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NDN-Based Message Delivery with Collaborative Communication for Reducing Base Station Power Consumption in Disasters

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SUMMARY This paper proposes an NDN-based message delivery protocol over a cellular network in disasters. Collaborative communication among cellular devices is integrated into the protocol so that power consumed by battery-operated base stations (BSs) is reduced when a blackout occurs. A key idea is to reduce consumed radio resources by making cellular devices of which radio propagation quality are better forward messages of neighboring devices. The radio resource reduction contributes to reducing power consumed by a battery-operated BS. We empirically and analytically evaluate how the proposed message delivery protocol reduces the power consumption of a BS assuming a densely populated shelter.
key words: *collaborative communication, disaster, energy efficiency, long term evolution, named data networking*

1. Introduction

The cellular-based Internet plays an important role in disasters; however, it is difficult for cellular networks to provide connectivity with refugees in a large-scale disaster time. A large-scale disaster causes a large-scale blackout and thus many base stations (BSs) are operated by their batteries even if their backhaul links to a cellular core network are not in failure. The report of the Great East Japan Earthquake [1] shows that about 67% of BSs in the disaster areas are battery-operated due to the blackout and that their batteries run out before the blackout is restored since it continues for about three days.

Reducing power consumed by BSs is a key to provide refugees with connectivity to the Internet during such three days. Focusing on that some of power consumed by a near-future BS is proportional to its load, this paper proposes to integrate collaborative communication among cellular devices [2] which have local wireless interfaces as well as cellular interfaces into LTE (Long Term Evolution)-based cellular communication. A key idea of collaborative communication is to reduce consumed radio resources by making cellular devices of which radio signal quality is better than neighboring devices send and receive their messages to and from a BS on behalf of them. Radio resources are reduced because the better radio signal quality of a sending/receiving cellular device becomes, the less an amount of radio resources used by doing so becomes. The radio resource reduction leads to reduction in power consumed by a BS because power consumed by near-future BSs would be proportional to their loads [3]. Hereafter, we refer to a cellular device of sending/receiving a message from/to a BS and such a neighboring cellular device as a representative device and a delegating device, respectively.

In the previous study [4], we preliminarily designed a message delivery protocol for well-considered applications in disasters and analytically validated the protocol on a few unjustified assumptions on radio signal quality, e.g., we assumed that the average radio signal quality of devices is different even if the devices are in the same room. In this paper, we validate the assumptions by empirically measuring radio signal quality of an LTE link with a commercial smartphone. The empirical measurements enable it to validate the protocol and to obtain a hint for selecting a suitable periodical interval to select a representative device.

The contributions of the paper are three-fold: First, we design a simple but a practical message delivery protocol based on the name-based [5] and publish/subscribe approaches. The adoption of name-based approach enables the protocol to be resilient to failures of servers such as DNS (Domain Name System) servers. On the contrary, one-to-many communication provided by the publish/subscribe approach [6] avoids repetition of crucial information delivery. This enables to efficiently use radio resources which are not so plentiful in disasters as at the usual time.

Second, we empirically measure radio signal quality of an LTE link with a commercial smartphone, which will be used as a communication devices in a disaster time, and reveal that collaborative communication reduces at least about 30% of the consumed radio resources of a BS by using the simulation with the measured radio signal quality.

Third, we analytically calculate how collaborative communication reduces power consumed by a BS as well as radio resources. The analysis shows that the power consumed by a BS is reduced at most about 30% compared with the protocol without collaborative communication in ideal cases. As far as we know, this paper is one of the first papers which address BSs' power reduction especially in a disaster time.

This paper is organized as follows. We first describe the requirements to disaster communications in Sect. 2. Section 3 describes the publish/subscribe protocol based on the name-based approach and Sect. 4 describes an analytical model for evaluating how collaborative communication reduces power consumed by a BS. In Sect. 5, we empirically measure the radio signal quality of an LTE link to validate the

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assumptions made for collaborative communication. Then, in Sect. 6, we evaluate how the proposal reduces radio resources and power consumed by a BS by using simulation with the measure radio signal quality and the developed analytical model. We introduce the related work in Sect. 7 and finally conclude the paper in Sect. 8.

