Cooperative Mobility Control for Maintaining Required Throughput in Multiple Ad Hoc Networks with Autonomous Mobile Robots

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***Abstract*— We proposes a travel route control method that achieves a required throughput value for a long time where multiple autonomous mobile robots (AMRs) communicate with the network edge using a wireless LAN ad hoc network. While a related work used the time-integral value of throughput as an evaluation index to improve throughput as much as possible, we focus on the time to achieve a certain required throughput value. The proposed method determines the travel route of AMRs that help relaying, called relay-AMRs, based on a heat map of throughput for each relay-AMR location, by specifying only the location at the start and end of the relaying process. This proposed method improves the time to achieve the required throughput by up to 19.4% compared to conventional method .**

***Keywords*— Wireless LAN, Ad hoc network, AMR, IEEE802.11**

I. Introduction

Recent Autonomous mobile robots (AMRs) have been attracting attention in various fields in recent years. AMRs are robots that determine their own travel routes, detect and avoid obstacles, and move autonomously to designated destinations without any external instructions. Currently, AMRs are being put to practical use in a limited range of private property, mainly in warehouses and factories, helping to improve work efficiency and reduce labor costs. Although most of these applications are currently on such private property, in the future, AMRs are expected to be used in the delivery industry, automated wheelchairs, and other applications that run on public roads. However, when AMRs run on public roads, unlike on private property, they cannot use terrain data or other aids, so autonomous driving must be achieved using only data from the sensors mounted on the AMR. The AMR envisioned in this study is thus an AMR that runs on public roads, has a starting point and a destination, and is capable of making detours within a limited time.

To achieve real-time processing of sensor data such as LiDAR (Light Detection And Ranging), which is necessary for autonomous driving, edge computing, in which the computation is performed on an external edge server, is one possible solution. When processing sensor data on an external edge server, AMR requires high throughput to keep sending sensor data stably. In this study, we assume the use of the IEEE802.11 standard as the communication method for AMR to send sensor data to an access point (AP). Other candidate communication standards include cellular systems, with 5G/6G as the most common. Cellular communication is capable of high-speed communication over a wide area and is considered effective for AMR communication. However, cellular communications are expensive to use, which may prevent the spread of AMR. Therefore, this study assumes the use of the IEEE802.11 standard, which is available to everyone free of charge. However, the IEEE802.11 implementation has a short communication range, so a method to maintain communication even when the AMR is far from the AP is necessary.

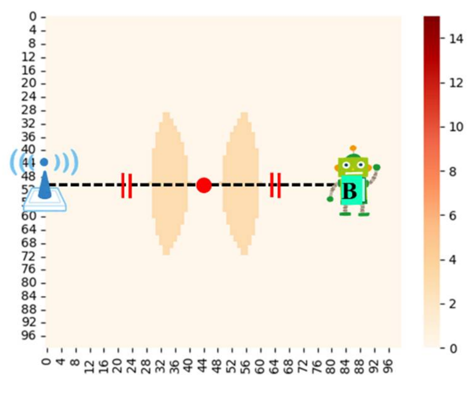

Figure 1. Non-optimal example in the case the position of the B-AMR is at the midpoint.

As a method to maintain communication even when an AMR called benefit-AMR or simply B-AMR is located far from an AP, the authors have improved total throughput, which is the time-integral value of throughput, by constructing an ad hoc network in which another AMR called relay-AMR or simply R-AMR makes a detour and relays

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packets [1]. Specifically, by having an relay-AMR face the midpoint between the B-AMR and the AP to construct an ad hoc network, throughput is improved by relaying even when the B-AMR is located far from the AP. By heading the R-AMRs to the midpoint that is suitable for relaying, the maximum throughput can be improved.

However, given actual autonomous driving, achieving a certain required throughput for a longer period of time may be more important than the time-integral value of throughput. For safe autonomous driving, the system must be able to respond to vehicles and people that suddenly jump out of the way. Therefore, autonomous driving requires continuous processing of sensor data in real time. Given such demands, conventional research that increases throughput at the instance without considering time constraints is not suitable.

Therefore, this study proposes a travel routing method for R-AMR to achieve a certain required throughput for a long time. In this study, only the time to achieve a certain required throughput is considered, without considering the ups and downs of throughput higher than a certain required throughput. The properties of the proposed method are evaluated and validated by theoretical calculations.

