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A Mobility-Based Mode Selection Technique for Fair Spatial Dissemination of Data in Multi-Channel Device-to-Device Communication

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***Abstract*—Wireless communication devices have spread widely in our society. However, they usually depend heavily on communication infrastructure, leaving them vulnerable to disasters or congestion of base stations. In these situations, a method to send out data without the support of infrastructure is required. Data transmission by D2D communication is a reliable method that does not rely on infrastructure. In this paper, we aim to improve the data dissemination using D2D transmission by applying the concept of assigning "modes" to devices according to their own mobility. In our study, we assume a multi-channel environment, where devices will be allocated different amounts of frequency channels according to their modes. We propose a mode selection function that uses velocity information of the devices to assign modes. By using this function, it is possible to allocate more frequency channels to devices of high mobility, so that they can transmit their data to more devices as they move through a wide area. By mathematical analysis, we evaluate the fairness of disseminated data density among devices of various velocities and the obtained results indicate the effectiveness of the proposed method for improving the efficiency of data dissemination.**

***Index Terms*—Channel allocation, Multi-channel D2D, Spatial efficiency, and Data Dissemination.**

I. INTRODUCTION

Data dissemination using device-to-device (D2D) transmission has attracted attention as an alternative to conventional communication methods heavily dependent on communication infrastructure. In the past few years, wireless devices such as smart phones and tablets have spread widely enough to say that the access to networks is possible at almost any time in any place. However, because of the high dependence on communication infrastructure, wireless devices cannot operate as communication devices if the infrastructure is down, due to damage or loss of power. This actually happened in the Great East Japan Earthquake and Tsunami on March 11th, 2011, when communication infrastructure and power plants were destroyed over a wide area. As a result, the people affected by the disaster were not able to send out safety information to their family and friends or inform others of disaster information. From this experience, we learned that a method of data dissemination that does not depend on infrastructure must be implemented. In addition to disaster situations, D2D data transmission may also be applied to alleviate the load on the infrastructure in areas where data traffic of base stations may become extremely heavy and congested. This issue is expected to become increasingly important due to the expanding use of wireless devices and the rise of concepts such as big data and the Internet of Things. As a specific example, the Olympic Games of 2020 in Tokyo is expected to attract many people to the Tokyo area, and D2D data transmission may be used for distributing data such as game results and local information, alleviating the load on infrastructure.

This work focuses on the efficiency of data dissemination by D2D transmission. When D2D transmission is implemented in disaster areas or congested places as described above, this service must disseminate data from each device efficiently to many devices and to a wide area because in these situations, it is assumed that the users cannot rely on communication infrastructure. Therefore, we aim to propose a method which improves the efficiency of data dissemination.

To measure this efficiency, we introduce the concept which we call the fairness of disseminated data density. Disseminated data density is a measure of the amount of data disseminated by a particular device over area. The fairness of this value among devices indicates an effective dissemination of data among a considered area. This is because when we consider the different mobility of devices, the devices of high mobility cover a large area as they move through space, while devices of low mobility stay in a similar location. Therefore, it is appropriate that devices of high mobility disseminate more data than those of low mobility.

To improve the fairness of disseminated data density, it is necessary to operate each device effectively based on their situation and environment. This is because the situation and environment of devices affect their potential of data dissemination. To determine this difference of operation, the assignment of "modes" to devices have been proposed in the past. In an existing study, two communication modes, DTN mode and MANET mode, are assigned to devices based on their acceleration and remaining battery [1] [2] [3] [4]. In this paper, we use velocity as the mobility information to assign the modes to devices. We assume that the devices can only obtain information of their own mobility and do not receive information of the surrounding environment. Here, multi-channel D2D transmission is considered [5], where frequency channels are allocated to devices according to their modes. To assign the modes, we propose a mode selection function which allocates more frequency channels to devices of higher mobility by reducing the usage of channels by devices of low mobility. To evaluate the performance of the proposed method, we mathematically model the dissemination of data and assess the fairness of disseminated data density. The obtained results are compared to those of the method which does not use mobility information, to indicate the effectiveness of our proposed method.

The remainder of this paper is organized as follows. The supposed network model, including the concept of modes and frequency channel allocation, is explained in Section II. In Section III, we introduce our proposed mode selection function. Then, the evaluation by mathematical analysis is presented in Section IV. Finally, the paper is concluded in Section V.