2. Requirements in Disasters

This paper addresses situations in a disaster area several hours later after a disaster. In such situations, refugees evacuate to shelters such as schools and many of them reside in the shelters until the infrastructures for electricity and water are restored. Since it takes about more than three days by the infrastructures are restored, an important requirement is to offer minimal connectivity to refugees under conditions that various resources for power and communication are limited. Especially, batteries of BSs in blackout areas are the most critical resources.

2.1 Requirements from Applications

We carefully choose the applications which should be provided minimally for the three days so that usage of critical resources is minimized [7]. The first application is that refugees in shelters deliver safety-confirmation messages to relatives/friends in order to confirm that they are safe. The second application is that state authorities (e.g., a local government, a police station and a fire department) deliver disaster related information to refugees. Examples of information are warnings or information on where to go or how to behave.

In terms of resources, the above applications need one-to-many communication because they inherently assume multiple recipients. For example, the safety confirmation message is delivered to several relatives/friends. Besides reducing the number of messages in the down link direction is especially important because a BS usually allocates less radio resources to the uplink direction than the downlink.

2.2 Requirements to Power Consumption

A key problem during these days is a large scale blackout. BSs in blackout areas are operated by their batteries, but it is difficult for them to have sufficient capacities for a long time. Thus it is necessary to minimize usage of their batteries to prolong their battery lives. A main goal of this paper is to prolong BSs' battery lives by reducing power consumed by them. We assume that the traffic amount becomes as large as usual several hours later. Since large part of power is consumed by an amplifier to emit radio signals in the downlink direction, the paper focuses on message delivery in the down link direction.

3. Message Delivery Protocol

3.1 Overview

We adopt NDN/CCN as a basis of our message delivery protocol because of the following reasons: First, NDN/CCN naturally support most of the functions of TCP, including reliable transport and flow control, as discussed in [5]. Futhermore, NDN/CCN realize more fine-grained flow control, i.e., per-face, per-prefix and per-content performance measurements, congestion control and flow prioritization, than TCP/IP [5], [8]. Such fine-grained flow control is one of crucial features for message delivery protocols, especially during a disaster time [1]. Second, we adopt COPSS [6], which provides publish/subscribe communication based on NDN/CCN. The network load, i.e., the total amount of traffic in a network, due to COPSS is smaller than that due to IP multicast, as Chen et al. discussed in [6]. Since the traffic load in a disaster time is generally much higher than that in a normal time [1], employing COPSS on NDN/CCN networks rather than IP multicast on IP networks is a reasonable solution.

3.2 Protocol Stack

The message delivery protocol is designed assuming a cellular communication network based on LTE. As shown in Fig. 1, NDN/CCN routers are installed next to a cellular core network and devices forward messages based on NDN/CCN. The S-GW (Serving Gateway) and the P-GW (Packet Data Network Gateway) are nodes which provide UDP/IP tunnels between the NDN/CCN router and the devices. We select UDP tunnels rather than TCP ones since NDN/CCN naturally support transport functions of TCP, i.e., reliable transport and flow control [5]. We assume that devices have a local wireless interface, i.e., Wi-Fi, as well as a cellular interface. Representative and delegating devices communicate with each other using Wi-Fi.

