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PAPER

Reachability Analysis of Multi-Hop D2D Communications at Disaster

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SUMMARY During a disaster, users will not be able to communicate with their families and friends using mobile terminals, e.g., smartphones, in many cases due to failures of base stations and backhaul of cellular networks. Even when cellular networks normally operate without failure, they will become seriously congested due to dramatically increased traffic demand. To solve these problems, device-to-device (D2D) communications, in which mobile terminals directly communicate without cellular networks, have been investigated. Multi-hop D2D communication using multiple mobile terminals as relay nodes will be effective in maintaining connectivity during a disaster. It is preferable to estimate the success probability of multi-hop D2D communication by using a simple method that offers optimal parameter control, e.g., the ratio of mobile terminals using D2D communications and the maximum hop length. Moreover, when evaluating the reachability of multi-hop D2D communication, we need to consider the evacuation behavior during a disaster because success probability depends on the geographical distribution of mobile terminals. Therefore, in this paper, we derive a formula for estimating the success probability of multi-hop D2D communication in a simple manner and analyze its reachability using a multi-agent simulation that reproduces the evacuation behavior expected during an earthquake in Tokyo Shinjuku Ward.

key words: D2D, disaster, multi-agent simulation

1. Introduction

In cellular networks, a large number of mobile terminals share common bandwidth in macrocells; therefore, throughput degrades when the number of mobile terminals increases. To overcome the shortage of bandwidth in cellular networks, the heterogeneous network (HetNet), in which picocells or femtocells covering smaller areas are deployed over macro cells, was adopted by 3GPP release 10, and is a principal LTE-Advanced technique [1]. During large-scale disasters, such as earthquakes, base stations and backhaul of cellular networks will become damaged, and mobile terminals, e.g., smartphones, will be unusable with high probability. In fact, during the Great East Japan Earthquake, mobile terminals were disconnected due to failures of cellular networks, even though mobile terminals were usable by using solar-power generators [2]. Unlike the base stations of macrocells, which are installed on the roofs of ro-

bust buildings, the base stations of picocells and femtocells will be damaged and become unusable with high probability during disasters. In addition to the decrease in communication capacity of cellular networks, the communication demand will dramatically increase because of safety checks among families, colleagues, and friends, even though 70 to 95% of voice-communication requests were regulated during the Great East Japan Earthquake [3]. Therefore, during large-scale disasters, traffic demand will seriously increase, and communication reachability will likely decrease dramatically.

Device-to-device (D2D) communication, in which mobile terminals communicate directly without requiring base stations of cellular networks, has gathered wide attention as an alternative communication method for improving reachability and reducing the traffic load of cellular networks [4]. Single-hop D2D communication, in which a source mobile terminal (ST) directly communicates with a destination mobile terminal (DT), and multi-hop D2D communication, in which an ST communicates with a DT through other mobile terminals, have been investigated [5]. During disasters, cellular-network facilities, i.e., base stations and backhaul, are likely to become damaged and unusable. This is why multi-hop D2D communication has gathered wide attention [2], [6]–[8]. Multi-hop D2D communication is also expected to offload traffic from cellular networks in which communication capacity is likely to dramatically decrease due to the dramatic increase in demand and sudden decrease in communication bandwidth. Multi-hop D2D communication will be effective as an alternative method of obtaining connectivity during disasters by enlarging the reachable area. However, to maximize the effect of improving reachability and increasing the amount of traffic detoured by multi-hop D2D communication, cellular-network operators need to optimally control various parameters, e.g., the ratio of mobile terminals using D2D communication and the maximum hop count of multi-hop D2D communication, so it is preferable to enable network operators to estimate the success probability of multi-hop D2D communication by using a simple method. The reachability of multi-hop D2D communication depends on the geographical distribution of mobile terminals, so we need to consider the evacuation behavior of victims during disasters to estimate the success probability of multi-hop D2D communication.

Although there have been studies on evaluating the success probability of multi-hop D2D communication during disasters [6], [7], [9]–[11], mobile terminals were assumed

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to be located at random positions or in line, and the evacuation behavior of victims during disasters was not considered. The contributions of this paper are summarized below:

1. Derive a simple approximation formula for estimating the success probability of multi-hop D2D communications
2. Reproduce the evacuation behavior of victims during an earthquake in Tokyo Shinjuku Ward through multi-agent simulation (MAS)
3. Analyze the reachability of multi-hop D2D communication by applying the geographical distribution of mobile terminals obtained through MAS to the derived formula

In this paper, we evaluate multi-hop D2D communications with cellular-network support, where an ST determines locations of a DT and relaying terminals by inquiring the cellular network regarding them. In this evaluation, we assume the HetNet environment, where base stations of picocells and femtocells are damaged but those of macrocells only survive. Thus, we assume that the communication capacity of a cellular network is reduced due to the damage to base stations of picocells and femtocells but cellular network functionality is available through the base station of macrocells.

After summarizing D2D communication and related work in Sect. 2, we derive a simple approximation formula for estimating the success probability of multi-hop D2D communication in Sect. 3. In Sect. 4, we present numerical results obtained through MAS of reproducing the evacuation behavior of victims during an earthquake in Tokyo Shinjuku Ward, and we conclude this manuscript in Sect. 5.

2. Summary of D2D Communication and Related Work

To deploy multi-hop D2D communication in practice, we need to solve several technical issues, examples of which are as follows [2], [5].

Multiple wireless access interfaces

To improve the possibility of different devices directly communicating, it is preferable to develop communication terminals equipped with various wireless interfaces. The classification of D2D communication from the viewpoint of the spectrum of various wireless access interfaces is summarized in Sect. 2.1.

Power control, resource allocation, and interference management

Because common wireless spectrum resources are shared by multiple mobile terminals using D2D communication as well as those of conventional cellular networks, efficient power control, resource allocation, and interference management schemes are indispensable to improve the availability of D2D communication [5]. The main techniques of major wireless access interfaces are also described in Sect. 2.1.

Routing

In multi-hop D2D communication, packets are transferred over multiple mobile terminals, and the routing that determines relay terminals between ST and DT strongly determines the overall efficiency and availability of multi-hop D2D communications. In this paper, we use shortest path routing (SPR), which is a well-known routing method of the mobile ad hoc network (MANET), and briefly describe the SPR mechanism in Sect. 2.2.

