacy approach using the even distribution can only operate a limited number of robots, and is unsuitable for operating more than N robots. Therefore, the proposed frequency operation method is dynamically determined without setting the division ratio in advance.

3.1 Resource Allocation by the Robot Teaming Scale

The method of distributing the bandwidth according to the scale of robot teaming is as follows.

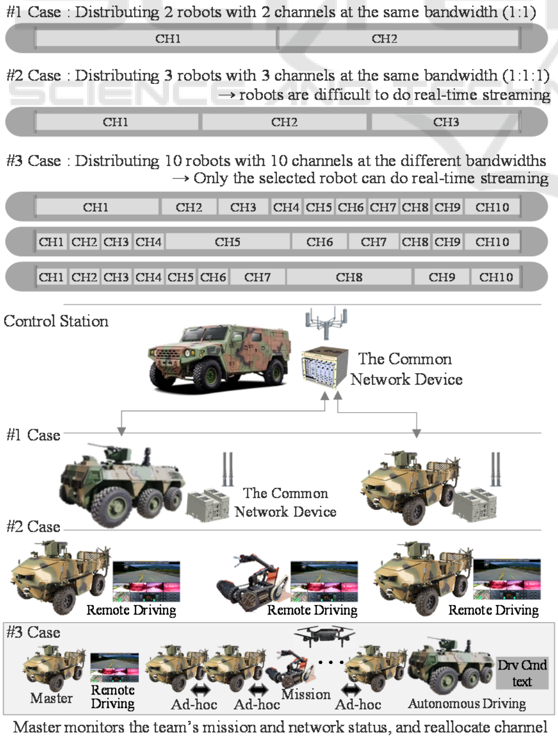

Figure 4: The channel allocation by the teaming scale.

In the figure 4, case#1 and case#2 are examples of frequency allocation using even distribution. When the number of robots is small, remote control is possible through real time image. However, as the number of robot increase, it becomes difficult to provide real time image. In the case#3, the master of the robot team monitors the current task and network status of each member, and send a channel reallocation request to the control station at a predetermined time interval. It can accept this bottom-up request and provide new bandwidth dynamically. When sharing information among robots within a robot team, some portion of the existing frequency bands can be used. However, in order to maximize available frequency range, the separated network as ad-hoc type is utilized. This area uses a temporary frequency domain because it is a short distance communication that exchanges simple data such as status information of each robot. In order to prevent attenuation by distance, ad-hoc needs to maintain the distance between robots.

3.2 Network Channel Reallocation Process and Criteria

Reallocating the wireless network bandwidth as a bottom-up approach requires a formal process and standard.

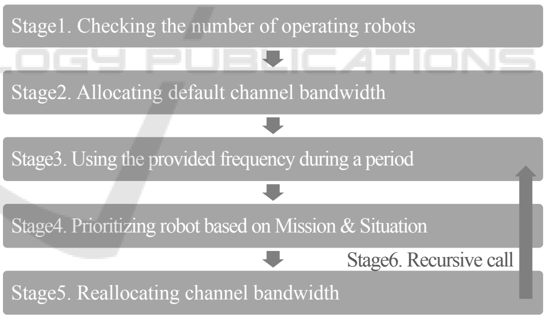

Figure 5: The recursive process for bandwidth reallocation.

In the above figure, except for the initialization process (stage1 and stage2), it shows the cycle of continuous circulation according to a certain time period. The factors considered in channel reallocation are the priority of the task being executed and the urgency of the situation. This information is provided to nearby robots and the master. Based on the data, the bandwidth allocation is determined.

The criteria of the channel reallocation process is based on the task priority table. It is as follows.

Table 1: Task Priority Matrix from the Operation Concept.

Driving Status	Task for Mission		
	Surveillance	firing	No mission
Remote Driving	2	1	3
Autonomous Driving	5	4	6
Stop	8	7	9

The missions of robots are simplified as surveillance, shooting, and moving. The highest priority is shooting. This is because the target must be captured with real-time video and fire commands should be delivered without delay. In case of driving, remote driving and autonomous driving are classified. The remote driving requires a large amount of communication bandwidth because it needs real-time video streaming. Disconnection of network during the driving cab lead to accidents. On the other hand, autonomous driving requires relatively fewer videos, so it can be operated with a small traffic volume (DeSouza, Guilherme N., et al., 2002). Through a combination of mission and driving, the situation of firing during remote driving requires the most resources. Conversely, if it does nothing and stops, it has the lowest priority. In this case, the network bandwidth is reduced dynamically.

3.3 Frequency Reuse Considering Interference

If a multi-robot team is operated by the proposed method, interference of the network frequency can be predicted considering the operation range of each team. It is shown in the figure below.