3.3 One-to-Many Communication

We adopt COPSS [6], which provides publish/subscribe communication based on NDN/CCN. The publish/subscribe communication naturally supports one-to-many communication as shown in (a) and (b) of Fig. 2. A publisher pre-defines a name that specifies a topic and the name is recorded at a rendezvous node. Users subscribe the name by sending a subscribe message to the rendezvous node. When the publisher sends a message to the rendezvous node, it is delivered to all users that subscribe to the name. Thus, one-to-many

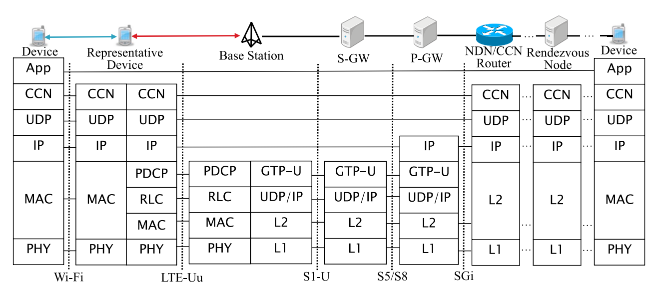

Fig. 1 Protocol stack for message delivery in disaster.

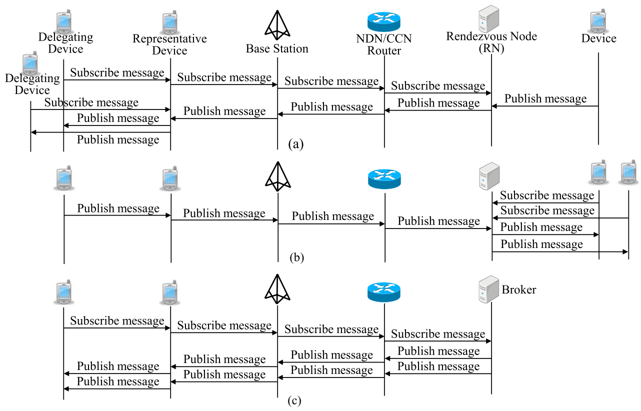

Fig. 2 Publish/Subscribe-based Message Sequences.

communication is naturally supported. A NDN/CCN router provides routing for COPSS as well as that for NDN/CCN. It is noted that a representative device plays the role of COPSS router for its delegating devices. COPSS can have a broker, which acts as a store for all published messages in order to support asynchronous message delivery. A salient feature of COPSS is that a subscriber need not to be online when messages are published and it can asynchronously receive all the un-received messages by sending just one subscribe message to the broker, as shown in (c) of Fig. 2.

3.4 Collaborative Communication

Collaborative communication among cellular devices [2] is a promising way to reduce power consumed by a BS. A key observation is that the better their radio signal quality becomes, the less radio resources devices use. Thus, we propose that a device of which radio signal quality is better than neighbors send and receive messages to and from a BS on behalf of the neighbors. This reduces consumed radio resources and results in reduction of power consumed by an amplifier which consumes most power of a BS.

(1) Wi-Fi One Hop Adjacency

Efficiency of collaborative communication depends on probability that a device with bad radio signal quality finds a neighboring device of which quality is better than it. We decide that devices do not use Wi-Fi multi-hop communication, but one-hop communication because a shelter is so highly populated that several devices exist within the distances of Wi-Fi one-hop. The analytical model in Sect. 4 shows that one-hop Wi-Fi adjacency is enough for collaborative communication to be effective to reduce BSs' power consumption.

(2) Selection of Representative Device

A key issue is how to select a representative device, which plays a role of a router based on NDN/CCN and COPSS. We design a simple but practical protocol with the concern about fluctuations in radio signal quality. Such fluctuations are mainly caused by shadowing and fading. Fluctuations due to shadowing are steady and affect the average radio signal quality. In contrast, those due to fading are time-varying. Assuming that fluctuations due to fading is absorbed by schedulers of BSs and considering changes in the average radio quality due to shadowing, we periodically select a representative device as follows: Each device periodically broadcasts its average SINR (Signal to Interference-plus-Noise Ratio) which is a radio signal quality, to neighboring devices using Wi-Fi. A device selects the device with the best SINR among neighboring devices and including itself as a representative device.