II. RELATED WORKS AND ISSUES

The target communication systems can be categorized as ad hoc networks and throughput improvement control in optimal mobile paths. There have been many studies on improving throughput by moving nodes, for example in [1-3]. In this chapter, we explain the differences between those previous studies and this research.

In the literature [2], throughput is improved by having the communicating robot take a detour considering the location of the AP, thereby changing the physical distance to the AP. However, since relaying is not taken into account, no suitable travel route for relaying is proposed. In addition, when the AMR is physically away from the AP due to reasons such as the robot's destination being far from the AP, no improvement can be expected.

In the literature [3], for systems where robots send data to APs, throughput is improved by moving a relay-only robot to the optimal location and establishing an ad hoc network. However, this method cannot be applied to AMR systems we assume because it uses relay-only robots. In our assumptions, all AMRs have their own destinations so that an R-AMR does not always take the optimal location for B-AMR.

In the literature [1], total throughput or the time integral of throughput, is improved by creating an ad hoc network by having R-AMRs which make detours to help B-AMRs communicate with each other on their way to a certain destination. It uses total throughput as an evaluation metric and make no assumptions about the time it takes to achieve a required throughput. Therefore, there is room for further improvement if the period to achieve a certain required throughput is required to be longer. Another problem is that although the R-AMR aims at the midpoint between the AP and the B-AMR, the midpoint may not be optimal due to the convenience that the transmission rate is a step function. An example is shown in Figure 1. The red circle in the figure is the midpoint between the AP and the B-AMR, and the heat map shows the throughput when relaying for each location of the R-AMR. In the example in this figure, higher throughput is obtained in the area extending to the left and right of the exact midpoint, the red circle, than in the area to the exact midpoint, the red circle. Thus, even if the R-AMR is at the midpoint, it does not necessarily provide optimal throughput.

In this study, we propose a travel route control method for AMRs to achieve a certain required throughput for a long time in a system where there are multiple AMRs that communicate with APs and go to their destinations, and they can make detours within time constraints in order to help communication.

III. TRAVEL ROUTE CONTROL METHOD TO MEET REQUIRED THROUGHPUT FOR LONGER PERIOD

This chapter discusses the proposed travel route control method.

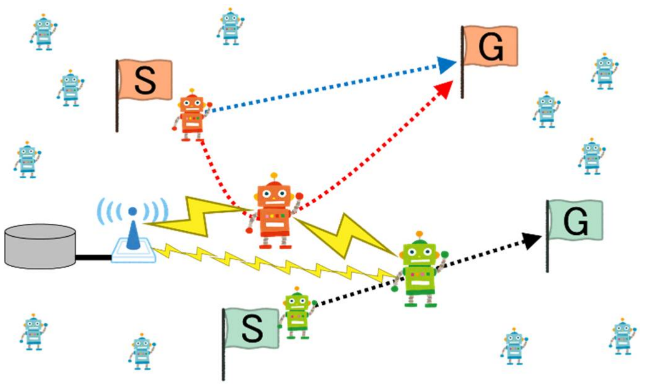

Figure 2. AMR system model

A. AMR System Model

The target AMR system consists of a relay-AMR and a benefit-AMR, the start and goal positions of each AMR, and APs, as shown in Figure 2. Note that for this initial study, we use a simple model.

AMRs are given a starting point, a goal, and a time constraint, and can take detour if the detour are within the time constraint. The distance between the R-AMR and the benefiting AMR is d_{bc}, the distance between the AP and the R-AMR d_{ac}, the distance between the R-AMR and the destination of the R-AMR d_{cg} and the distance between the B-AMR and the B-AMR is d_{bg} be the distance between the destination of the R-AMR and the B-AMR. In this study, the time constraint (L) condition is the time to reach the destination (T_{goal}) and the time taken by the AMR to reach the destination in the fastest time (T_{min}), which is given by Equation (1). For example, if the shortest time to destination is 20 seconds and the detour takes 10 seconds, i.e., the destination must be reached within 30 seconds (20 seconds + 10 seconds), the time constraint L is,10/20=50%.

$$T_{goal} = T_{min} * \left(1 + \frac{L}{100}\right) \quad (1)$$

Within the time constraints, there is no cost to make detour. The maximum speed of the AMR is assumed to be v_{max}.

