Co^2-Robot : A Collaborative Communication Protocol for Swarm Robots

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***Abstract*—Modern high-end scientific and technological robots have been utilized in various fields. With regard to distribution, reliability, flexibility, and economy, swarm robots can accomplish more arduous tasks in parallel and demonstrate a superior performance compared to single robot. However, information interaction, which causes extra time overhead, is essential to realize synchronization or coordination in multi robot system. This paper focuses on improving the edge coverage ability of base stations especially when swarm robots cover a wide range. It proposes a novel collaborative communication protocol named Co^2-Robot for these robots in order to carry out distributed beamforming, thus enhancing the coverage range. In particular, efficient strategies are designed to cut down the time overhead among swarm robots. Subsequently, we develop a novel cluster head selection scheme to be responsible for the parallel operations. Then, distributed beamforming is performed to improve the uplink coverage when no signal from anyone of swarm robots can reach the base station. In addition, several practical user-cases are considered and analyzed in distributed beamforming, in order to enhance the robustness of this parallel system. Finally, extensive simulations show that Co^2-Robot will just result in a small amount of time overhead, which is acceptable in most scenarios. Furthermore, it can substantially extend the coverage range up to nearly 1000m while single robot can just cover a coverage range of more than 100m.**

***Index Terms*—Collaborative Communication, Swarm robots, Distributed Beamforming, Time Overhead**

I. Introduction

Nowadays, different kinds of robots have been widely deployed in various scenarios, such as industrial mission critical control, logistics service, and medical care [1], [2], [3]. Meanwhile, robot development schemes has been worked out in many developed countries or alliances, including US-A, European Union, and Japan [4]. While traditional single robot replaces monotonous, repetitive, high-risk task, swarm robots based on efficient collaboration mechanism are also exerting their distinctive superiority, gradually penetrating into industrial areas and working together with humans [5]. Especially, they can accomplish burdensome tasks which can not be completed by just a single robot. Besides, substantial improvements such as coverage and efficiency can be obtained through efficient collaboration in the working process.

Extensive research work has already verified that swarm robots outperform a single robot in terms of distribution, reliability, flexibility, and economy [6]. Following the rapid development of swarm robots, they are employed and play their advantages in several fields. Different scenarios have different requirements for swarm robots. In the field of health care, swarm robots are utilized to assist smooth operation, or monitor human health in real time [7]. Obviously, high data rates and instant connection without delay among swarm robots in this particular scenario should be provided. Another typical application scenario for swarm robots is safety protection management, such as emergency rescue and military patrol [8]. Coverage range, link robustness, and reliability are crucial factors under these harsh scenes. Finally, for logistics service, swarm robots are employed to distribute goods and act as robot "attendants". Link robustness and reliability are critical to reduce interference and collision between swarm robots.

As a crucial step, information interaction plays a decisive role in realizing synchronization and coordination among swarm robots. Reasonable and efficient communication can significantly cut down the time overhead and enhance the system efficiency. Conventional wireless communication techniques for swarm robots include WiFi, Bluetooth, WIA-PA, 3G/4G, and satellite communication. Each technique has its merits and demerits. For example, WiFi and Bluetooth are suitable for short range communication with low cost. On the contrary, satellite communications are always utilized for long distance wireless communication in the absence of ground infrastructure, which will bring high transmission cost. Based on deployed base stations, 3G/4G are also a promising candidate to realize longer distance communication for swarm robots compared to WiFi and Bluetooth.

In the meantime, with the advent of 5G Era, the data rate peak can reach up to 10Gbps [9], [10]. Transmission delay in 5G network decreases to about 1 millisecond, which is much less than 50 milliseconds in 4G network. It implies that devices can be controlled in real time even at a long distance away. In addition, China Mobile and NOKIA have demonstrated the application of 5G to support high-speed collaboration between swarm robots. It verifies that multi robots can realize real-time collaboration based on 5G networks. Consequently, the future 5G network provides a substantial potential for collaborative communication between swarm robots.

However, existing swarm robots just cover a small range due to limited power and attenuation [11]. Although relatively long communication distance for downlink can be ensured due to high transmission power of base stations, the transmission distance for uplink will be much shorter caused by limited transmission power in a single robot. Therefore, the uplink coverage extension for swarm robots is a pressing problem that needs to be addressed. Consequently, we focus on extending the uplink coverage range through collaborative communication and parallel operation in this paper, which is referred to as distributed beamforming. To achieve this goal, four major challenges exist. Firstly, efficient communication among swarm robots should be realized in order to minimize the time cost and develop a highly efficient protocol. Secondly, as a critical technique to enhance the coverage range, distributed beamforming has been investigated in this paper. Consequently, a selection scheme of the cluster head from swarm robots is needed based on energy balance, so as to control other robots to form the beam [12], [9]. Thirdly, since swarm robots are randomly located in a small area, which is completely different from conventional beamforming based on antenna arrays, we should devise a novel strategy to realize synchronization among swarm robots in order to perform distributed beamforming. Fourth, we should also design novel mechanisms to deal with abnormal scenarios when a subset of robots can not attend distributed beamforming [13].

To address these challenges, we propose a collaborative communication protocol named Co^2-Robot for swarm robots, in which efficient collaborative communication among swarm robots can be realized and then the uplink extension. The main contributions of this paper is summarized as follows.

- We design a collaborative communication protocol for swarm robots based parallel systems. Novel strategies are developed to ensure efficient communication and parallel operation between these robots.
- A novel scheme considering the power balance is proposed to select the cluster head to be responsible for distributed beamforming.
- Design enhancements for Co^2-Robot is presented to improve the accuracy and robustness, including realizing synchronization among swarm robots and dealing with the abnormal situation when a subset of robots can not attend beamforming.
- Extensive simulations verify that Co^2-Robot can cover almost the same range with the same size of antenna array. Compared to a single robot, the coverage range of swarm robots based on Co^2-Robot is considerably extended. Meanwhile, it just brings a certain amount of time overhead. Yet this overhead is acceptable for distributed beamforming.