II. Supposed Model to Describe the Dissemination of Data

In this section, we introduce the supposed system model to describe the dissemination of data by mathematical expressions. Firstly, the assumptions to define the network model are described. Then, the two steps in modeling the dissemination of data are explained: the number of devices that received data and the disseminated data density.

A. Network Assumptions

In this study, we assume a network model of infinite area where mobile devices exist at a uniform density of μ. All devices move at a certain velocity, but we assume that the density of devices, μ, is constant in any point of the model at any given time. For simplicity, we consider that all devices start their movement to a random direction at a certain time, which we set as t=0, and from then on, the devices move in uniform linear motion.

In this model, a set of devices is defined as $N = \{n_1, n_2, \cdots, n_i, \cdots, n_{|N|}\}$. From here on, let n_i represent a particular device which we focus on for explanatory purposes. We consider that the assumptions and concepts we define for n_i are also valid for any other device because n_i can be any device within the considered area and it is expected that conditions are equal for all devices. It is assumed that n_i possesses its original data that it intends to transmit to other devices. Every time n_i obtains the opportunity to use a frequency channel, it broadcasts its data to all devices within its coverage area.

Figure 1 shows the model of broadcasts by n_i. The radius of the communication range of n_i is shown as R_{n_i}. We consider a particular broadcast, BC_k, which represents the kth broadcast. Then, the previous broadcast can be called BC_{k-1}. The time when BC_k and BC_{k-1} occur are t_k and t_{k-1}, respectively. The time between the two broadcasts is D_{n_i} and this is the time it takes for n_i to gain the opportunity to use a frequency channel and accomplish a broadcast. The velocity of n_i is v_{n_i}, so n_i moves a distance of $D_{n_i} v_{n_i}$ during the time between broadcasts.

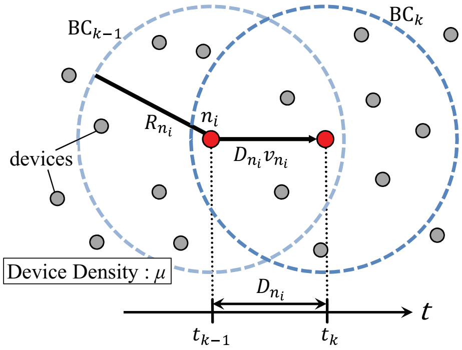


Fig. 1. Model of broadcasts by n_i.

Regarding the modes and frequency channels in this environment, let the mode assigned to n_i be written as m'_{n_i}. The set of modes is defined as $M = \{m_1, m_2, \cdots, m_{|M|}\}$, where $|M|$ is the number of modes. By the use of the mode selection function, m'_{n_i} is chosen from this set. The set of available frequency channels is defined as $C = \{c_1, c_2, \cdots, c_{|C|}\}$, where $|C|$ is the total amount of channels. The allocation of these channels is defined to be such that when $m'_{n_i} = m_j$, n_i can use j channels, along with other devices assigned to the same mode m_j. Among the j channels, n_i randomly chooses one channel to use. Here, the devices assigned to other modes cannot use those j frequency channels. Therefore, all devices assigned to mode m_1 must compete to use 1 frequency channel, while all devices assigned to mode $m_{|M|}$ can share the usage of $|M|$ frequency channels. Assuming the above, the relationship between $|C|$ and M is written as follows:

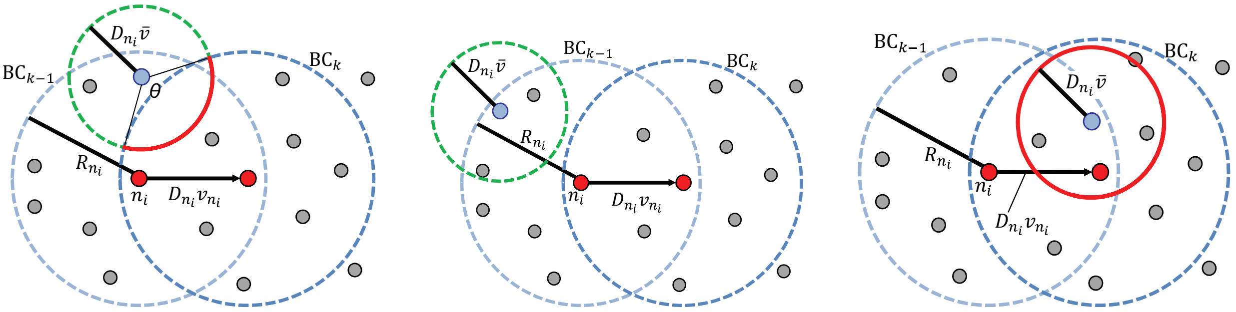
$$|C| = \sum_{m_j \in M} j. \tag{1}$$

B. Modeling the Dissemination of Data by $N_{n_i}^{\mathrm{data}}$

Here, we mathematically define the number of devices that have received the data from n_i. We call this $N_{n_i}^{\mathrm{data}}$, and this value increases as n_i repeatedly broadcasts its data. At the first broadcast of n_i, there are no devices that have received data from n_i. Therefore, the increase in $N_{n_i}^{\mathrm{data}}$ is simply equal to the number of devices within the communication range of n_i, which we denote as $N_{A_{n_i}}$. This $N_{A_{n_i}}$ is expressed as follows:

$$N_{A_{n_i}} = \mu \cdot \pi \cdot R_{n_i}^2, \tag{2}$$

using the density of devices, μ, and the radius of communication range, R_{n_i}. However, at the second broadcast and then on, the increase of $N_{n_i}^{\mathrm{data}}$ should be less than $N_{A_{n_i}}$ because of the existence of devices within the range of communication that have already received data from n_i. Considering the above,



(a) $0 < \theta < 2\pi$. (b) $\theta = 0$. (c) $\theta = 2\pi$.

Fig. 2. Method to calculate θ.

$N_{n_i}^{\text{data}}$, as a function of the number of broadcasts k, can be expressed as follows:

$$N_{n_i}^{\text{data}}(k) = \begin{cases} 0 & (k < 1) \\ N_{A_{n_i}} + (1-\alpha)N_{A_{n_i}} \cdot (k-1) & (k \geq 1) \end{cases}, \tag{3}$$

where α is the ratio of devices that have already received data from n_i among the devices within the range of a broadcast. The time change of k can be written as $k{=}\left\lfloor \frac{t}{D_{n_i}} \right\rfloor$, thus $N_{n_i}^{\text{data}}$ can also be written as the function of time. The parameters D_{n_i} and α are thoroughly explained below.

1) Time to Accomplish Broadcast, D_{n_i}: The time it takes for n_i to accomplish a broadcast of data, D_{n_i}, can be defined as the sum of the time until the device obtains the opportunity to transmit and the delay involved in sending the data. Here, we mathematically evaluate the factors that affect the value of D_{n_i} and calculate the expectation value of this time period.

First, we must consider the access control scheme of the frequency channels to define the value of D_{n_i}. As the access control scheme of our model, Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) is assumed [6]. In this scheme, devices select random "backoff time" according to the value of their contention window to avoid data collisions. CSMA/CA is a well-known method, so extensive explanations of the scheme is omitted in this work. Let CW_w represent the size of the contention window of CSMA/CA after w data collisions. Then, D_{n_i} is expressed as follows:

$$D_{n_i} = \sum_{w=0}^{\infty} p_w \cdot (1-p_w)^w \cdot \left\{ \frac{CW_w \cdot L}{2} + \delta \cdot (w+1) \right\}, \tag{4}$$

where p_w represents the probability that a data transmission of a device succeeds after w retransmissions, L is the length of a time-slot of the backoff time, and δ is the required time for the transmission of data. Regarding p_w, a data transmission of a certain device succeeds when no collision occurs and no other device starts transmission before that device. Therefore, considering that all devices select their backoff time at random, p_w is expressed as follows:

$$\begin{aligned} p_w = & \sum_{j=1}^{CW_w-1} \left(1 - \frac{1}{CW_w}\right)^{j-1} \\ & \cdot \frac{1}{CW_w} \left(\frac{CW_w - j}{CW_w}\right)^{N_{c_{n_i}}-1}, \end{aligned} \tag{5}$$

where $N_{c_{n_i}}$ is the number of devices that use channel c_{n_i}, which is the channel that n_i uses. Because each device randomly uses a channel which it can use according to its mode, $N_{c_{n_i}}$ is equal to the number of devices assigned to mode m_j divided by j. The delay for data transmission, δ, of (4) is expressed as follows:

$$\delta = \frac{DS}{BW} + SIFS + DIFS, \tag{6}$$

where DS, BW, $SIFS$, and $DIFS$ represent the data size, bandwidth of one channel, short interframe space, and DCF (distributed coordination function) interframe space, respectively.