The reasons why the simple selection scheme is enough for collaborative communication to reduce radio resources are as follows: First, schedulers of BSs may compensate for the fluctuations in radio signal quality. The radio signal quality of a representative device is degraded due to fading if a long time elapses after it is selected. However, schedulers of BSs allocate more radio resources to devices with the better radio signal quality [9]. It implies that the BS tentatively reduces the number of radio resources if the radio signal quality is tentatively degraded, but increases the number after the tentative fluctuation finishes. Second, when a device in a disaster area sends a publish message, it selects a representative device and sends the message to it. No message is replied back from a rendezvous node in the downlink direction and thus we need not care about radio signal quality fluctuations of representative devices. On the contrary, when a device in a disaster area sends a subscribe message, in order to reduce the duration between a subscribe message and the corresponding publish messages, a device does not send a subscribe message to a rendezvous node but a broker so that publish messages are immediately replied.

4. Base Station Power Reduction with Collaborative Communication

4.1 Overview

In this section, we construct an analytical model for evaluating the power reduction of a BS due to collaborative communication. We use a BS power consumption model proposed in [3], which relies on the LTE downlink resource structure. Thus, we first describe radio resources in LTE and the power consumption of a BS before modeling the BS power reduction. The BS power consumption depends on the amount of consumed radio resources and it depends on a modulation scheme and a code rate, which are determined by the BS according to the radio signal quality. In the following subsections, we model each relation in sequence.

4.2 Radio Resources in LTE

The downlink resources in LTE have domains of time and frequency, as shown in Fig. 3. In the time domain, the resources are divided into 1 ms subframes, each of which is split into two 0.5 ms slots. Each slot consists of seven symbols. In the frequency domain, 12 subcarriers constitute one unit of resources, which occupies 180 kHz in the frequency domain. One unit of 12 subcarriers for the duration of one

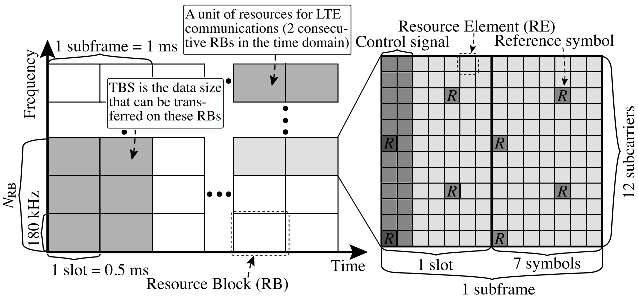

Fig. 3 A schematic of LTE downlink resources.

slot is called a resource block (RB) and the smallest unit of resource is a resource element (RE), which consists of one subcarrier for the duration of one symbol. That is, one RB consists of 84 REs. We simply refer to both RBs and REs as radio resources, hereafter. In LTE, a pair of RBs, i.e., 1 ms subframe and 12 subcarriers, is used as a unit of its communications. LTE adopts Adaptive Modulation and Coding (AMC), which changes a modulation scheme and a code rate depending on radio signal quality of devices. Thus, BSs can transfer more data to devices with better radio signal quality.

4.3 Power Consumption of Base Station

A power consumption of a BS is approximately modeled with a linear function of its load [3]. The BS power consumption $e(l(t))$ at time t is calculated as

$$e(l(t)) = \Delta_E l(t) + E_0, \tag{1}$$

where E_0 is the constant power consumption regardless of the load on the BS and Δ_E is a coefficient of the load dependent power consumption. In [3], the load on the BS at time t, $l(t)$, is defined as the ratio of the sum of the transmission power of REs used for data transmission at time t to maximum transmission power of the BS. Assuming that the transmission power of each RE is constant, $l(t)$ can be defined as $l(t) = n(t)/N_C$, where $n(t)$ is the number of consumed RBs at time t in the frequency domain and N_C is that of available RBs.

N_C can be easily derived from frequency bandwidth of a BS. For instance, N_C is 100 for most of current BSs with 20 MHz bandwidth. However, it is difficult to derive an exact value of $n(t)$ since it depends on scheduling algorithms of the BS, which are confidential. In this section, aiming at deriving the average power consumption of a BS, we use the expected number of RBs used for data transmission $\overline{n} = \mathbb{E}[n(t)]$ instead of $n(t)$. To simplify notations, we refer to $\overline{n}$ and N_C as RB consumption and RB capacity, hereafter.