II. Related Work

Available literature related to coverage enhancement between base station and mobile terminals can be divided into two kinds of schemes. (i) Deployment of relay nodes in the transmission process. (ii) Pre-coding before transmission.

Based on relay nodes. The most conventional method for extending the coverage range is to employ relay nodes [14], [15]. The relay selection strategy in [16] is specified according to the nodes' spatial distribution, which can determine the channel statistics. Firstly, the optimal relay location is derived in order to minimize the outage probability. Subsequently, two different cases are investigated: a relay assignment based on existing nodes, and an infrastructure-based relay-assignment scheme based on added fixed nodes. These added nodes are responsible for forwarding data. However, the scheme belongs to static relay selection, which is not suitable for dynamic scenarios. In order to adapt to dynamic environments, Gueguen et al. [17] propose a dynamic relay selection protocol to extend the wireless communication coverage. They employ an incentive approach and a scheduling scheme to incite potential mobile relaying nodes to forward data. However, relay based coverage improvement will result in a certain amount of time overhead and extra expenditure.

Based on pre-coding. In the downlink, pre-coding technique has already been exploited to extend the cell coverage in massive MIMO communication systems [18], [19]. Majority of research on pre-coding has a strict requirement for perfect channel state information (CSI) at the transmitter [20]. Nevertheless, perfect CSI can not be easily obtained in most cases. Meanwhile, CSI based pre-coding scheme always bring substantial overhead to wireless systems. Therefore, Nguyen et al. [21] propose a downlink coverage extension scheme based on orthogonal random precoding (ORP), only requiring partial CSI at the transmitter. Specifically, a precoding matrix composed of orthogonal vectors is applied at the transmitter to enhance the maximum signal-to-interference-plus-noise ratio (SINR). However, these schemes are suitable for downlink coverage enhancement and can not be applied for uplink coverage improvement.

III. Preliminaries

A. Problem Statement

In this paper, we consider swarm robots in the same plane are carrying out missions in the suburbs, and communicating with one base station in the meantime. The number of swarm robots ranges from 2 to 16. Each robot is equipped with two antennas. One is utilized for communication with the base station based on existing LTE network [22]. And the other one is applied for information interaction with other robots, which is based on 802.11P [23]. Transmission power of the base station is much higher than that of robot, which implies that the base station can cover a much wider coverage range than a single robot.

Communication between the base station and these robots follows conventional LTE protocol [24]. In addition, information interaction between swarm robots complies with 802.11P protocol. In order to enable communication for any pair of robots, swarm robots are randomly deployed in a small area. If the signal strength received by the base station is lower than a threshold, then the link between the base station and robot is regarded as disconnected. Consequently, when the base station is outside the coverage range of all robots, none of swarm robots can not deliver data traffic to the base station. In order to extend the coverage range of swarm robots, distributed beamforming should be performed based on collaborative communication and parallel operation, thus trying to reach the base station.

B. Problem Definition

Assuming that there are M elements in the antenna array. Conventional beam amplitude diagram based on antenna arrays is depicted as below.

$$F(\Theta) = |y(n)| = \left| w^H \alpha(\theta) \right|, \tag{1}$$

Where,

$$w = [w_1, w_2, ..., w_M]^T, \tag{2}$$

$$\alpha(\theta) = [1, exp(j\varphi), ..., exp(j(M-1)\varphi)]^T, \tag{3}$$

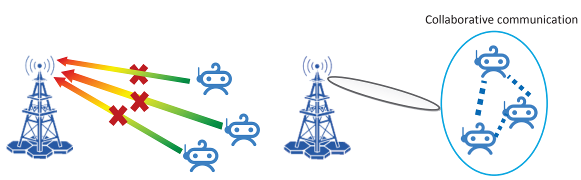
$$\varphi = \frac{2\pi d}{\lambda} \sin(\theta), \tag{4}$$

λ is denoted as the wavelength and d denotes the distance between two adjacent element. w represents the weight vector of antenna elements. $\alpha(\theta)$ is the output of the antenna array. The main beam direction is set to θ. Then, if the main beam direction is the normal direction, and w is set to [1,...,1], beam pattern can be transformed into:

$$\begin{aligned} F(\theta) = \left| w^H \alpha(\theta) \right| &= \left| \sum_{m=1}^{N} a_M exp(j(m-1)\varphi) \right| \\ &= \left| \frac{\sin(M\varphi/2)}{\sin(\varphi/2)} \right| \end{aligned} \tag{5}$$

Therefore, the signal strength of the main lobe can be up to M, which is much stronger than that of a single antenna. In result, the coverage range of antenna arrays through beamforming can be significantly improved. However, problems in this paper become much more challenging. For instance, swarm robots are randomly located and in continuous movement. Therefore, the distance between any robot pair are constantly changing, totally different from the same distance d in regular antenna arrays. Then, as shown in Fig. 1(a), if the base station is outside the transmission range of anyone of swarm robots, they should be informed to perform distributed beamforming. Hence, information interaction among swarm robots is necessary since each robot is not aware of the location of other robots. Finally, different from conventional beamforming based on antenna arrays, a cluster head from swarm robots should be selected to be responsible for distributed beamforming, during which synchronization among these robots should also be realized.

Consequently, the target of Co^2-Robot is to maximize the uplink coverage while minimizing the time overhead caused by collaborative communication and parallel operation between swarm robots. Therefore, based on proposed schemes, distributed beamforming is developed to extend the coverage range of swarm robots. The example of distributed beamforming is shown in Fig. 1(b).