Peer discovery

Before transmitting packets, two mobile terminals must find each other and set up D2D connection. The two peer-discovery approaches are briefly described in Sect. 2.3.

Security

Packets are delivered through different unknown participants, so a message can be intercepted by malicious participants who may view, modify, or prevent the message from reaching the DT. Therefore, to enable the wide use of multi-hop D2D communication during a disaster, security needs to be addressed. However, we do not discuss this issue further in this paper.

2.1 Spectrum

Two types of D2D communication are used for the frequency band: inband D2D using the spectrum used in cellular networks, i.e., licensed band, and outband D2D using an unlicensed band, e.g., WiFi Direct, Bluetooth, ZigBee, and Industry Science Medical [4]. Inband D2D is classified as an underlay type, in which D2D communication shares the spectrum with conventional cellular (CC) mobile terminals, or overlay type, in which channels for D2D are separated from those used by CC terminals [12]. For outband D2D, two types of architectures have also been proposed: controlled, in which a cellular network offers various functions for controlling D2D communication, e.g., authentication, connection management, and resource allocation, [13], and autonomous, in which mobile terminals autonomously communicate without the control of a cellular network [14], [15].

2.2 Routing

In multi-hop D2D communication, the ST and each relay terminal (RT) autonomously select the peer terminal with which to directly communicate using the D2D single-hop link, and the route of packets is determined through the autonomous selection of peer terminals. This routing problem has been extensively investigated in the mobile ad hoc network (MANET), and shortest path routing (SPR) and interference avoidance routing (IAR) are the most common routing methods in multi-hop D2D communication [16]. Although SPR can yield reasonable performance and minimize the delay, it may not always yield the best reliability performance. This is because when cross-tier interference be-

tween CC and D2D transmissions is considered, selecting the shortest path is not always the optimal strategy. Therefore, IAR attempts to use the path on the coverage boundary of macro base stations where the cross-tier interference is minimized [8]. However, the hop length of communication dramatically increases in IAR, so the D2D outage probability in IAR is larger than that in SPR when the D2D communication distance is below about 80 % of the cell coverage diameter [8]. Therefore, we assume that SPR is used as the routing protocol in multi-hop D2D communication. With SPR, it is assumed that each mobile terminal can measure its position coordinates using GPS [8], [9], and the cellular network collects the coordinate information of all mobile terminals. The ST can obtain the coordinate information of the DT by requesting it from the cellular network [16]. The ST and each RT autonomously select the peer terminal of D2D communication so that the hop count between the ST and DT is minimized [8], [9], [16]. The SPR procedure is summarized as follows.

1. The sending terminal, i.e., the ST, or each RT, checks the coordinates of the surrounding mobile terminals using the method described in Sect. 2.3.
2. The ST narrows down the candidates to the terminals located closer to the DT than itself.
3. The ST further selects one candidate terminal with the maximum distance from it and sends data to the selected terminal.
4. This process is repeated until the packets reach the DT.

2.3 Discovery of Surrounding Terminals

As mentioned in the previous section, each ST needs to autonomously discover the peer terminal it communicated with, and there are two approaches of discovering peer terminals. In the first approach, which is also used in ad hoc networks, the ST autonomously discovers the peer terminal by broadcasting a beacon signal to surrounding terminals [17]. Each mobile terminal receives the beacon signal and returns its coordinates to the ST. In the second approach, which is applicable to D2D communication supported by a cellular network, the ST can determine the coordinates of the surrounding terminals by inquiring the cellular network regarding them [17]. The 3GPP release 12 adopted Proximity Services (ProSe) using these two approaches [18], [19].

2.4 Benefits from D2D Communication at Disasters

The following are the benefits from D2D communication during a disaster in addition to the cellular-network service.

1. **Efficient transmission of local information:** The single-hop D2D link is limited among mobile terminals located nearby, so information related to the location of users, e.g., damaged roads and condition of shelters, can be efficiently transmitted to users [5]. During a disaster, the information related to the nearby location is

important for evacuees.

2. **Improvement of throughput:** During a disaster, traffic demand will seriously increase, so it is highly anticipated that the cellular network will be congested, and the throughput will be seriously degraded. By using multi-hop D2D communication in addition to conventional cellular communication, some of the traffic load of a cellular network is offloaded to multi-hop D2D communication, so throughput will be improved.

2.5 Related Work

The use of multi-hop D2D communication as an alternative communication method when cellular networks are damaged and unusable during a disaster has been investigated. For example, Nishiyama et al. conducted a field experiment of outband multi-hop D2D communication with about 20 hops using the MANET and delay tolerant network (DTN) as routing methods [2]. Yuan et al. proposed a routing method called interference aware routing, which routes packets at the periphery of cells to prevent interference with the CC terminal when using inband-underlay multi-hop D2D communication during a disaster [8]. Al-hourani et al. and Tanha et al. analyzed the success probability of inband-overlay multi-hop D2D communication during a disaster [6], [7].

The success probability of multi-hop D2D communication has also been investigated. For example, Wang et al. derived the success probability of inband-underlay multi-hop D2D communication with SPR using the Poisson point process considering interference with the CC terminal [9]. Wei et al. evaluated the success probability of inband-overlay multi-hop D2D communication using computer simulation when the mobile terminals are located in line [10]. Al-hourani et al. and Tanha et al. analyzed the success probability of inband-overlay multi-hop D2D communication using the Poisson point process [6], [7]. Melki et al. evaluated the reduction in power consumption and increase in accommodated user count of inband-underlay multi-hop D2D communication using computer simulation in which mobile terminals were randomly located [11]. However, these studies set the location of mobile terminals at random positions, in line or at positions determined by Poisson point process, and the evacuation behavior of victims during a disaster was not considered. The reachability of multi-hop D2D communication depends on the location of RTs, so we need to consider the evacuation behavior of victims when evaluating the success probability of multi-hop D2D communication during a disaster.

3. Simple Approximation Formula of Success Probability of Multi-Hop D2D

In this section, we derive an approximation formula of success probability of multi-hop D2D communication to simply estimate it from the geographical distribution of mobile

terminals.