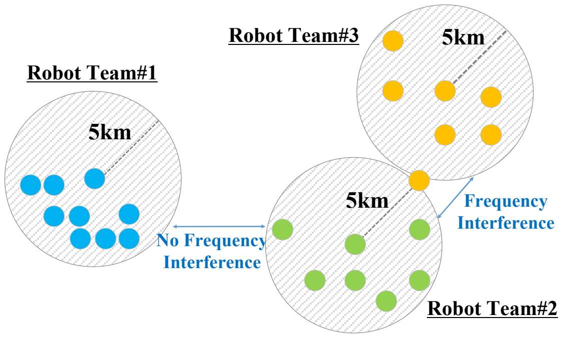

Figure 6: Frequency Reuse Situation based on the distance.

Because there is no interference between Robot Team#1 and Robot Team#2, frequency reuse is possible. The communication radius between the robot and the control station is 5km, which is beyond the supportable range of the network device. There is no problem to use the same frequency in different teams. However, when an operation is performed at a close distance, such as the Robot Team#2 and the Robot Team#3, some robots can be overlapped. In this case, frequency interference occurs and noise is generated. To overcome this situation, we set a unique OP-Code for communication network of each team and set a robot key for individual end node. The OP-Code can be generated by the Random Number Generator with AES256 standard (Keller, Sharon S, 2005). Because of this function, even if the communication is interrupted, unauthorized control of the robot is impossible. This concept can be achieved through a network process design that is adaptable to dynamic bandwidth changes and a packet structure with security considerations.

3.4 Packet Structure for Dynamic Channel Change

The above-referred security-enhanced packet structure can be seen in Figure 7 as a runtime view. Especially, the design focused on the function of the main console server of the control station enables to cope with the changes of the robot's mission and driving status.

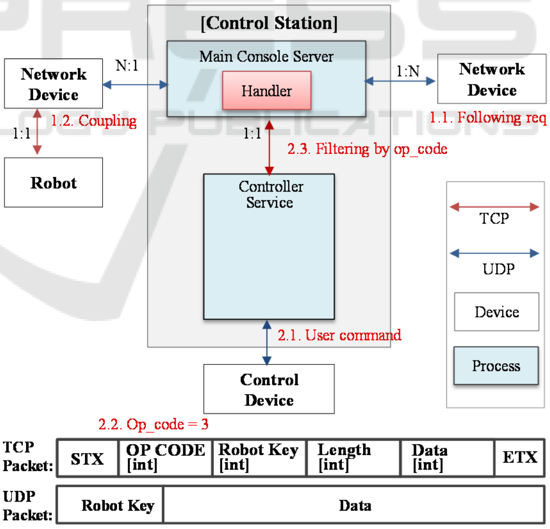

Figure 7: Dynamic bandwidth process and packet structure.

The network structure is implemented to prevent the robot from being lost due to operator's miss-control, network disconnection, and frequency interference. The robot and each manipulation device are not directly connected, but data is exchanged through the server. Also, the authority of a massage packet is changed according to whether the current driving state of the robot is remote driving or autonomous driving. With this design, the authority and the security can be maintained when allocating dynamic bandwidth. Such a mechanism can provide a wireless communication environment in which reliability and security are considered.

4 EXPERIMENT

In order to verify the proposed frequency distribution scheme, the following comparative experiments were conducted. One control station and four network devices are selected, and a total of five network devices are utilized.

4.1 Experimental Conditions

For the convenience of experiment, we used network devices of two mobile robots and three stationary terminals.

Figure 8: Experimental equipment and conditions.

The experimental site used the terrain with the road side and the ground side. The network device has the 1W output and 4x4 MIMO type antennas. Also, the frequency is 2.2~2.5GHz and the bandwidth is basically 20MHz.

In the first experiment, we measured the transmission performance by distance through the static channel distribution. The second experiment, which we suggested, we confirmed how efficiently the transmission performance can be improved through the dynamic channel distribution.

4.2 Result of Static Channel Distribution

When the control station was set as the origin, the bandwidth was distributed to the same 5MHz for each channel of each node. We measured the signal sensitivity (SNR: Signal to Noise Ratio) by increasing the distance of the nodes.

Table 2: Signal Sensitivity of Static Channel Distribution.

Distance	Node's bandwidth			
	MUGV [5MHz]	UCV [5MHz]	ST#1 [5MHz]	ST#2 [5MHz]
0m	52dB	58dB	69dB	65dB
500m	35dB	42dB	50dB	44dB
1000m	30dB	35dB	42dB	34dB
1500m	22dB	34dB	39dB	34dB
2000m	20dB	30dB	32dB	33dB
2500m	17dB	24dB	32dB	26dB
3000m	15dB	20dB	23dB	20dB
3500m	8dB	11dB	26dB	21dB
4000m	11dB	18dB	23dB	21dB
4500m	15dB	17dB	28dB	21dB
5000m	11dB	12dB	29dB	21dB

When the signal sensitivity is 30dB or more, 5MHz can be used as a full condition. Between 20dB and 30dB, 3Mbps can be used. Less than 20dB can be used below 1Mbps, so it is difficult to transmit video in real-time. It can be expressed as follows.