4.4 Modeling Power Reduction with Collaborative Communication

To derive the RB consumption $\overline{n}$, we first model the AMC and radio signal quality. Then, we model $\overline{n}$ in the case with and without collaborative communication. Finally, we have the power reduction due to collaborative communication from Eq. (1). In principle, we use capital letters to express constant parameters and small ones for variables, respectively.

4.4.1 Modeling Adaptive Modulation and Coding

With the AMC, a BS determines a Modulation and Coding Scheme (MCS) index (I_{MCS}), which specifies a modulation order index (I_{MO}), which indicates a modulation scheme, and a transport block size (TBS) index (I_{TBS}), which indicates a code rate, according to radio signal quality of devices, i.e., SINR. Regarding the AMC, we derive i) the number of RBs necessary for transmitting 1 bit data for each MCS index and ii) MCS indexes from devices' SINR.

To obtain the number of RBs necessary for transmitting 1 bit data, we have to derive TBS, which is the data size [bit] that can be transferred on N_{RB} RBs in the frequency domain for the duration of 1 subframe. In LTE, the TBS is determined by I_{TBS} and N_{RB}, which is the number of RBs in the frequency domain assigned by a BS for transmitting data and the I_{TBS} is determined by I_{MCS} [10]. We derive S_k, which is the expected data size transmitted over a pair of RBs (1 subframe). Note that LTE uses a pair of RBs as a unit of its communications, as mentioned in Sect. 4.2. An example of N_{RB} and TBS is shown in Fig. 3. Since N_{RB} depends on the scheduling algorithms of the BS, we derive the expected value for S_k. We use a term $S_{TBS}(I_{MCS}, N_{RB})$ as the TBS in the case that I_{MCS} and N_{RB} is specified. In the case of $I_{MCS} = k$ and $N_{RB} = i$, $S_{TBS}(k, i)/i$ bits of data can be transferred on each pair of RBs. Calculating its mean for all $N_{RB} \in [1, 110]$, S_k is derived as $S_k = 1/110 \sum_{i=1}^{110} S_{TBS}(k, i)/i$.

Next, we derive a map from a SINR value to a MCS index. Since the map is also confidential, we derive it via spectral efficiency. That is, we make two maps; one is a map from SINR values to the spectral efficiency based on Shannon-Hartley theorem in the similar way to [11] and another is a map from MCS indexes to the spectral efficiency based on the specifications of LTE. Then, we make the map from a SINR value to a MCS index by combining the two maps.

According to Shannon-Hartley theorem and its extension used in [11], a spectral efficiency to keep the bit error rate below B in the case that the SINR is β, is derived as,

$$\eta_{SINR}(\beta) = \log_2 \left(1 + \frac{\beta}{-\ln(5B)/1.5}\right). \tag{2}$$

To derive $\eta_{MCS}(k)$, which is the spectral efficiency in the case of $I_{MCS} = k$, we compute the data size that is actually transmitted on N_{RB} RBs in the frequency domain and one that can be physically transmitted on the RBs with the modulation scheme specified by the MCS index I_{MCS} and $S_{RB}(I_{MCS}, N_{RB})$. Since LTE employs two-level Cyclic Redundancy Check (CRC) as its error detecting code, we have to consider the CRC data size S_{CRC}. In the two-level CRC, 24 bit CRC data for all transport block is added. If the transport block, including the first CRC data, exceeds 6144 bits, the transport block is divided into blocks of 6120 bits and additional 24 bits of CRC data is added to each divided block [12]. The data size actually transmitted on the N_{RB} RBs is $S_{TBS}(I_{MCS}, N_{RB}) + S_{CRC}$.