3.1 Assumption

In this paper, we simply assume that W channels of inband or outband D2D communications are provided at any location. In the case of outband D2D, we assume that a MAC protocol, e.g., inter-system CSMA/CA [15], is used to prevent interference with devices using an unlicensed band, and the request of D2D communication is not accepted if all the W channels in the communication area are used at the time of request. We define G as the average throughput of D2D communication after the channel is reserved, r as the maximum distance of single-hop D2D communication, and H as the maximum hop limit of multi-hop D2D communication.

How to give users an incentive to cooperate as RTs is an open issue in ad hoc networks and multi-hop D2D communication, and various incentive mechanisms have been proposed. For example, Li et al. proposed that base stations give monetary incentive to mobile users for cooperation in D2D communications [20]. Although this issue is still a problem even during a disaster, we regard this problem as out of the scope of this paper and leave this issue for future work.

To send data in D2D communication, mobile terminals are required to transmit data with 23-dBm transmission power, for example [21]. However, battery shortage can be solved in parts of mobile terminals with which mobile solar cells are attached [2]. We define a terminal with D2D-communication ability as one with a sufficient amount of battery or with mobile solar cells, as well as a transmitter of outband D2D communication in the case of outband D2D. Let s denote the ratio of terminals with D2D-communication ability among all mobile terminals.

Each mobile terminal generates a request for transmitting data of a length obeying the geometric distribution with an average of L according to the Poisson process with rate λ , so A , the traffic intensity of each mobile terminal, is $A = \lambda L/G$. It has been noted that Internet traffic exhibits bursty nature and does not follow the Poisson process. However, some studies indicate that aggregate flow-level traffic, that are generated by user behavior, can be modeled as Poisson traffic [22]. Of course, it is not certain that this holds also for disaster periods, but if we can assume that communications occur independently among users, then it seems to be plausible as an initial evaluation. Assuming that the base stations of a macrocell and the backhaul are normally operated, the mobile terminals can measure their coordinates using GPS or other methods, and the cellular network collects the coordinate information of all the mobile terminals by periodically inquiring the mobile terminals regarding them. The ST requests the DT to communicate, and the RT relays the packets between the ST and DT. Prior to the communication, the ST obtains the coordinate information of the DT by inquiring the cellular network regarding the information. We assume SPR [8] as the routing method of multi-hop D2D communication, and the ST and RTs select the peer terminal of single-hop D2D communication by ProSe [18].

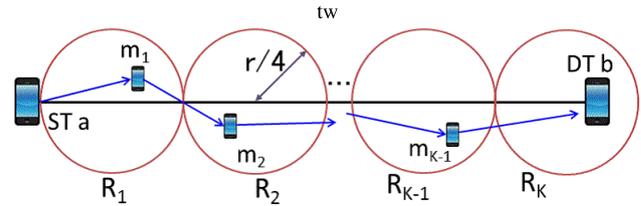


Fig. 1 Position model of relay terminals.

In summary, as mentioned in Sect. 1, we assume that the base stations of a macrocell and the backhaul are normally operated, and use ProSe as a peer-discovery mechanism with the support of a cellular network, which is described in Sect. 2.3. After the discovery of DT or RT, D2D communication procedure is possible without cellular network support, which is composed of communication-channel sensing and actual data transmission.

3.2 Location Model of Relay Terminals

As shown in Fig. 1, we divide the straight line between ST a and DT b into K circular regions R_1, R_2, \dots, R_K with a $r/4$ radius, where ST a is located at the edge of R_1 , and DT b is located in R_K . The ST a sends data to any RT m_1 in R_1 , and m_1 relays data to any RT m_2 in R_2 using a single-hop D2D link. In the same way, RT m_k relays data to any RT m_{k+1} in R_{k+1} , and finally, RT m_{K-1} in R_{K-1} relays data to DT b using a single-hop D2D link. The distance between ST a and RT m_1 takes the maximum value $r/2$ when RT m_1 is located at the boundary between regions R_1 and R_2 on the straight line between ST a and DT b . For any k of $1 \leq k \leq K-2$, the distance between RT m_k and RT m_{k+1} takes the maximum value r when RT m_k is located at the boundary between regions R_{k-1} and R_k , and RT m_{k+1} is located at the boundary between regions R_{k+1} and R_{k+2} on the straight line between ST a and DT b . Similarly, the maximum distance between RT m_{K-1} and DT b is r . Therefore, when the radius of these K circular regions is $r/4$, all ST a , $K-1$ RTs, and DT b can relay data to their peer terminals by single-hop D2D communication.

Let C_k denote the center of R_k . The coordinates of ST a and DT b , X_a and X_b , are obtained by

$$C_k = X_a + \left\{ \frac{r}{4} + \frac{r(k-1)}{2} \right\} \frac{X_b - X_a}{|X_b - X_a|}. \quad (1)$$

Here, C_k is located in line with an interval of $r/2$, so the maximum distance between the ST and DT in multi-hop D2D communication with a hop limit of H is $rH/2$.

3.3 Success Probability of Single-Hop D2D Communication

Let Q_k denote the success probability of single-hop D2D communication between RT m_{k-1}^\dagger and RT $m_k^{\dagger\dagger}$. Although

[†]This is an ST in the case of $k = 1$.

^{††}This is a DT in the case of $k = K$.

the request of D2D communication between m_{k-1} and m_k is accepted when one or more D2D channels are unused in the space between RT m_{k-1} and RT m_k , we assume the request is accepted when one channel can be reserved in R_k . Let N denote the total number of mobile terminals in the area evaluated, and N_k is the number of mobile terminals in R_k . Moreover, let h denote the average hop length of multi-hop D2D communication. We assume that each multi-hop D2D flow generates traffic load in h circular regions on average and that the number of terminals in regions around R_k is also approximated to N_k . The probability that ST, RT, or DT exists in R_k is N_k/N , so the probability that D2D communication flow goes through R_k is given by $1 - (1 - N_k/N)^h$. Using the binomial expansion and ignoring terms with $(N_k/N)^n$ of $n \geq 2$, we can approximate it by $N_k h/N$. We assume that requests of multi-hop D2D communications are generated between two mobile terminals randomly located, so flows of multi-hop D2D communications between two mobile terminals in various areas go through R_k . Therefore, we assume that the success probability of the D2D request going through R_k is given by P , that is, the success probability of multi-hop D2D communication in the area evaluated. Note that a mobile network operator can measure N_k and P because we assume that a cellular network is still available, and requests of D2D communications are received by cell base stations.