(a) (b)

Fig. 1. Communication scenarios

IV. Overview of Co^2-Robot

In this section, the flow chart for Co^2-Robot is introduced. Different cases are taken into consideration in order to develop a universal protocol, including two-way communication between the base station and all robots, two-way communication between the base station and a subset of robots, one-way communication from the base station to all robots, and no communication between the base station and all robots. For different situations, corresponding strategies are designed.

Detailed flow chart is shown in Fig. 2. Steps are described as below:

1) The base station judges whether signals from swarm robots can be received, periodically.
2) If all robots can deliver data traffic to the base station, then nothing is needed to be done.
3) Nevertheless, if only a subset of robots' signals can be received by the base station, the base station will inform these robots to act as relay nodes.
4) Subsequently, these robots broadcast their own information to other robots that can not transmit data to the base station. Therefore, they can forward the data traffic from other robots to the base station.
5) Further, if none of swarm robots can transmit data to the base station, then the base station will broadcast the signal reception information to swarm robots, informing them to perform distributed beamforming.
6) A time window is set in swarm robots to avoid substantial time overhead for the arrival of broadcast information.
7) During the time window, once any robot receives information from the base station, it starts broadcast among swarm robots. The broadcast information consists of the robot's ID and location, and other parameters.
8) In contrary, if there is no robot receiving information from the base station during the time window, then swarm robots start broadcast as long as exceeding the time window.
9) A cluster head is selected from swarm robots, which is responsible for distributed beamforming. It will derive beamforming parameters according to the location of the base station and other robots, and then broadcast relevant information to these robots.
10) Finally, swarm robots perform distributed beamforming according to the received information.

From the above description of Co^2-Robot, we have covered all communication circumstances between the base station and swarm robots, thus rendering the proposed protocol more universal. It is assumed that the location information of base station has been stored in swarm robots in case that information data can not be transmitted to swarm robots. In addition, we employ the LTE broadcast mechanism for the base station to inform swarm robots to perform distributed beamforming. The reason why we select this mechanism lies in that the delay based on broadcast can be shortened compared to peer-to-peer communication, thus contributing to much less time overhead. In the meantime, the broadcast mechanism is also utilized for information interaction in swarm robots, which needs to be executed only once. Obviously, the delay time in Co^2-Robot can be further cut down.

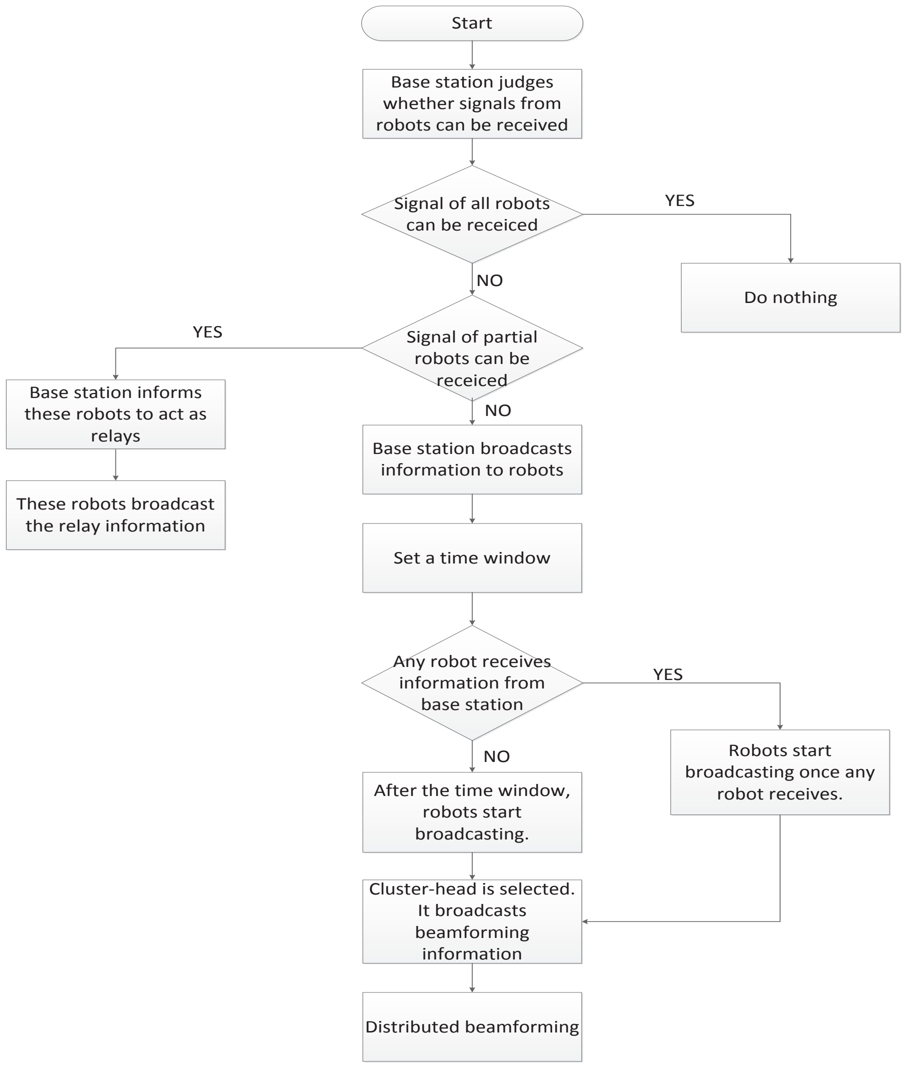


Fig. 2. Co^2-Robot flowchart

When the signals of swarm robots can not be received by the base station, the base station will broadcast the signal reception information to robots. In order to avoid excessive waiting time overhead, a time window is set in Co^2-Robot. During the time window, swarm robots start to broadcast beamforming related information and subsequently perform distributed beamforming if any robot receives the broadcast information. Nevertheless, when exceeding the time window, during which no robot receives the broadcast information from the base station, swarm robots start their broadcast and then carry out distributed beamforming.