Next, we compute $S_{RB}(I_{MCS}, N_{RB})$. To derive this, we consider the number of REs used for data transmission, as shown in Fig. 3. A pair of RBs, i.e., 12 subcarriers for the duration of 1 subframe, contains 168 REs. 8 REs are used for reference symbols, which cannot be used for data transmission. Moreover, up to 4 REs from the beginning in the time domain are used for control signals [12]. Assuming that the first two REs are used for control signals, 138 REs can be used for data transmission among the pair of RBs. Thus, the data size that can be physically transmitted over N_{RB} RBs is derived as $S_{RB}(I_{MCS}, N_{RB}) = 138 N_{RB} S_{MO}$, where S_{MO} is the data size transmitted over one RE, which is determined according to the modulation scheme specified by I_{MCS}. The date size that can be transmitted on one RE is equivalent to the spectral efficiency since one RE is a radio resource of 15 kHz and about 66.7 μs. Hence, the spectral efficiency in the case of $I_{MCS} = k$ is

$$\eta_{MCS}(k) = \frac{1}{110} \sum_{i=1}^{110} \frac{S_{MO}\left(S_{TBS}(k,i) + S_{CRC}\right)}{S_{RB}(k,i)}. \tag{3}$$

Finally, comparing $\eta_{SINR}(\beta)$ and $\eta_{MCS}(k)$, the map from the SINR value β to the MCS index k is determined as

$$k = \max\{0 \le n \le 28 \mid \eta_{SINR}(\beta) > \eta_{MCS}(n)\}. \tag{4}$$

4.4.2 Modeling Radio Signal Quality

Since fading and shadowing degrade devices' radio signal quality, we have to incorporate those effects to model the radio signal quality.

Regarding fading effects, assuming an urban area, where there are many objects to scatter the radio signal, we employ Rayleigh fading, which is a model for the effect of a propagation environment on a radio signal. The amplitude of the faded radio signal is expressed with the Rayleigh-distributed random variables. Since a signal level is the square of its amplitude, signal levels are expressed with the exponentially distributed random variables.

To express shadowing effects, we change the average SINR, in the same way as [2], i.e., we set the smaller average SINR of the above-mentioned random variables for devices that receive degraded radio signal due to shadowing effects. We categorize devices into several classes $\mathbf{C}$ and change the average SINR γ_c, where $c \in \mathbf{C}$, according to the shadowing effects. We refer to the classes as radio signal quality classes.

Integrating the effects of fading and shadowing, the probability density function of the SINR of devices in the radio signal quality class c is expressed as,

$$f_c(z) = \frac{1}{\gamma_c} \exp\left(-\frac{z}{\gamma_c}\right). \tag{5}$$

4.4.3 Modeling Power Reduction Effects

To obtain the BS power reduction, we have to derive $\overline{n}^{\text{with}}$ and $\overline{n}^{\text{without}}$, which are the RB consumption with and without collaborative communication, respectively. These values are determined according to the MCS index values of devices that communicate via LTE links, i.e., representative devices in the case with collaborative communication and each device in the case without collaborative communication.

Using Eq. (5), the probability of $I_{MCS} = k$ for devices in the radio signal quality class c is derived as $\pi_{c,k} = \int_{\theta_{k-1}}^{\theta_k} f_c(z)\,\mathrm{d}z$, where θ_k is the maximum SINR value in the case of $I_{MCS} = k$, which can be derived from Eq. (4). By using $\pi_{c,k}$, the probability of $I_{MCS} = k$ is derived as the average of $\pi_{c,k}$ with the weights of the probability of being the radio signal quality class c (p_c) as follows:

$$\pi_k = \sum_{c \in \mathbf{C}} \left(p_c \int_{\theta_{k-1}}^{\theta_k} f_c(z)\,\mathrm{d}z \right). \tag{6}$$

$\overline{n}^{\text{without}}$ is calculated as data transmission rate for the duration of 1 subframe, U bit/ms, multiplied with the weighted average of the expected number of RBs for transmitting 1 bit data, which is the inverse of S_k, with the weights of the probability of $I_{MCS} = k$, π_k^{without} as

$$\overline{n}^{\text{without}} = U \sum_{k=0}^{28} \frac{1}{S_k} \pi_k^{\text{without}}. \tag{7}$$

π_k^{without} is derived as $\pi_k^{\text{without}} = \pi_k$.