Now, the traffic load of D2D communication in R_k is given by $sN_k h A P$, where s is the ratio of terminals with D2D-communication ability. The transition of used-channel count in R_k can be modeled by the birth and death process. However, although one or more D2D channels are available in R_k , the request is not accepted when no RT exists in R_k , or a single-hop D2D link is not accepted in other areas on the route between the ST and DT. Therefore, the effective traffic load of R_k is $sN_k h A P$. The single-hop D2D request between RT m_{k-1} and RT m_k for $k \leq K - 1$ is accepted when both conditions, (i) one or more RT m_k exists in R_k , and (ii) one D2D channel can be reserved in R_k , are satisfied. Therefore, Q_k is obtained by

$$Q_k = \begin{cases} \left\{ 1 - (1 - s)^{N_k} \right\} \left\{ 1 - E_b(W, sN_k h A P) \right\}, & 1 \leq k \leq K - 1 \\ 1 - E_b(W, sN_k h A P), & k = K, \end{cases} \quad (2)$$

where $E_b(W, sN_k h A P)$ is the Erlang B formula of channel count W and offered traffic $sN_k h A P$.

Figure 2 plots Q_k obtained by (2) against N_k for several values of h and s when setting $W = 50$, $A = 1.0$, and $P = 0.5$. We set $s = 0.5$ in Fig. 2(a) and set $h = 10$ in Fig. 2(b). We confirm that Q_k sharply increases as N_k increases when N_k is small because finding a mobile terminal with the ability of D2D communication is difficult in this range of N_k . However, Q_k gradually decreases as N_k increases when N_k is large because D2D channels are more congested as N_k increases. Although this tendency depends on s , we observed the decrease in Q_k in a large- N_k region for various values of s , as shown in Fig. 2(b). As h or s in-

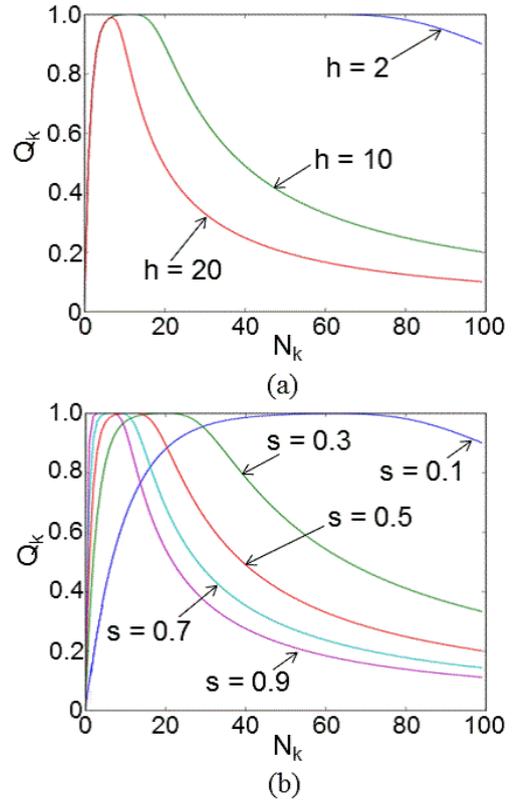


Fig. 2 Q_k , success probability of single-hop D2D communication, against N_k , number of mobile terminals in region R_k .

creases, the number of requests in each D2D channel grows, so Q_k decreases.

3.4 Success Probability of Multi-Hop D2D Communication

We define $P(\mathbf{R})$ as the success probability of K -hop D2D communication going through K regions $\mathbf{R} = \{R_1, R_2, \dots, R_K\}$. The multi-hop D2D communication going through \mathbf{R} is accepted only when single-hop D2D communication is accepted at all regions R_k of \mathbf{R} , so we have

$$P(\mathbf{R}) = Q_1 \times Q_2 \times \dots \times Q_K. \quad (3)$$

Because Q_k depends on P , as shown in (2), we derive $P(\mathbf{R})$ by using a root-finding algorithm, e.g., Brent method [23].

4. Numerical Evaluation Using MAS

Many social organizations and pivotal industries have established offices in Tokyo Shinjuku Ward, and the effect of a large-scale earthquake on the economy and society would be enormous. Therefore, assuming that an earthquake occurring in Tokyo Shinjuku Ward, we obtained the data of geographical patterns of victims and demand patterns of communication by using MAS reproducing the communication behavior of victims while walking toward shelters and their

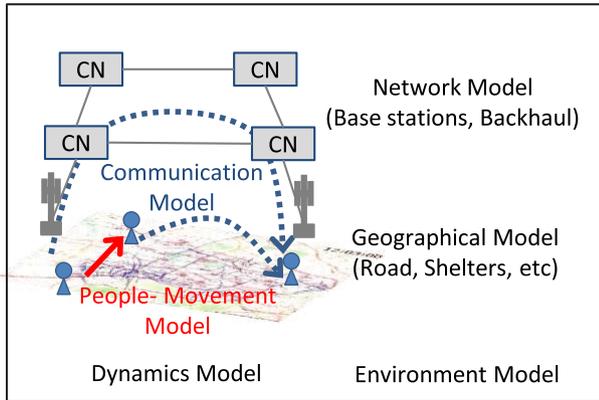


Fig. 3 Components of MAS model.

homes. We present some of the numerical results from applying the geographical distribution of mobile terminals and demand patterns of communication obtained through MAS to the equations to derive the formula for estimating the success probability of multi-hop D2D communication introduced in Sect. 3.

4.1 MAS Model

As shown in Fig. 3, Our MAS model has four components: geographical model, network model, people-movement model, and communication model. The first two components are related to the environment, and the last two components are related to the dynamics of victims. We describe each component below.

4.1.1 Geographical Model—Road, Shelter, and Initial Deployment of Victims

We use the public coordinate data obtained from OpenStreetMap [24] for the location of roads and streets in Shinjuku Ward. We selected roads and streets (*ways* hereafter) that can be used by pedestrians (excluding motorways, which are only used for cars) and generate a graph composed of ways. We define nodes of the graph as the intersections of ways and edges as the ways between nodes. We also define curving points of ways as nodes, which have only two connecting edge. We use MAS to calculate the number of victims and walking speed for each edge. As indicated with the red points in Fig. 4[†], we use the geographical locations of 49 shelters publicly available at the website of Shinjuku Ward, regard the daytime and nighttime populations in each district as the initial number of victims in each district, and use the data shown in Fig. 5 provided by the Tokyo Metropolitan Government Bureau of General Affairs. Note that the daytime population consists of company employees and enrollment population during daytime and nighttime, and the nighttime population consists of residents. Therefore, we calculate the daytime population by subtracting the

[†]We used the image data obtained from OpenStreetMap for all the map images in this manuscript.