V. Implementation of Co^2-Robot

In this section, detailed implementation of Co^2-Robot is presented, including the link status judgement between the base station and swarm robots, cluster head selection strategy, and beamforming scheme.

A. Judgement Process

In Co^2-Robot, there exist several kinds of link states between the base station and swarm robots. For example, if the signal strength of robot i received by the base station is smaller than the set threshold SS_{th}, then the wireless link status from robot i to the base station, referred to as $L_{i,B}$, is set to 0, otherwise 1. The base station will inform a subset of robots to act as relay nodes if the link states of all robots satisfy below formula:

$$\exists L_{i,B} = 0, L_{j,B} = 1, \forall i, j \in N, \tag{6}$$

However, if all robots can not transmit data to the base station, i.e., the reception status should satisfy the formula described as follow:

$$L_{i,B} = 0, \forall i \in N, \tag{7}$$

As a result, the base station will inform them of the link states, utilizing existing LTE broadcast mechanism. LTE broadcast is carried out every 40ms. Conventional LTE broadcast information consists of master information block (MIB) and system information block (SIB). MIB is composed of downlink bandwidth, PHICH configuration, and system frame number. An mark bit is added to the end of MIB, which is shown in Fig. 3. If the base station can not receive information from any robot, it will set the mark bit to 1. Else, the mark bit will be set to 0. As long as swarm robots receive the broadcast information and identify the mark bit as 1, swarm robots start broadcast and then distributed beamforming.

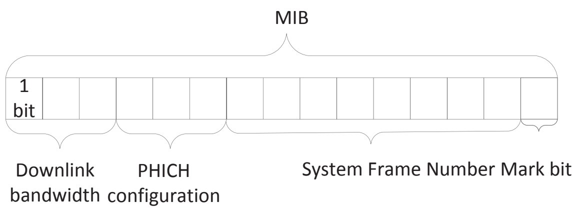


Fig. 3. The structure of MIB in broadcast information

However, an extreme case that needs to be considered is that all of swarm robots can not receive the broadcast information from the base station. Therefore, in order to avoid substantial time cost, a time window is set in swarm robots. As long as exceeding the time window, swarm robots will also start broadcast and distributed beamforming, thus making the utmost efforts to reach the base station.

B. Selection of The Cluster Head

When the base station broadcasts to swarm robots, two cases may occur. Firstly, a subset of robots can receive information from the base station. In this case, once one of these robots receives information from the base station, another broadcast among swarm robots will start, then followed by beamforming. This mechanism can reduce the time overhead.

Secondly, if all swarm robots can not receive information from the base station, a time window T_w will be set as the waiting time. T_w is equal to the round-trip delivery time between the base station and swarm robots, thus highly depending on the distance between the base station and swarm robots. After the time window, swarm robots start distributed beamforming.

For both two scenarios, an utility value for each robot is derived to serve as the selection benchmark for the cluster head in swarm robots, which is responsible for distributed beamforming. Assuming that the computing power and residual electricity for robot i is C_i and E_i, respectively. Maximum computing power and capacity for each robot is C_{max} and E_{max}. Consequently, the utility value u_i for robot i, which is denoted as R_i, can be formulated as:

$$u_i = k_1 \times \frac{C_i}{C_{max}} + k_2 \times \frac{E_i}{E_{max}}, \tag{8}$$

$$k_1 + k_2 = 1, \tag{9}$$

k_1 represents the weight for robot's computing power while k_2 denotes the weight for the residual electricity in the selection process of the cluster head. It is expected that the robot with more computing power is selected as the cluster head, in order to reduce the time cost in Co^2-Robot. From another perspective, we also hope that the robot with more residual electricity can be selected as the cluster head since much more electricity consumption will occur in the cluster head. Even after power consumption induced by computation and broadcast, the cluster head can still maintain a high level of residual electricity, facilitating the electric balance among swarm robots. Therefore, these two factors are chosen as the benchmarks of the cluster head selection, which depend on the application type. For instance, k_1 will be set with a higher value when dealing with delay-sensitive applications. Otherwise, k_2 will be set as a higher value.

According to above equations, it can be observed that the robot with larger utility value is more likely to be selected as the cluster head. The reason lies in that the robot with higher computing power and electricity can accomplish the beamforming parameters derivation more quickly, further reducing the time of Co^2-Robot. In particular, the utility value u_i for robot i will be added to the broadcast packet. Therefore, broadcast information, including ID number, location, and utility value of each robot will be shared within swarm robots. As long as broadcast is completed, the cluster head R_c can be determined.

$$R_c = \{R_i \mid u_i = max\{u_j, 1 \le j \le N\}\} \tag{10}$$

After determining the cluster head, it derives the beamforming parameters according to the location of the base station and swarm robots. Subsequently, it will broadcast these parameters to other swarm robots. Finally, based on these received parameters, swarm robots adjust corresponding parameters such as phase to perform distributed beamforming.