B-AMR and R-AMR are now defined again as follows, respectively. A B-AMR is an AMR that is helped by an R-AMR in terms of communication quality. In this study, they go straight to their own destination without controlling the travel route. An R-AMR is an AMR that go toward the position between an AP and a B-AMR and helps them relay. This study improves throughput by controlling the travel path of this R-AMR. Originally, there is no distinction between R-AMRs and B-AMRs, and both AMRs head equally for their own destinations, but for the sake of explanation, they are defined separately for readers' convenience. In this study, only one each of R-AMRs and B-AMRs is considered.

A B-AMR contains a specific value of throughput that must be satisfied: the required throughput (Th_d) is specified as the specific value of throughput to be met. The objective of this study is to increase the period to satisfy the required throughput. In this study, only whether or not the required throughput is met is considered regardless of values themselves.

The standard for wireless communication between AMR-AP and AMR-AMR is the IEEE 802.11 standard. The transmission rate is determined by the communication distance and varies in discrete as a step function as evaluated in previous studies [1].

Traffic characteristics in the communication model of the AMR system in this study will be described. it is assumed that the sensor data generated by the AMR is sent to the edge server via an AP, so the majority of the traffic is accounted for by packets from the AMR to the AP. Assume that the AMR buffer is saturated so that all bandwidth is in use at all times. In such a system, when all AMRs are capable of carrier sense, the overall system throughput (*Th*) can be calculated from the literature [4] as the number of links (*N*) and the distance between each link d_i As, the distanced The transmission rate by $f(d_i)$ The calculation can be approximated by Equation (1) from the following equation.

$$Th = \frac{1}{\sum_{i=1}^{N} \frac{1}{f(d_i)}} \quad (2)$$

B. Problem definition

The objective of this study is to achieve relaying for as long as possible in an AMR system such as the one described in Section III.A, such that a B-AMR achieves a throughput above that required by a R-AMR relay while satisfying the R-AMR's time constraints. In this section, we define the conditions for this time constraint and throughput.

First, a condition regarding the required throughput is presented. This condition can be expressed as follows using the required throughput (Th_d) then, using equation (2), it can be expressed as follows.

$$Th = \frac{1}{f(d_{bc}) + f(d_{ac})} < Th_d \quad (3)$$

The R-AMR must always be within this range to achieve the required throughput when relaying.

Next, conditions regarding time constraints are presented. An R-AMR must arrive at its own destination within a given time constraint. As shown in Fig. 3, this condition can be expressed as follows, assuming that the distance between the R-AMR and its destination is d_{cg} Then, it can be expressed as follows.

$$d_{cg} < v_{max}(T_{goal} - t) \quad (4)$$

As time t is larger, the conditions for the R-AMR and the distance to the destination become smaller.

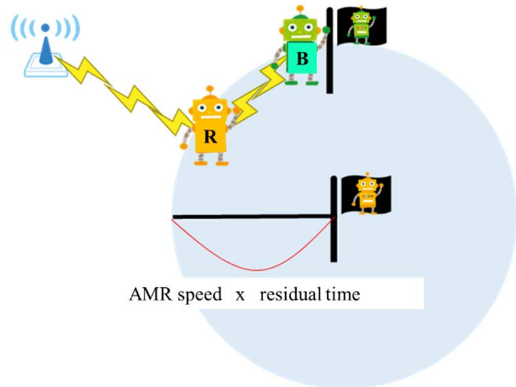

Figure 3. Range satisfying the time constraint

The proposed method aims to always meet the required throughput by moving the B-AMR to a range that satisfies these two conditions when it needs a relay. In the AMR system model, the B-AMR heads straight to its destination without control, so given the starting point of the AMR, it can be known in advance by calculation when and how long it needs to relay. Let the time when the relay starts to be needed at this point is T_{start} and the end of the time when a relay is needed is T_{fin}.

C. Transfer route control method Relay both ends designation (BED) method

Based on the policy described in Section III.B, we propose a *relay both-ends determination method* (BED method) to determine R-AMR routes. The BED method is a heuristic method that aims to satisfy the required throughput for a long time. The time when relaying starts to become necessary T_{start} and the end of the time when relaying becomes necessaryT_{fin} are the only two points in time when the route is determined to be within the range to satisfy the conditions described in section III.B.

At the T_{start}, an R-AMR must satisfy the two conditions described in section III.B. Thus, we select a location that satisfies equation (5) based on the distance from the initial location of an R-AMR(d_{cs}) and the elapsed time since the AMR departure time (t). If the above conditions are met for a range of locations rather than a single point, the closest location to where the R-AMR should be at the time of T_{fin} is chosen. This is because keeping as close to the next destination as possible allows for a longer time relay.