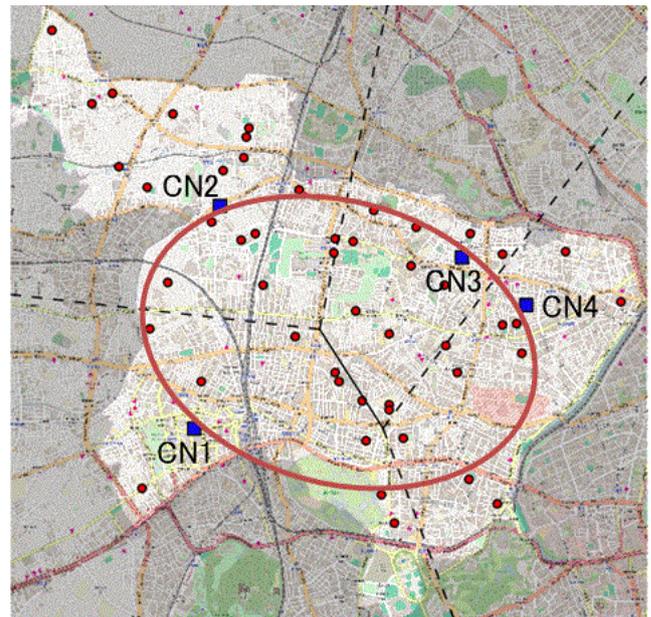


Fig. 4 Location of 49 shelters and 4 core nodes.

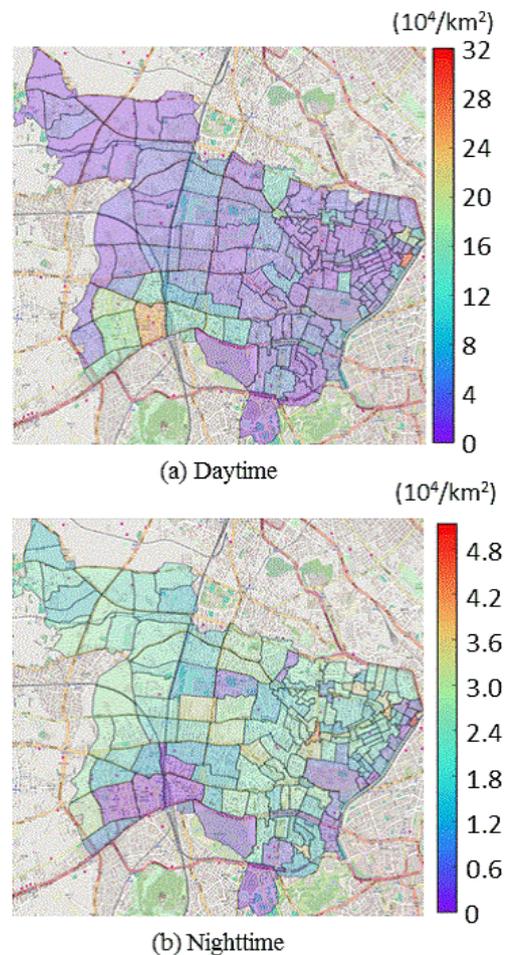


Fig. 5 Population density of each district in Shinjuku Ward.

nighttime population from the total population.

4.1.2 Network Model — Cellular Network

We observe that the base stations of the three major cellular network operators tend to be two-dimensionally provided at approximately every 100 meters around Shinjuku station and along the main ways approximately every 300 meters in other areas in Shinjuku Ward. Therefore, we define the dense area as that surrounded by Koushu Road, Ome Road, Shinjuku Road, and Junisha Street around Shinjuku station, and we define the normal area as other areas in Shinjuku Ward. After setting the center points of each trunk, primary, and secondary ways, which correspond to national highways and prefectural roads, respectively, extracted from OpenStreetMap as the location candidates of base stations, we repeat randomly selecting one candidate and place a base station at that selected location if the minimum distance to the base station already placed is more than 100 meters in the dense area or 300 meters in the normal area until all the candidates are selected. We assume that the backhaul of the cellular network is connected with core nodes (CNs), which are located at housing stations [25]. We select four representative housing stations as CN locations, which are indicated with the blue squares in Fig. 4. Each base station is connected to the closest CN, and the gateway function is placed at CN1 which is placed near Shinjuku station.

4.1.3 People-Movement Model — Evacuation Behavior

We regard each victim in Shinjuku Ward as an agent in MAS, and we set the behavior pattern to each agent at the beginning of MAS, i.e., the occurrence of an earthquake, based on the following percentages. Because we anticipate that many agents would be in robust buildings, 80% of the nighttime population would remain at their initial locations. The remaining 20% would randomly select one shelter i with the probability proportional to the multinomial logit model, $\exp(1000V_i)/\sum_j \exp(1000V_j)$, where the inverse of the distance to shelter i on the shortest path is set to the utility V_i , and start walking toward the selected shelter. The multinomial logit model has been widely used when modeling human behavior in random selection [26]. We ignore the capacity of shelters and assume agents would stay at the shelters until the end of simulation. In reality, a local government might have its own evacuation plan and assign shelters to people based on shelter capacity. Compared with this case, more evacuees will move toward shelters in areas with high population density, so roads toward them will be more congested under our assumption. Therefore, the success probability of multi-hop D2D communication in our simulation will be lower than that in a realistic situation. Moreover, 80% of the daytime population also remain at their initial locations, and the remaining 20% randomly start walking out of Shinjuku Ward in the east, west, north, and south directions with equal probability on the shortest paths toward the selected direction. After arriving at the exit

locations, the agents are removed from MAS. The evacuation route is the shortest path on the topology of ways and edges described in Sect. 4.1.1.