C. Beamforming Scheme

In the beamforming scheme of this paper, only the signal phase will be adjusted so as to make the best of the power of each robot. Therefore, phase-only algorithm is adopted in the distributed beamforming. We apply a beamforming strategy named small phase perturbation constraint algorithm. Consider the element pattern

$$f_0(u,v) = \sum_{n=1}^{N} a_n \exp(-jk(\left|\vec{d_n}.x\right| * u + \left|\vec{d_n}.y\right| * v)) \tag{11}$$

Specifically, $d_n.x$ and $d_n.y$ represent the x and y coordinates of d(n), respectively. $u = \sin\theta$, $v = \cos\theta$, θ represents the angle of beam arrival. k is equal to $2\pi/\lambda$. a_n is the excitation of the nth robot. $d = [\vec{d_1}, \vec{d_2}, ..., \vec{d_N}]$. In particular, $\vec{d_m}$ denotes the coordinate difference vector between the mth robot and the cluster head. Through adding the phase perturbation value to the original element pattern, we can obtain the phase perturbation pattern, which is described as follows.

$$f(u,v) = \sum_{n=1}^{N} a_n \exp(j\varphi_n) \exp(-jk(\left|\vec{d_n}.x\right| * u + \left|\vec{d_n}.y\right| * v)) \tag{12}$$

Therefore, by looking for N phase perturbation values $\varphi_1, \varphi_2, ..., \varphi_n$, orientation function $f(u,v)$ can have L zero points, respectively as $u_1, u_2, ..., u_L$. Assume that $L \ll M$, and the required phase perturbation is very small, which implies that $|\varphi_n| \ll 1$. Based on these assumptions, equation (12) can be converted through performing a Taylor expansion of the phase factor of the perturbed excitation coefficients $a_n \exp(j\varphi_m)$. Meanwhile, since φ_m is very small, we can only retain the first two terms. The deformation of the formula (12) is as follows:

$$\begin{aligned} f(u,v) \cong & \sum_n a_n \exp(-jk(\left|\vec{d_n}.x\right| * u + \left|\vec{d_n}.y\right| * v)) + \\ & j \sum_n a_n \varphi_n \exp(-jk(\left|\vec{d_n}.x\right| * u + \left|\vec{d_n}.y\right| * v)) \\ & = f_0(u,v) + f_c(u,v) \end{aligned} \tag{13}$$

In this formula, $f_c(u,v)$ denotes a cancellation pattern with L desired zeros. Coupled with minimum constraint conditions in the mean square sense of phase perturbations, the optimization objective can be formulated as:

$$f_0(u_l, v_l) + f_c(u_l, v_l) = 0, l = 1, 2, ..., L \tag{14}$$

$$\min(\sum_n \varphi_n^2), \tag{15}$$

In this paper, we define the phase perturbation vector of N dimension, i.e., $\Phi = (\varphi_1, ..., \varphi_N)$, and constraint vector $c_l = [a_1 \exp(-jk(\left|\vec{d_n}.x\right| * u_l + \left|\vec{d_n}.y\right| * v_l)), ..., a_N \exp(-jk(\left|\vec{d_n}.x\right| * u_l + \left|\vec{d_n}.y\right| * v_l))]$. Then, solution of phase perturbation vector can be derived and described as:

$$\Phi = \sum_{l=1}^{L} r_l Imc_l \tag{16}$$

Imc_l denotes the imaginary part of complex vector c_l. $r_l, l = 1, ..., L$ denotes L unknown coefficients, which can be determined based on the L linear equations (14).

Therefore, distributed beamforming can be carried out according to useful information, such as ID numbers and location of robots, and beamforming parameters, which can be obtained through collaborative communication among swarm robots. Utilizing distributed beamforming, the coverage range of swarm robots can be significantly improved. Consequently, swarm robots try their best to transmit data to the base station when a single robot fails to do so.

VI. Design Enhancement

Beamforming performed by swarm robots differs from conventional beamforming based on large antenna arrays. For instance, in the process of distributed beamforming, the distance between any robot pair will undergo constant change, unlike a fixed one between two elements in antenna arrays. Meanwhile, due to the random distribution of swarm robots, part of them may not be able to attend beamforming caused by breakdown or other factors. However, these robots have been taken into account when the cluster head derives the beamforming parameters. Therefore, two actual user cases, respectively as synchronization among swarm robots and occurrence of abnormal situation, are presented and addressed with proposed schemes, thus enhancing the robustness of the protocol design.

A. Synchronization between Swarm Robots

In the actual scenario, swarm robots are randomly located. Accordingly, the cluster head is selected as the "controller" of swarm robots to perform distributed beamforming. It derives the beamforming parameters and distributes these param eters to other swarm robots through broadcast. However, the distance between two robots can reach up to tens of meters, which is much larger than the element spacing in antenna arrays. Therefore, the transmission delay must be taken into consideration in the process of distributed beamforming while it is fixed in antenna array based beamforming. As mentioned above, we can get the perturbation pattern $f(u,v)$ through adding corresponding perturbation phase value to each robot, which can be captured in formula 12. In this formulation, only the transmission delay from other robots to the cluster head is considered, which is under the assumption that all other robots can receive the beamforming parameters from the cluster head simultaneously. Nevertheless, other robots will receive the broadcast information asynchronously since the distance between the cluster head and other swarm robots varies.

Assuming there exist 5 robots, robot 1 is selected as the cluster head according to Equations (8) and (9). It is responsible for beamforming parameters deduction and then distribute these parameters to other robots at time T. It is assumed that the distance between robot 2 and robot 1 is d_2. Similarly, the distance between robot 3 and robot 1 is d_3, and d_4 and d_5 for robot 4 and robot 5, respectively. Meanwhile, $d_2 < d_3 < d_4 < d_5$. The transmission speed of electromagnetic signal is c. The starting time of beamforming for robot 1, 2, 3, 4, 5 is $T, T+d_2/c, T+d_3/c, T+d_4/c, T+d_5/c$. Thus, each robot starts parallel transmissions to form the beam at different times, differing from the derivation process for conventional beamforming.