2) Ratio of transmission completed devices, α: Figure 2 shows the method to calculate the number of devices within the range of BC_k which already received data from n_i at BC_{k-1}. Here, note that k should be greater than 1. The ratio of such devices to all devices in the communication range is defined as α. To calculate α, we start by geographically analyzing the motion of devices that received data at BC_{k-1}. Taking any point within the range of BC_{k-1} as the center, it is possible to form a circle of radius $D_{n_i}\bar{v}$, where $\bar{v}$ shows the average velocity of all devices. This circle shows the set of positions where a device that received data at that point in BC_{k-1} is expected to exist at BC_k, because $D_{n_i}\bar{v}$ is the average distance that a device moves during D_{n_i}. Here, we simplify the calculation by assuming that the devices around n_i move at the average velocity, $\bar{v}$. Note that n_i itself also moves a distance of $D_{n_i}v_{n_i}$ between BC_{k-1} and BC_k, where v_{n_i} is its velocity. As in Fig. 2a, among the circumference of this circle, there may exist an arc that is within the range of BC_k. The ratio of this arc to the whole circumference of the circle is $\frac{\theta}{2\pi}$ where θ is the angle in radians which indicates the arc. Using the law of cosines and considering a coordinate plane which the origin is at the point where n_i existed at BC_{k-1}, θ is expressed as follows:

$$\theta = 2cos^{-1}\left\{\frac{(D_{n_i}\overline{v})^2 + (D_{n_i}v_{n_i} - x)^2 + y^2 - R_{n_i}^2}{2D_{n_i}\overline{v}\sqrt{(D_{n_i}v_{n_i} - x)^2 + y^2}}\right\}, \quad (7)$$

where (x, y) are the coordinates of the center of the circle of radius $D_{n_i}\overline{v}$. However, there are exceptions shown in Fig. 2b and 2c where it is not possible to use the law of cosines. In Fig. 2b, the circle of radius $D_{n_i}\overline{v}$ is at a position where no part of the circumference is within the range of the next broadcast, so in this situation, we set θ to 0. In Fig. 2c, the circle is at a position such that the whole circle is within BC_k. In this situation, θ is set to 2π to indicate the arc being the whole circle. In this manner, we obtain the value of θ for all points within BC_{k-1}. Thus, α is the ratio of devices expected to be within the range of BC_k that already received the data at BC_{k-1} to all devices that were within the range of BC_{k-1}, so it can be expressed as follows:

$$\alpha = \frac{\int_{\mathrm{BC}_{k-1}} \frac{\theta}{2\pi} dxdy}{\int_{\mathrm{BC}_{k-1}} dxdy}. \quad (8)$$

Here, note that we can calculate this value as the ratio of area without using the density of devices, μ, because μ is constant throughout the model. Therefore, (8) can be rewritten as follows:

$$\alpha = \frac{\int_{\mathrm{BC}_{k-1}} \frac{\theta}{2\pi} dxdy}{\pi \cdot R_{n_i}^2}. \quad (9)$$

In reality, we must consider all broadcasts previous to BC_k, meaning the broadcasts from BC_1 to BC_{k-1}. However, in our model, it is sufficient to only consider BC_{k-1} instead of considering all previous broadcasts. This is because devices that had received the data from n_i at a past broadcast and then went out of the range of n_i do not return to the range of n_i again, due to the uniform linear motion of all devices. On the other hand, any device that had received data at a past broadcast and exists in the range of BC_k at t_k ought to be within the range of BC_{k-1} at t_{k-1}, also due to the uniform linear motion. In this manner, among the devices existing in BC_k at t_k, the devices that received data at BC_{k-1} encompasses the devices that already received data in broadcasts from BC_1 to BC_{k-2}.

Using α, the increase of $N_{n_i}^{\mathrm{data}}$ at BC_k, where k is greater than 1, is expressed as $(1-\alpha)N_{A_{n_i}}$, as written in (3).