The walking speed of agents on each edge e , v_e , will decrease as d_e , the density of victims on edge e , increases, so we obtain v_e from the walking-speed model proposed by Mori and Tsukaguchi [27],

$$v_e = \begin{cases} -0.204d_e + 1.48, & d_e < 1.5 \\ \max\{1.32 \log \frac{9.16}{d_e}, v_{min}\}, & d_e \geq 1.5 \end{cases} \quad (4)$$

We assume the width of edges is one meter and set the length of edge e as d_e . The walking-speed model [27] provides a negative value when the density increases, so we modified the model so that v_e provides values that are more than or equal to the lower limit $v_{min} = 0.1$.

4.1.4 Communication Model — Communication Behavior Using D2D

The agents of MAS, i.e., victims, are classified into the four states: (i) those remaining at the initial location, (ii) those walking toward shelters or exit points, (iii) those staying at shelters, and (iv) those being removed from MAS after arriving at the exit points. According to the report of the Ministry of Internal Affairs and Communications (MIC), the number of voice calls per subscriber per day was roughly 1.5 during the Great East Japan Earthquake [28]. It was also reported that the number of calls during this disaster was 60 times larger than that during normal periods [29]. In other words, calls were generated in a time interval of an average of 16 minutes. For simplicity, we set the average interval of requests to 10 minutes. Except agents of state (iv), each agent generates a request of communication with the time interval obeying the exponential distribution with an average of 10 minutes. Because obtaining the actual data of geographical distribution of communication targets during a disaster is difficult, we simply assume that each request randomly selects the communication target, i.e., the DT, from outside or inside Shinjuku Ward with equal probability.

If the DT is selected from inside Shinjuku Ward, the request of D2D communication of sending data of a length obeying the geometric distribution with an average of 4 Mbytes is generated to randomly selected DT. In this paper, we assume a major application during a disaster is voice call over IP for safety checks or sharing disaster situations. We also assume the call duration is 5 minutes on average, which corresponds to roughly 4 Mbytes, when we assume 100-kbps VoIP application. If a DT is selected from outside Shinjuku Ward, the request of D2D communication is not generated. Chen et al. reported that 96-kbps coded audio with Opus, which has been used in Skype, provided satisfactory QoE [30]. Therefore, we set the average throughput of D2D communication to $G = 100$ kbps and set the maximum distance of single-hop D2D communication to $r = 100$ meters. Unless otherwise stated, we set the number of D2D channels to $W = 50$, ratio of terminals with ability of D2D

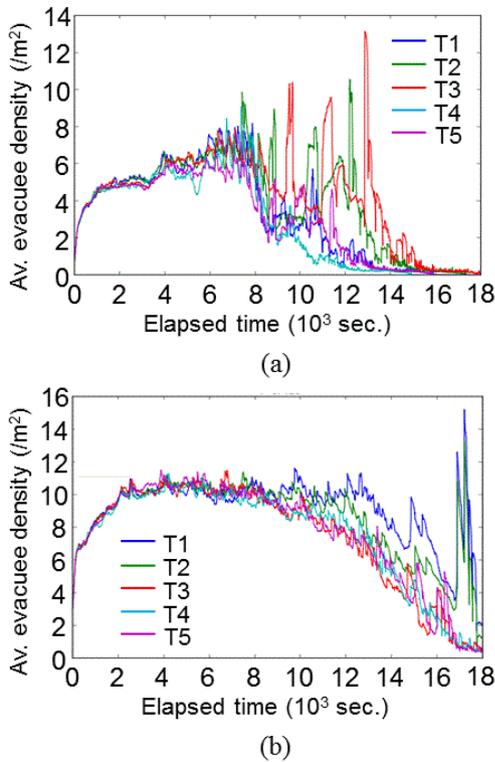


Fig. 6 Time series of average evacuee density when using (a) all roads and (b) only primary and secondary roads.

communication to $s = 0.5$, and maximum hop limit of multi-hop D2D communication to $H = 10$. The Q_k , the success probability of single-hop D2D communication in each region R_k , is calculated using (2).

4.2 Time Series of Density and Moving Speed of Evacuee

Figure 6(a) plots the time series of the average density against the elapsed time from earthquake occurrence. We repeated MAS five times with different random seeds. Figure 6(a) shows the results of each of the five trials where T1, T2, \dots , and T5 stand for the first, second, \dots , and fifth trials. These results are the average d_e weighted by d_e of each edge e and correspond to the average density evacuees experienced. Just after earthquake occurrence, there were just a few evacuees on edges, so the average density was small, whereas the average walking speed was high. As time progressed in the approximately initial 8,000 seconds, the evacuee density increased. However, after about 8,000 seconds, the number of evacuees arriving at shelters and exit points increased, so evacuee density decreased as time progressed.

To investigate the effect of road topology on evacuee density, Fig. 6(b) plots the time series of average density on the road topology consisting of only primary and secondary ways. When evacuees could use only a limited number of ways, the average density increased, and the variation of density on time decreased compared with the case in which evacuees could use a wider variety of ways, as shown in Fig. 6(a). However, we also observed a sharp increase in

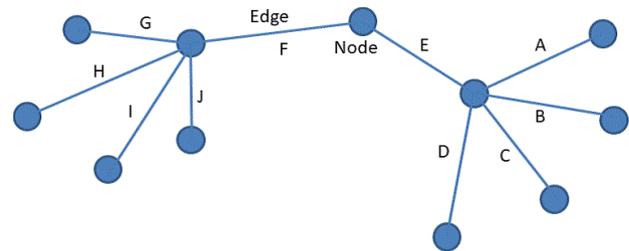


Fig. 7 Topology around congestion point at density spike.

density just after the disaster and a gradual decrease in density after the initial period.

We observed spikes at which the average evacuee density sharply increased and sharply decreased. To investigate the causes of these spikes, we checked the density of each edge at around 13,000 seconds of the third trial, i.e., red curve in Fig. 6(a). We found that the density of all edges except one edge (edge E in Fig. 7) was not so high. As shown in Fig. 7, edge E connected to four edges, i.e., A, B, C, and D, and a huge number of agents arrived at edge E from those four edges; therefore, the density of edge E sharply increased because the speed of agents decreased as the density increased. Just after serious congestion of edge E, agents on edge E moved to adjacent edge F, and the congestion propagated to edge F. However, edge F connected to four edges, i.e., G, H, I, and J, so agents were distributed over these four edges; thus, the average density sharply decreased. As a result, we observed some spikes of average density.