Consequently, the transmission delay of beamforming parameters from the cluster head to other robots can not be ignored, which will generate a tremendous influence on the direction and intensity of formed beams. For example, conventional cycles for LTE signals are at nanosecond level. If the distance between two robots is tens of meters, then the transmission delay between these two robots is at microsecond level. It implies that the starting time of signals emitted from different robots to form the beam may vary hundreds of cycles. Therefore, the case that the signal crest from one robot and the signal trough from another robot are superimposed may occur, which is completely opposite from the expected situation that signal crests of these two robots are superimposed. Obviously, it will lead to the desired beam direction biased and substantially reduce the beam intensity in the target direction.

In result, the beamforming pattern considering the delivery delay from the cluster head to other robots is shown as below:

$$f(u,v) = \sum_{n=1}^{N} a_n \exp(j\varphi_n) \exp(-jk(2*\left|\vec{d_n}.x\right|*u + 2*\left|\vec{d_n}.y\right|*v)) \tag{17}$$

We develop a simple strategy to overcome this challenge. For example, the distance between robot i and the cluster head is denoted as d_i, which can be derived by the cluster head. Therefore, the arrival time of broadcast information from the cluster head to robot i can be expressed as the time $T + d_i/c$. Finally, we can obtain the maximum time T_{max} from these N

arrive time. It can be described as follows.

$$T_{max} = \max\{T_i, 1 \le i \le N\} \tag{18}$$

Then, $T_{max} + \partial$ will also be added to the broadcast information to inform other robots of the starting time for distributed beamforming. Here, ∂ is a tolerance parameter to account for the factor that information reception at robots will introduce extra time consumption. Consequently, swarm robots will perform beamforming at the same time $T_{max}+\partial$. In order to avoid time waste, ∂ is set to 10 microseconds, which is a little more than conventional read and cache time. Finally, accurate beamforming for swarm robots can be realized based on this simple strategy.

B. Dealing with Abnormal Situation

Distributed beamforming is based on the assumption that the cluster head can broadcast information to all other robots. However, broadcast packet loss may happen owing to some special factors, such as long distance and poor channel quality. Consequently, a subset of robots can not receive related information for distributed beamforming. Only a subset of robots which can receive beamforming parameters from the cluster head will continue to complete distributed beamforming. Nevertheless, phase perturbation vector Φ is derived based on the condition that all of swarm robots can attend to form the beam in the expected direction. Assume that robot m can not perform beamforming ($m < N$). Thus, the actual phase perturbation pattern can be computed as below.

$$\begin{aligned} f(u,v) = &\sum_{n=1}^{(m-1)} a_n \exp(j\varphi_n)\exp(-jk(\left|\vec{d_n}.x\right| * u + \left|\vec{d_n}.y\right| * v)) \\ &+ \sum_{n=m+1}^{N} a_n \exp(j\varphi_n)\exp(-jk(\left|\vec{d_n}.x\right| * u + \left|\vec{d_n}.y\right| * v)) \end{aligned} \tag{19}$$

Then, it can be transformed into the formula described as below.

$$\begin{aligned} f(u,v) = &\sum_{n=1}^{N} a_n \exp(j\varphi_n)\exp(-jk(\left|\vec{d_n}.x\right| * u + \left|\vec{d_n}.y\right| * v)) \\ &- a_m \exp(j\varphi_m)\exp(-jk(\left|\vec{d_m}.x\right| * u + \left|\vec{d_m}.y\right| * v)) \end{aligned} \tag{20}$$

It can be observed that the former part in equation 20 is the expected formula for distributed beamforming. The latter part represents the signal of robot m at the cluster head. Obviously, the substraction of these two parts will result in the deviation of actual beam direction from the expected direction, as well as the decline of signal strength. In conclusion, in the absence of robot m, the formed beam direction will deviate from the intended direction and beam intensity will be reduced. Therefore, we adopt the similar method in [25]. Any LTE packet from one single robot starts with a preamble including 64 bits. Since each robot transmits the same preamble and signal for beamforming, the cluster head can also receive the signals from other robots. The actual number of robots attending beamforming can be detected by these received preambles at the cluster head utilizing correlation calculation. Specifically, the cluster head detects the actual number of robots by correlating the known preamble with the received packets. Since the preamble in LTE networks consists of 64 bits, the cluster head aligns these 64 samples with the first 64 received samples, then computes the correlation. After the computation, the cluster head shifts the alignment by one sample and then re-computes the correlation. This operation will be repeated until the end of the packet.

Assume that there are two robots attending to perform beamforming besides the cluster head. The correlation Γ at position Δ between the known preamble and received packet can be computed based on the formula as below.

$$\begin{aligned} \Gamma(\Delta) &= \sum_{k=1}^{64} s^*(k) y[k+\Delta] \\ &= \sum_{k=1}^{64} s^*[k](y_A[k+\Delta] + y_B[k+\Delta+\Delta_{Delay}] + n[k]) \end{aligned} \tag{21}$$

Here, y is denoted as the received signal, y_A is denoted as the signal from one robot while y_B represents the signal from the other robot. Owing to the same preamble sent by each robot, in this paper, y_A is equal to y_B. n denotes the noise term. $s[k]$ is referred to as the know preamble, and $s^*[k]$ is denoted as the complex conjugate, $1 \le k \le 64$. Δ_{Delay} represents the sampling point offset caused by packet-level time offset. Obviously, the preamble is independent of the noise. Consequently, the correlation between them is about zero. The correlation value at position Δ is transformed into the equation below.

$$\begin{aligned} \Gamma(\Delta) &= \sum_{k=1}^{64} s^*[k](y_A[k+\Delta] + y_B[k+\Delta+\Delta_{Delay}]) \\ &= \sum_{k=1}^{64} s^*[k] * y_A[k+\Delta] + \sum_{k=1}^{64} s^*[k] y_B[k+\Delta+\Delta_{Delay}] \end{aligned} \tag{22}$$