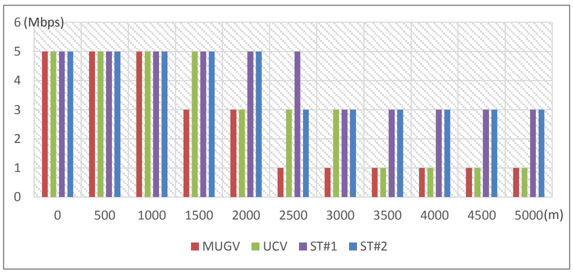

Figure 9: Throughput of Static Channel Distribution.

There is some performance difference between antennas, but communication sensitivity is further reduced in the case of moving robots. It limits the distance remotely controllable. The stationary terminals do not need to move, so the network sensitivity does not need to be good. However, since they exhibit better signal sensitivity, waste of resources occurs.

4.3 Result of Dynamic Channel Distribution

The bandwidth of each node is differently distributed. By increasing the priority of the mobile robots, more bandwidth was allocated to MUGV (Multi-purpose UGV) and UCV (Unmanned Combat Vehicle) by 8MHz, respectively. Likewise, we measured the signal sensitivity by increasing the distance from the origin (Control Station). Unlike the first experiment, if the SNR is over 30dB in 8MHz node, 8Mbps can be used. If the SNR is less than 20dB in 8MHz node, still it can use 4Mbps. However, a node that has been allocated a 2MHz bandwidth can only use 2Mbps at 30dB. The table shows the following.

Table 3: Throughput table by SNR and Bandwidth.

SNR	Node			
	MUGV [8MHz]	UCV [8MHz]	ST#1 [2MHz]	ST#2 [2MHz]
30dB~	8Mbps	8Mbps	2Mbps	2Mbps
20~30dB	6Mbps	6Mbps	1.2Mbps	1.2Mbps
~20dB	4Mbps	4Mbps	0.5Mbps	0.6Mbps

The available range of communication derived from the above table is as follows.

Table 4: Signal Sensitivity of Dynamic Channel Distribution.

Distance	Node's bandwidth			
	MUGV [8MHz]	UCV [8MHz]	ST#1 [2MHz]	ST#2 [2MHz]
0m	52dB	58dB	67dB	62dB
500m	33dB	41dB	52dB	45dB
1000m	31dB	36dB	43dB	33dB
1500m	22dB	35dB	37dB	31dB
2000m	21dB	32dB	28dB	30dB
2500m	18dB	33dB	29dB	24dB
3000m	16dB	23dB	23dB	20dB
3500m	11dB	12dB	25dB	19dB
4000m	10dB	13dB	24dB	19dB
4500m	15dB	15dB	28dB	21dB
5000m	11dB	13dB	27dB	21dB

The sensitivity of the signal along the distance is similar to the first experiment. However, even though the SNR of the mobile robot decrease according to the distance, it can be confirmed that the throughput at the long distance is more than 4Mbps because the allocated resources are large. On the other hand, the stationary terminal does not have a small SNR, but the allocated bandwidth is so small that the throughput is not enough to transmit videos even at close distance. It is shown in the graph below.

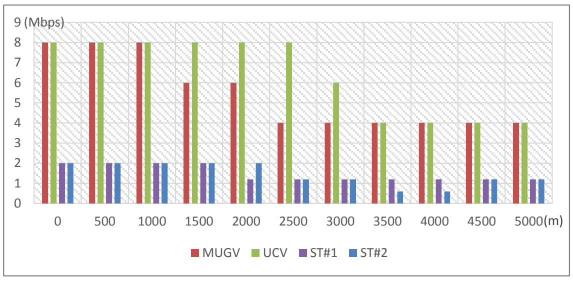

Figure 10: Throughput of Dynamic Channel Distribution.

5 CONCLUSIONS

Since a large number of defense robots are expected to be operated in the near future, the method for efficiently using a limited network frequency has suggested. The communication bandwidth was reallocated on the basis of the mission and the driving situation of the robots. As a result, we overcome the shortage of network resource as much as possible. We also proposed a network architecture and a packet structure that can be applied irrespective of frequency interference. The mechanism was verified by two comparative experiments such as the static and the dynamic channel distribution. If you use the dynamic channel distribution to provide a significant amount of resources to robots that require them, it is experimentally confirmed that it is possible to communicate smoothly even at a distance of about two to three times as compared with the existing one.

In the future, more robots will be operated to confirm the scalability of the proposed method. We will also complete a mathematical model that takes into account various optimization parameters such as climate, terrain, jamming, increasing hop, and moving speed of the robot. Through this, it is expect to improve the reliability of the proposed method by testing multi-robots with more than four nodes in the virtual environment that could not be performed in the field experiment.

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