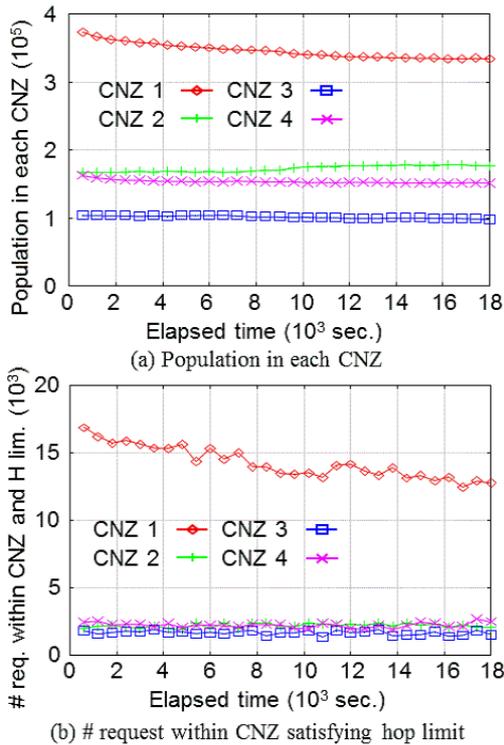
4.3 Number of Requests

We assume that each mobile terminal accesses the closest base station when using the cellular network, and we define the CN zone (CNZ) of CN x as the area covered by the base stations connected to CN x . The boundaries of CNZs are illustrated with dotted lines in Fig. 4. We measured the properties at time t for requests generated for 1 minute from t , and we obtained the properties at every 10 minutes. Because MAS was executed for five hours after earthquake occurrence, there were 30 sample points. Table 1(a) summarizes the average number of requests at all 30 sample points for each CNZ pair, where a row is a CNZ accommodating STs, and a column is a CNZ accommodating DTs. In other words, the statistics averaged over the 30 sample points are summarized in this table. In Table 1 as well as Tables 2 to 5, we show the results from one trial. The population of CNZ1 was much larger than those of the other CNZs, so the number of requests whose ST or DT was in CNZ1 was larger than those of the other CNZs.

As described in Sect. 3.2, multi-hop D2D communication was only possible when the direct distance between the ST and DT was smaller than or equal to $sH/2$, and we summarize the number of requests satisfying this condition in Table 1(b). The maximum distance in which multi-hop D2D communication was possible was just several hundred me-

Table 1 Average number of requests between core-node zones (CNZs).

	(a) all				(b) within hop limit			
	CN1	CN2	CN3	CN4	CN1	CN2	CN3	CN4
CN1	6894	3669	2116	3405	1276	12	8	11
CN2	3778	1976	1094	1802	8	202	11	0
CN3	2160	1132	602	916	9	11	151	8
CN4	3384	1819	1058	1651	6	0	15	248

**Fig. 8** Time series of (a) population in each CNZ and (b) number of requests within same CNZ satisfying hop-count limit.

ters to one km when $H = 10$, so almost all the requests satisfying the distance limitation was the case in which both the ST and DT exist in the same CNZ, and the elements, except the diagonal elements, were close to zero. To effectively improve the connectivity and reduce the traffic load against failure of base-station, we need to further increase H .

Figure 8(a) plots the number of agents in each CNZ[†] at each sample time point. We also show the number of requests satisfying the hop limit for which both the ST and DT exist in the same CNZ in Fig. 8(b). As shown in Fig. 5, the daytime population in CNZ1 was higher than those in other CNZs, whereas the nighttime population in CNZ1 was smaller than those in other CNZs. As mentioned in Sect. 4.1.3, 20% of the daytime population moved out of Shinjuku Ward, and 20% of the nighttime population moved to shelters randomly selected based on the multinomial logit model. Therefore, a majority of these 20% populations in CNZ1 moved away from CNZ1, whereas that of these 20%

[†]This is the sum of agents staying at the initial location, those walking to shelters or exit points, and those staying at shelters.

Table 2 Success probability of single-hop device-to-device (D2D) communication in each CNZ on various parameter sets.

s	CNZ				H	CNZ			
	CN1	CN2	CN3	CN4		CN1	CN2	CN3	CN4
0.1	0.973	1.000	1.000	1.000	2	1.000	1.000	1.000	1.000
0.3	0.866	0.998	1.000	1.000	10	0.791	0.996	1.000	0.998
0.5	0.791	0.996	1.000	0.998	20	0.468	0.928	0.968	0.852
0.7	0.734	0.993	0.999	0.993	W	CN1	CN2	CN3	CN4
0.9	0.695	0.991	0.998	0.986					

populations in the other CNZs moved to shelters in the same CNZ because shelters located close to evacuees were more likely selected. As a result, both properties of CNZ1 slightly decreased as time elapsed, whereas they were stable in the other CNZs.

4.4 Success Probability of Single-Hop D2D Communication

Table 2 shows the average Q_k , where each s , H , and W changed from the base setting, $s = 0.5$, $H = 10$, and $W = 50$. We selected these setting values for s , H , and W so that we could confirm rough tendencies of the effect of these parameters on the results. In CNZ1, the number of mobile terminals was larger than the other CNZs, so Q_k was smaller than those in the other CNZs. As s increased, H increased, or W decreased, the traffic load of each D2D channel increased, so Q_k decreased.

4.5 Success Probability of Multi-Hop D2D Communication

We define P_{reach} as the success probability of multi-hop D2D communication for demand satisfying the distance constraint of $rH/2$ between ST and DT, and we show the average of P_{reach} of each CNZ in Table 3. The effect of each parameter on P_{reach} was similar to that on Q_k , and P_{reach} of CNZ1 was smaller than those of the other CNZs. Only when single-hop D2D communication was accepted in all regions the flow went through, was the multi-hop D2D communication accepted, so P_{reach} was smaller than Q_k , and the reduction in P_{reach} compared with Q_k was noticeable when Q_k was small. As mentioned in Sect. 4.4, the traffic load on D2D channels increased, and Q_k decreased as H increased. Moreover, the reduction degree of P_{reach} compared with Q_k increased as H increased, so P_{reach} sharply decreased as H increased.