C. The Disseminated Data Density, $\rho_{n_i}^{\mathrm{data}}$

Once we obtain $N_{n_i}^{\mathrm{data}}$, the next step in modeling the dissemination of data is to calculate the disseminated data density, which we represent by $\rho_{n_i}^{\mathrm{data}}$. This is the measure of how widely the data is distributed as a result of the broadcast transmissions of n_i. This value is calculated by dividing the number of devices that have received data from n_i during a certain observation time, T, by the area covered by n_i. Therefore, $\rho_{n_i}^{\mathrm{data}}$ is expressed as follows:

$$\rho_{n_i}^{\mathrm{data}} = \frac{N_{n_i}^{\mathrm{data}}(T)}{A_{n_i,T}}, \quad (10)$$

where $A_{n_i,T}$ is the area that the communication range of n_i covered during T. This value is calculated as follows:

$$A_{n_i,T} = v_{n_i} \cdot T \cdot 2R_{n_i} + \pi R_{n_i}^2. \quad (11)$$

By obtaining the disseminated data density, $\rho_{n_i}^{\mathrm{data}}$, it is possible to evaluate the efficiency of data dissemination because the value of $\rho_{n_i}^{\mathrm{data}}$ indicates the area density of the data disseminated by n_i. It is preferred that the area density of data disseminated from each device is uniform because when each device has their own data that they desire to send out, the unevenness of area density indicates that the data of devices with low area density is not adequately disseminated.

III. PROPOSED METHOD OF ASSIGNING MODES

In this section, we introduce our proposed scheme which aims to improve the efficiency of data dissemination by achieving fairness of disseminated data density. First, we discuss the theoretical effectiveness of allocating more frequency channels to devices with high mobility. Then, we propose the mode selection function that realizes assignment of high number nodes to high mobility devices.

A. Effectiveness of the Proposed Method

Firstly, we explain the theoretical effectiveness of the proposed method on the number of devices that receive data, $N_{n_i}^{\mathrm{data}}$. When more frequency channels are allocated to devices, those devices require less waiting time between broadcasts, because they can choose from more frequency channels to use. Therefore, they can accomplish more broadcasts in a given time and, as a consequence, they can transmit their data to more devices. By devices with higher mobility being allocated more frequency channels, it can be predicted that the data will be received by more devices, meaning that the value of $N_{n_i}^{\mathrm{data}}$ will become higher. This is because a device with higher mobility has a greater chance of having new devices in its communication range due to its own movement and the movement of the devices around it. On the contrary, a device with low mobility has a smaller chance of having new devices in its communication range because it depends mostly on the movement of the devices around it to have new devices in its range. From the reasons above, when devices with low mobility broadcast their data, they are likely to send the same data to the same devices. Therefore, we can conclude that it is reasonable to allocate more frequency channels to devices with higher mobility by limiting the usage of channels by devices with lower mobility.

Additionally, we can also predict that the disseminated data density, $\rho_{n_i}^{\mathrm{data}}$, will be more uniform among devices when more frequency channels are allocated to high mobility devices. Considering the mobility of devices, it is understandable that devices of higher mobility require more opportunities to transmit if they are to obtain an equal value of $\rho_{n_i}^{\mathrm{data}}$ to devices of lower mobility because they cover more area in a given time. The aim of our proposal is to accomplish this, so that the $\rho_{n_i}^{\mathrm{data}}$ value of high mobility devices does not decrease.

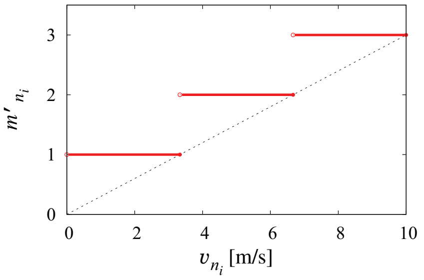


Fig. 3. Mode selection function using velocity.