It can be observed that when Δ is equal to zero, we can obtain the correlation as follows.

$$\begin{aligned} \Gamma(\Delta) &= \sum_{k=1}^{64} s^*[k] * y_A[k+\Delta] + \sum_{k=1}^{64} s^*[k] y_B[k+\Delta+\Delta_{Delay}] \\ &= \sum_{k=1}^{64} \left|s^2[k]\right| + \sum_{k=1}^{64} s^*[k] y_B[k+\Delta_{Delay}] \end{aligned} \tag{23}$$

The magnitude of $\Gamma(\Delta)$ is the sum of energy in the preamble, thus it is significantly large. Hence, we can conclude that when the preamble aligns with the beginning of the packet from one robot, the magnitude of the correlation spikes. Similarly, above conclusion can also be appropriate for the case that $\Delta + \Delta_{Delay}$ is equal to 64. Consequently, we can obtain the actual number of robots attending beamforming by computing the number of spikes.

Therefore, the actual number of robots can be obtained at the cluster head based on the introduced mechanism. In order to address this challenge, we have developed a simple retransmission mechanism. As long as the actual number of robots attending beamforming is detected, the cluster head will compute and retransmit the beamforming parameters based on available robots. Through simulations, this mechanism is verified to bring very little time overhead.

VII. Simulation Results and Analysis

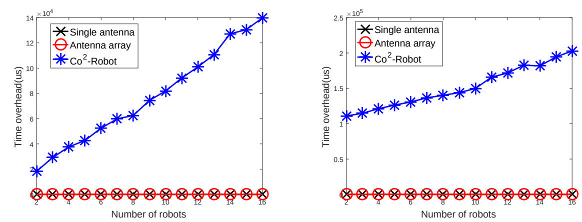
A. Simulation Settings

The simulation is carried out in NS3, which is a discrete event simulator. The location of the base station is set to (500, 500, 0). Swarm robots are within a fixed small area, so as to form a full connected network. Communication between the base station and these robots is based on LTE protocol. Meanwhile, information interaction between robots is based on 802.11p protocol. For the case when partial robots can transmit information to the base station, these robots will be informed to act as relay nodes so as to forward the data traffic from the rest of swarm robots, of which the base station is out of the communication range. Therefore, the process is quite simple and the time overhead is just at microsecond level. In this section, we mainly focus on the case that when the signals transmitted from all robots can not be received by the base station, which means that swarm robots are far away from the base station.

B. Simulation Results and Analysis

The number of swarm robots ranges from 2 to 16 incrementally. The power of the base station is set to 33dBm. Consequently, the transmission range of the base station can be up to 1000m. First of all, we measure the time overhead caused by collaborative communication for distributed beamforming. Two main situations are considered. One is that one or a subset of robots is within the transmission range of the base station. In result, broadcast among swarm robots will start once any robot receives the information from the base station. The other one is that all of swarm robots are outside the transmission range of the base station. The power of each robot is set to 10dBm. Thus, the coverage range of robots can be derived, which is equal to about 150m.

The time overhead caused by collaborative communication is demonstrated in Fig. 4(a). The figure simulates the situation that one of swarm robots is within the coverage range of the base station, while others are located outside the range. This situation is referred to as scene 1 in this paper. The distance between two adjacent robots is set to 2m. Meanwhile, the distance between any two robots is less than 100m. It can be observed that with the increase in the number of robots, the time cost based on Co^2-Robot is also increasing. When the number of robots reaches 16, the time delay is a little more than 1 second, which is acceptable. This is because more robots imply that more steps for information interaction among swarm robots are necessary, extending the time for collaborative communication. Meanwhile, we can observe that the delay time based on Co^2-Robot is longer than those of single antenna and antenna arrays. Obviously, the reason is that no time consumption occurs in a single antenna and antenna arrays. The major time overhead is induced by the transmission delay from a single antenna or antenna arrays to the base station.



(a) (b)

Fig. 4. The time overhead of Co^2-Robot in different scenarios

In NS3, the delay time from a single robot to the base station and base station to robot is about 5000 μs. Therefore, the time window is set to 10000 μs when all swarm robots are outside the coverage range of base station. This situation is called scene 2 in this paper. The time overhead in this scenario is shown in Fig. 4(b). As more robots are deployed, it will result in the increase of delay time caused by collaborative communication for distributed beamforming. Finally, a conclusion can be obtained: in any scene, the delay time based on Co^2-Robot will be extended with the increase in the number of robots. However, the time overhead is acceptable for distributed beamforming.

As shown in Fig. 5, the time overhead in scene 1 is smaller than that of scene 2 with the same number of robots. This is because no robot can receive information from the base station in scene 2. Swarm robots should wait during the time window to make sure that they can not receive the signal transmitted by the base station. Consequently, they can be aware of that the signals from all robots can not be received by the base station. Subsequently, they start to perform distributed beamforming. In contrast, in scene 1 distributed beamforming will be performed as long as any robot receives information from the base station. This mechanism can avoid excessive time cost for waiting and further improve the efficiency of Co^2-Robot.