Next, we define P_{all} as the success probability of multi-hop D2D communication for all requests, and Table 4 summarizes the average P_{all} of each CNZ over all sample time points. The number of mobile terminals in CNZ1 was larger than those in the other CNZs, so the probability that the ST existed within the reach range of multi-hop D2D communication, $rH/2$, when requests were generated in CNZ1 was larger than those in the other CNZs. Therefore, the difference between P_{all} and P_{reach} in CNZ1 was smaller than those

Table 3 P_{reach} : success probability of multi-hop D2D communication within hop limit in each CNZ.

s	CN1	CN2	CN3	CN4	H	CN1	CN2	CN3	CN4
0.1	0.825	0.999	1.000	1.000	2	1.000	1.000	1.000	1.000
0.3	0.392	0.987	1.000	0.998	10	0.247	0.970	0.999	0.986
0.5	0.247	0.970	0.999	0.986	20	0.012	0.435	0.697	0.398
0.7	0.177	0.954	0.995	0.951					
0.9	0.140	0.944	0.990	0.906					
					W	CN1	CN2	CN3	CN4
					10	0.069	0.639	0.764	0.606
					50	0.247	0.970	0.999	0.986
					100	0.465	0.993	1.000	1.000

Table 4 P_{all} : success probability of multi-hop D2D communication in each CNZ.

s	CN1	CN2	CN3	CN4	H	CN1	CN2	CN3	CN4
0.1	0.154	0.113	0.249	0.147	2	0.012	0.007	0.019	0.011
0.3	0.073	0.111	0.247	0.143	10	0.046	0.109	0.246	0.143
0.5	0.046	0.109	0.246	0.143	20	0.006	0.150	0.446	0.166
0.7	0.033	0.108	0.246	0.140					
0.9	0.026	0.104	0.242	0.133					
					W	CN1	CN2	CN3	CN4
					10	0.013	0.072	0.189	0.088
					50	0.046	0.109	0.246	0.143
					100	0.087	0.113	0.251	0.146

Table 5 D2D-communication ratio: average ratio of requests supported by multi-hop D2D communication in each CNZ for various ratios of terminals with D2D-communication ability s .

s	CN1	CN2	CN3	CN4
0.1	0.083	0.100	0.100	0.100
0.3	0.118	0.296	0.300	0.299
0.5	0.124	0.485	0.500	0.493
0.7	0.124	0.668	0.697	0.666
0.9	0.126	0.850	0.891	0.815

in the other CNZs, and P_{all} of CNZ1 was larger than those of the other CNZs when s was small. As shown in Table 3, P_{reach} monotonically decreased as H increased, whereas P_{all} increased as H increased in the small range of H because the ratio of requests within the reach limit of multi-hop D2D communication increased. Hence, the existence of an optimum H maximizing P_{all} is expected.

The notation P_{reach} is the success probability of multi-hop D2D communication for only requests satisfying the distance constraint of $rH/2$ between ST and ST. On the other hand, P_{all} is the probability that requests are accepted among all requests of D2D communication. Therefore, we can obtain the ratio of requests accepted using D2D communication among all the requests, i.e., the *D2D-communication ratio*, by multiplying s by P_{all} instead of multiplying s by P_{reach} . Table 5 summarizes the D2D-communication ratios sP_{all} , and we confirm that sP_{all} largely increased as s increased because the effect of s on Q_k was small in the CNZs, except CNZ1. In CNZ1 with a high density of mobile terminals, however, the effect of s on Q_k was large, so sP_{all} was almost constant when s changed, except when $s = 0.1$. As shown in this example, when the terminal density is high, the D2D-communication ratio does not increase monotonously as s increases, and the existence of an op-

timum s for maximizing the D2D-communication ratio is expected.

5. Conclusion

When disasters, e.g., earthquakes, occur, the base stations and backhaul of cellular networks will likely be damaged and become unusable, so multi-hop D2D communication, in which mobile terminals directly communicate through some RTs, has gathered wide attention as an alternative communication method and a technique for offloading traffic load from congested cellular networks. Cellular networks need to control parameters, e.g., the D2D-communication ratio and maximum hop limit, to maximize the effectiveness of multi-hop D2D communication, so it is preferable for cellular networks to simply estimate the success probability of multi-hop D2D communication. Hence, in this paper, we derived a simple approximate formula for estimating and analyzing the success probability of multi-hop D2D communication for an earthquake occurring in Shinjuku Ward by reproducing the evacuation behavior of victims using MAS. Through numerical evaluation, we identified the following key findings.

- In areas with higher density of victims, the traffic load on each D2D channel was higher, and Q_k , the success probability of single-hop D2D communication, was smaller.
- When setting H , the upper limit of the hop length of multi-hop D2D communication, to about 10, the reachable distance of multi-hop D2D communication was up to about 1 km, and many D2D communications were limited to the case in which both the ST and the DT existed in the area covered by the same CN. Therefore, to improve connectivity against backhaul failure and reduce the traffic on cellular networks by multi-hop D2D communication, further extension of H is necessary.
- As H increased, the load of D2D channels increased, Q_k decreased, and P_{reach} , the success probability within the reachable distance of H -hop D2D communication, decreased. However, as a result of extending the reachable distance of multi-hop D2D communication, P_{all} , the success probability among all the requests of D2D communication, did not monotonously decrease as H increased, so we can expect that the optimum H maximizing P_{all} exists.
- As s , the ratio of terminals with ability of D2D communication, increased, the traffic load of D2D channels increased, so Q_k , P_{reach} , and P_{all} decreased. However, when the density of mobile terminals was low, the effect of s on P_{all} was small, and the D2D-communication ratio sP_{all} increased as s increased. In the areas where the terminal density was high, e.g., area around Shinjuku station, the sensitivity of s against Q_k was high, so the D2D-communication ratio did not monotonously increase with increase in s , and we can expect that the optimum s maximizing the D2D-

communication ratio exists.

Note that the above findings were obtained through a realistic scenario at Shinjuku Ward. While we confirm that the basic characteristics of the time series of average evacuee density are common for the case with different evacuation ways (Fig. 6), it is not certain that they also hold for other areas. We expect that the high-level findings, such as s and H , strongly affect multi-hop D2D-communication success ratio and there seems to be optimal values, which can be said to be general enough; however, this remains as future work. We can expect to maximize the effectiveness of multi-hop D2D communication on improving connectivity and off-loading traffic from cellular networks during a disaster by using our derived approximated formula for estimating the success probability of multi-hop D2D communication. In future, we will investigate an optimum control method of the ratio of selecting D2D communication and the hop limit of D2D communication.

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