An R-AMR should be at the time of the conditions are the distance from the initial location of the R-AMR(d_{cs}) and the time elapsed since the departure of the AMR(t). The location is chosen to satisfy equation (5) from If the above conditions are satisfied for a range rather than a single point, this will be discussed later,T_{fin} the closest location to where the R-AMR should be at the time of The purpose of this is to keep the next destination as close as possible, thus allowing for longer time relays.

$$d_{cs} < v_{max} * \left(T_{goal} - t\right) \qquad (5)$$

We here specify the location where the R-AMR should be at the time of T_{fin}. If there is a range that satisfies the two conditions described in section III.B, it is assumed to be within that range; otherwise, the location with the slowest time that satisfies the two conditions is specified by going back in time. In the former case, both the specified throughput condition and the time constraint condition can be satisfied within the range, so the same effect can be obtained at any location. In the latter case, it means that it is impossible to achieve the specified throughput by relaying at that point; therefore, it gives up on achieving the specified throughput at T_{fin} and searches backward to the time just before the specified throughput can be achieved. At this time, if there is no range that satisfies the two conditions even after going back to T_{start}, the relay itself is not performed. In this case, it is impossible to improve the period to achieve the required throughput by relaying. R-AMR goes straight from where it should be at T_{fin} to where it should be at T_{fin}.

D. Throughput characteristics of the relay both-ends designation (BED) method

This section describes the difference in throughput characteristics when comparing the BED method and the *midpoint follow-up routing method* (MID method) [1]. Basically, the MID method often achieves higher throughput in terms of a time-integral value. This is because MID method is controlled to obtain as high a throughput as possible. On the other hand, the BED method does not consider unnecessarily high throughput. However, the MID method does not consider time constraints and always aims for the ideal position at the current point in time. In contrast, the BED method considers the time constraint from the beginning and systematically controls the travel route, so the required throughput can be met until the very end of the time constraint. Therefore, in terms of period to achieve the required throughput, the BED method, which controls the travel route by calculating to achieve the required throughput until the very last minute, should be better.

Next, the relationship between the time to meet the required throughput of each method and the time constraint is explained. The explanation is divided into three cases: when the time constraint is extremely tight, when there is a margin for time constraint, and when the time constraint is not tight. In the case of extremely tight time constraints, there is almost no difference in throughput between the two methods. This is because when time constraints are extremely tight, there are almost no detour possible and no difference in travel paths by method. When there is a margin for time constraints, there are two possible cases: one is that there is almost no difference, and the other is that the BED method can achieve a longer time-required throughput. Basically, since both methods can continue relaying at the ideal position until the end, there is no difference in the maximum time to achieve the required throughput. However, as shown in Figure 1, the midpoint-following routing method may not achieve optimal throughput at the midpoint, and thereby may not achieve the required throughput. In such cases, the BED method, which is not affected by this, can achieve the required throughput for a longer time. In other cases, the BED method can achieve the required throughput for a longer time. This is because the MID method aims at the ideal position at that point in time, while the relay both-ends designation method computes and systematically controls the travel path.

IV. Period to Meet Required Throughput

In this chapter, we evaluate the validity of the proposed BED method by comparing it with the MID method to verify the degree of improvement in the time to meet the required throughput.

A. Evaluation Model

In this study, numerical evaluations were performed on the evaluation model shown in Figure 4. Assumptions for the numerical evaluation are shown below. The evaluation model uses a basic model to see the basic characteristics of the proposed method. A B-AMR heads straight to the destination, and the travel path of an R-AMR is controlled by the method to be applied. It is assumed that there are no obstacles that prevent the AMRs from moving. The required throughput that each AMR should achieve is 3 Mbps. A B-AMR generates and transmit packets. The bandwidth shall be scheduled to be divided equally between R-AMRs and B-AMRs. Therefore, when there is one R-AMR and one B-AMR each, as shown in Figure 4, the overall system shall require twice the required throughput per AMR. The time constraint for the R-AMRs is varied between 0% and 100%; the distance between AMRs is set to be limited to a maximum of approximately 112 m, so that all AMRs can be within carrier-sense range. It is assumed that the communication bandwidth is always in use and all AMRs use the same channel. The communication standard used is IEEE802.11g, and the transmission rate is determined only by the communication distance. Transmission opportunities are assumed to be equally available to all AMRs through CSMA/CA. The values of the transmission rate shall be taken from reference [5].