B. *The Mode Selection Function*

The goal of our proposed method is to allocate more frequency channels to devices that have higher mobility. We do so by assigning a number that we call "modes" to all devices according to their mobility. The basic idea of modes is that devices that are assigned to a higher mode will be able to use more frequency channels, as described in Section II. Hence, we must assign higher modes to devices with higher mobility. Figure 3 shows the mode selection function which assigns a mode, m'_{n_i}, to device n_i according to its velocity. This function is written as follows:

$$m'_{n_i} = \left\lceil |M| \frac{v_{n_i}}{v_{\max}} \right\rceil, \tag{12}$$

where $|M|$ is the highest mode that can be assigned and $v_{\max}$ is the maximum velocity considered among the devices. Figure 3 shows the function when $|M|$ is equal to 3 and $v_{\max}$ is 10m/s. This function signifies that a device, n_i, is assigned to a mode according to the ratio of its velocity, v_{n_i}, to the maximum velocity, $v_{\max}$.

IV. EVALUATION

In this section, we confirm the effectiveness of our proposed method by mathematical analysis using the model we explained in Section II. First, we present the values we used in the mathematical analysis. Then the environmental settings used in the analysis are provided. Finally, we explain the results of our evaluation.

A. *Values used in the Evaluation*

The first value we calculate for the evaluation is $N^{\text{data}}_{n_i}$. As we demonstrated in Section II, $N^{\text{data}}_{n_i}$ increases by time, according to (3). We model the increase of $N^{\text{data}}_{n_i}$ when we set v_{n_i} to various values between 0 and $v_{\max}$. For comparison, we obtain results for a method which equally allocates the frequency channels to all devices without considering their velocity. Then, we compare it to the results obtained for our method of selecting modes.

The second value we calculate is the disseminated data density, $\rho^{\text{data}}_{n_i}$. By using (10), we obtain $\rho^{\text{data}}_{n_i}$ for various values of v_{n_i} between 0 and $v_{\max}$. Then, we use the Fairness Index (FI) [8] to evaluate the fairness of $\rho^{\text{data}}_{n_i}$ among devices of different velocities. FI is defined as follows:

$$FI = \frac{(\sum_q x_q)^2}{X \cdot \sum_q x_q^2}, \tag{13}$$

where x_q and X represent the individual elements which are the $\rho^{\text{data}}_{n_i}$ values for each velocity and the total number of elements, respectively. The value of FI is between zero and one, and a large value indicates that the values of $\rho^{\text{data}}_{n_i}$ are uniform, meaning that the data dissemination is efficient.

TABLE I
PARAMETER SETTINGS

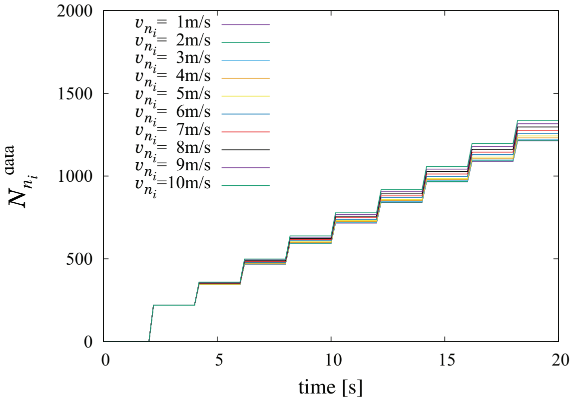
Coverage radius of devices (R_{n_i})	50m
Maximum velocity of devices ($v_{\max}$)	10m/s
Velocity distribution of devices	Uniform
Number of modes ($\lvert M\rvert$)	3
Amount of frequency channels (C)	6
Data Size (DS)	0.5Mbits
Bandwidth of one channel (BW)	10Mbps
Maximum value of contention window ($CW_{\max}$)	15
Minimum value of contention window ($CW_{\min}$)	1023
Short interframe space (SIFS)	16μs
DCF interframe space (DIFS)	34μs
Length of time-slot (L)	9μs
Observation time (T)	20s
Density of devices (μ)	0.028 devices/m^2