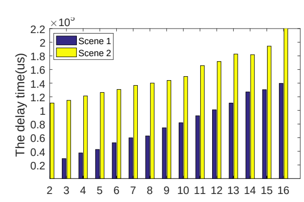
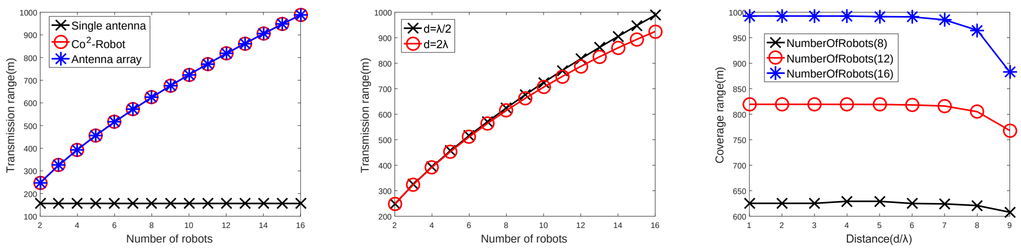


Fig. 5. Time overhead comparison between two different scenarios

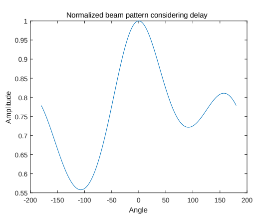
As mentioned above, the transmission delay from the cluster head to other robots must be taken into consideration since the cluster head should distribute beamforming parameters to other robots. Therefore, different beam patterns can be obtained in two situations: considering transmission delay and



(a) (b) (c)

Fig. 6. The coverage performance of Co^2-Robot

without considering transmission delay. For example, the base station is located in the normal direction of the cluster head. Eight robots within a small coverage collaborate to perform distributed beamforming. The simulation results are shown in Fig. 7(a) and 7(b). Fig. 7(a) demonstrates the results when the transmission delay from the cluster head to other robots is considered. The signal strength at the aiming direction of zero degree can be significantly enhanced. From Fig. **??**, it can be observed that the actual beam direction deviates from the expected direction when the transmission delay is not considered.



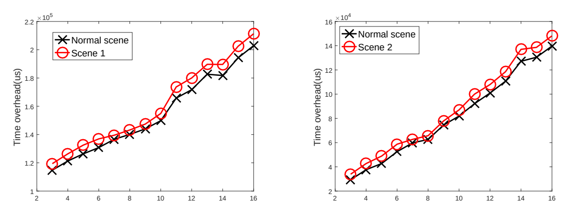
(a) (b)

Fig. 7. Performance comparison of distributed beamforming in different conditions

Based on distributed beamforming, the coverage range of swarm robots can be substantially extended compared to single robot. If the distance between two adjacent robots is set to $\lambda/2$, Fig. 6(a) demonstrates the coverage enhancement when the number of swarm robots increases from 2 to 16. Compared to the transmission range of only one robot, which is equal to about 150m, the transmission range based on distributed beamforming with 16 robots can be prolonged up to nearly 1000m. Obviously, the coverage extension based on Co^2-Robot is almost the same with that of conventional beamforming based on antenna arrays with the same size. Consequently, Co^2-Robot based communication for swarm robots can cover a much wider range than only one robot, just bringing an acceptable time overhead.

However, when the distance between two neighbour robots increases, the coverage extension will be influenced. The simulation results are shown in Fig. 6(b). The coverage range under the distance of $2 \times \lambda$ is always smaller than that when the distance is set to $\lambda/2$. Meanwhile, when the number of swarm robots increases, the coverage range gap in these two situations is also growing. Fig. 6(c) demonstrates that when the distance between two adjacent robots increases, the acquired gain from distributed beamforming is reduced continuously, thus shortening the transmission range. Especially, when the distance is relatively small, the coverage range remains almost the same. However, when it increases, the coverage range will undergo considerable reduction, which can be up to nearly 100 meters. The main reason lies in that grating lobes will occur if the ratio value of d/λ is more than $1/2$. Consequently, the gain of main lobe aiming at the base station will be cut down, resulting in the decrease of the transmission range.

In case of broadcast package loss and link failure or due to other factors, the beamforming parameters can not be delivered to a subset of robots. This specific scene should be taken into account to improve the robustness in the design of Co^2-Robot. In scene 1, the delay time for collaborative communication is shown in Fig. 8(a) if retransmission is necessary. Meanwhile, the delay time in scene 2 is shown in Fig. 8(b). Obviously, we can observe that in the case of different number of robots under scene 1, the time overhead is just a few milliseconds more than that of normal circumstances. In addition, the same conclusion is applicable for scene 2. This is because retransmission of beamforming parameters from the cluster head to available robots always brings several milliseconds time overhead. Therefore, the retransmission mechanism is simple and efficient to address the challenge.



(a) (b)

Fig. 8. The time overhead caused by retransmission

In conclusion, it is verified that Co^2-Robot is an efficient collaborative communication protocol for swarm robots. The protocol can significantly extend the coverage range of swarm robots despite it brings a little time overhead, which is acceptable in parallel systems for swarm robots.

VIII. Conclusion

This paper presents a collaborative communication protocol for swarm robots. Different communication scenarios between the base station and swarm robots are introduced. We mainly focus on the case when the base station can not receive signals from all robots. To address this problem, distributed beamforming has been proposed. Different from conventional beamforming based on large antenna arrays, collaborative communication among randomly located robots is necessary. Firstly, based on efficient communication, the time overhead caused by collaborative communication in Co^2-Robot is substantially reduced. Secondly, the transmission delay between the cluster head and other swarm robots is taken into account when performing distributed beamforming. A simple yet effective strategy is developed to realize synchronization among swarm robots. Thirdly, a novel scheme is proposed to deal with the case when one or a subset of robots can not receive beamforming parameters, thus enhancing the robustness of protocol design. Finally, extensive simulations demonstrate that Co^2-Robot based coverage range for swarm robots can be substantially extended while it only brings a small amount of delay time.

Acknowledgement

This work is partly supported by National Key Research and Development Program grant (2016YFE0100600), National Natural Science Foundation of China grants (61672349, 61672353, 61472252) and China 973 project (2014CB340303).

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