Figure 5 shows an overview of the trajectory of each AMR when the proposed BED method and the conventional MID method to be compared are applied to the evaluation model in Figure 4. In the MID method, the AMRs always keep heading in the direction of the midpoint of the AP and the B-AMR, so they reach the midpoint of the AP and the B-AMR by making a gradual detour. Once it reaches the midpoint, it continues to follow the midpoint as long as the time constraint allows, and when the limit of the time constraint arrives, it heads for its own destination. On the other hand, in the BED method, the R-AMR first moves so that it is in a position for the B-AMR to achieve the required throughput at the timing when the B-AMR begins to require relaying. Once it starts relaying, it then moves to the location where it should be at the end of the relay. When R-AMR finishes relaying at that location, it heads for its own destination. The reason why the distance of the path in the proposed method is short is that it slows speed down to stay as long as possible at the appropriate location for relaying.

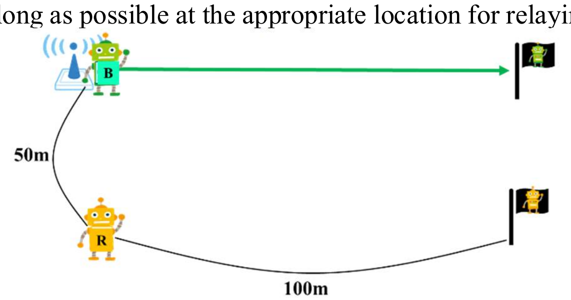

Figure 4. Evaluation model

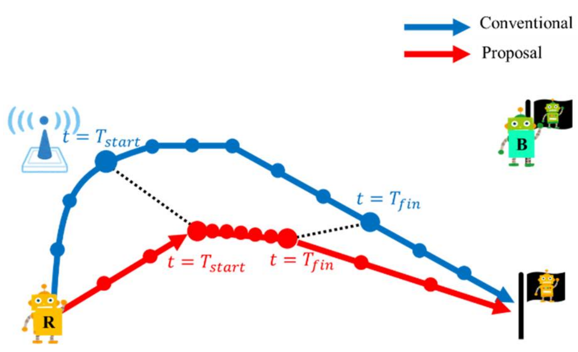

Figure 5. Relay-AMR trajectory

B. Evaluation Results

To evaluate the performance of the proposed method in the evaluation model in section IV.A, we use the percentage of time that satisfies the required throughput as a performance measure. The time constraints of the R-AMR are varied between 0% and 100%, and in each case, the percentage of time that satisfies the required throughput is evaluated and compared the proposed BED method with the conventional MID method.

Figure 6 shows the percentage of time to achieve the required throughput of the proposed BED method and the conventional MID method [1] for each time constraint of the relay-AMR. The vertical axis represents the percentage of time to achieve the required throughput, and the horizontal axis represents the time constraint of the R-AMR. When the time constraint for R-AMR is low, there is little difference, but when the time constraint exceeds 30%, the proposed BED method performs better with up to 19.2% improvement compared with conventional MID method. Note that when the improvement is 75% and 100%, only the performance of the MID method is worse. This is because, as shown in Figure 1, the throughput at the midpoint between the AP and the B-AMR is not optimal.

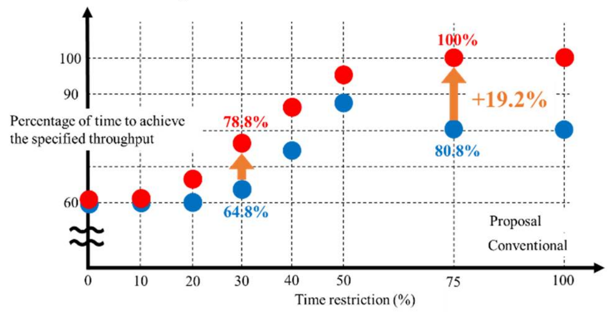

Figure 6. Time to achieve the required throughput.

V. Conclusion

We proposed an AMR travel path control method called the relay both-endpoint designation method (BED), which enables a required throughput to be kept for a long time along the travel path to the destination. BED method is a heuristic method and makes AMRs to make a detour to their straight route to their destination and form an ad hoc network. The detour route is simply specified with only the start and the end locations.

Numerical evaluation results show that the proposed method improves the percentage of time satisfying the required throughput by up to 19.2% compared to the conventional midpoint-following routing method .

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