B. *Parameter Settings*

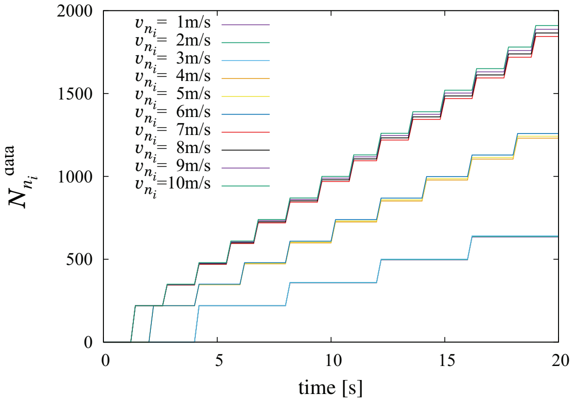
In Table I, the settings for our evaluation are summarized. Each device has a coverage area of radius 50 meters, which is approximately the range of communication of WiFi, which is one option of wireless communication technologies that can be used for D2D data transmission. The velocity of the devices are set to some value between 0 and 10m/s. The maximum velocity, 10m/s, is equal to 36km/h, which is close to the velocity of vehicles in urban areas. We assume that the velocity distribution among the devices is uniform. We set the number of modes to 3 and the number of frequency channels to 6. The data size and the bandwidth of one frequency channel that we consider are 0.5Mbits and 10Mbps, respectively. The minimum and maximum sizes of the contention window, the short interframe space, DCF interframe space, and the length of a time-slot in CSMA/CA are set according to values used in the IEEE 802.11a protocol [7]. The observation time is set to 20 seconds. Finally, the density of devices, μ, is set to 0.028 devices/m^2. This density is approximately double the population density of the 23 special wards of Tokyo that make up the most populous area of Japan. We consider the situation in the near future when most people in urban areas are likely to carry two or more wireless devices with them.

C. *Evaluation Results*

In Fig. 4 and Fig. 5, we show the evaluation results of the time change of $N^{\text{data}}_{n_i}$ and the FI of $\rho^{\text{data}}_{n_i}$, respectively. In



(a) Equal channel allocation method.



(b) Channel allocation using mode selection function.

Fig. 4. Time change of the number of devices that received data.

each evaluation, the velocity of n_i is changed from 1 to 10m/s in 10 steps.

From the results of Fig. 4, we can see that $N_{n_i}^{\text{data}}$ increases at certain intervals of time. These intervals show the D_{n_i} explained in Section II. In the method which equally allocates channels shown in Fig. 4a, all devices have equal intervals between broadcasts because they all equally share the available frequency channels. In the results of the mode selection function shown in Fig. 4b, three groups of devices with similar pattern of $N_{n_i}^{\text{data}}$ can be identified. These groups indicate the devices assigned to the same mode. The groups assigned to a higher number mode have shorter intervals between broadcasts, so they achieve higher values of $N_{n_i}^{\text{data}}$. The averages of the $N_{n_i}^{\text{data}}$ of all 10 velocities at 20 seconds for the equal allocation method and mode selecting function are 1,261 and 1,315 devices, respectively. Therefore, it is indicated that on average, the proposed method is able to let the devices disseminate data to more devices.

The results of Fig. 5 obtained for the FI of disseminated data density, $\rho_{n_i}^{\text{data}}$, show that the mode selection function has a greater value of FI than the method which equally allocates channels. This demonstrates that the assignment of modes using our mode selection function is able to eliminate the unfairness of disseminated data density among devices of different velocities, meaning that each device is able to efficiently disseminate its data to other devices.

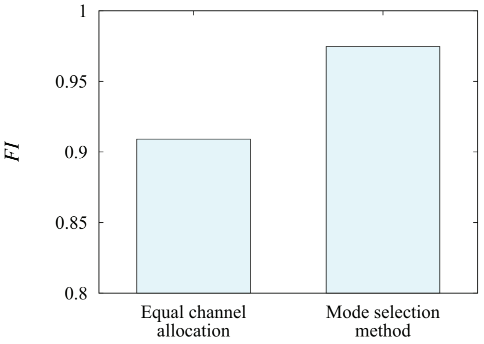


Fig. 5. Improvement of Fairness Index of disseminated data density by proposal.

As these results show, the use of our mode selection function was able to achieve more effective dissemination of data by considering the mobility of devices. However, since we only analyzed one simple type of mode selection function, there may exist other forms of the mode selection function that will achieve even better results.

V. CONCLUSION

In this paper, we introduced the method of assigning modes to devices according to their mobility with the aim of improving the efficiency of D2D data dissemination. We proposed a mode selection function based on the velocity of devices and conducted evaluations using mathematical models we constructed. The results showed that the dissemination of data was improved when the proposed method was used.

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