In the similar way, $\overline{n}^{\text{with}}$ is calculated as

$$\overline{n}^{\text{with}} = U \sum_{k=0}^{28} \frac{1}{S_k} \pi_k^{\text{with}}. \tag{8}$$

π_k^{with} is the probability that I_{MCS} of the nearby representative device with the best radio signal quality is k. Note that the time from representative devices' selection to data transmission via them is assumed to be short enough and therefore the radio signal quality of the representative device does not change during the time interval. π_k^{with} is derived as $\pi_k^{\text{with}} = \pi_k^{\text{up}} + \pi_k^{\text{remain}}$, where π_k^{up} and π_k^{remain} are the probabilities that I_{MCS} of the representative is higher than ones of devices and the same as ones of devices, respectively. To derive π_k^{up}, we derive the probability that I_{MCS} of the neighboring device with the best radio signal quality, which can be a representative, is k as follows:

$$\varsigma_k = \rho_k - \rho_{k-1}. \tag{9}$$

ρ_k is the probability that I_{MCS} of all neighboring device is less than or equal to k and it is derived as

$$\rho_k = \prod_{c \in \mathbf{C}} \psi_{c,k}^{d_c}, \tag{10}$$

where d_c is the number of neighboring devices of which radio signal quality class is c and it is derived from $d_c = p_c(\pi R^2 d - 1)$. R is the range of wireless local communication and d is the population density within cell. $\psi_{c,k}$ is the probability that I_{MCS} is less than or equal to k for devices in the radio signal quality class c and it is derived as $\psi_{c,k} = \int_0^{\theta_k} f_c(z)\,\mathrm{d}z$. By using ς_k, π_k^{up} is derived as

$$\pi_k^{\mathrm{up}} = \sum_{i=0}^{k-1} \pi_i \varsigma_k. \tag{11}$$

π_k^{remain} is derived as

$$\pi_k^{\mathrm{remain}} = \pi_k \rho_k. \tag{12}$$

Note that $\pi_0^{\mathrm{up}} = 0$ and $\pi_{28}^{\mathrm{remain}} = \pi_{28}^{\mathrm{without}}$ since I_{MCS} is defined in $[0, 28]$.

Finally, substituting $l(t)$ in Eq. (1) with $\overline{n}^{\mathrm{without}}/N_{\mathrm{C}}$ and $\overline{n}^{\mathrm{with}}/N_{\mathrm{C}}$, we obtain the ratio of the BS power reduction as

$$e_{\mathrm{Red}} = \frac{e^{\mathrm{without}} - e^{\mathrm{with}}}{e^{\mathrm{without}}} = 1 - \frac{\Delta_{\mathrm{E}}\overline{n}^{\mathrm{with}}/N_{\mathrm{C}} + E_0}{\Delta_{\mathrm{E}}\overline{n}^{\mathrm{without}}/N_{\mathrm{C}} + E_0}, \tag{13}$$

where e_{with} and e_{without} is the BS power consumption with and without collaborative communication, respectively.

5. Empirical Measurement of Radio Signal Quality

In this section, we measure radio signal quality of an LTE link related with shadowing and fading, i.e., 1) average radio signal quality and 2) intervals between changes in radio signal quality, respectively because of the following two reasons. First, to reduce the consumed radio resources with collaborative communication, it is an indispensable condition that the average radio signal quality of devices must be different even if they are in the same small area, where they can communicate each other via Wi-Fi. Second, a radio quality of a representative device might be degraded due to fading if a long time elapses after the device is selected as the representative. Thus, it is desirable that radio signal quality of an LTE link are steady during a time from the selection of a representative device to data transmission via the representative device. To validate that such conditions are satisfied in a shelter, we empirically measure radio signal quality of an LTE link by using a commercial smartphone inside/outside a building assuming areas inside/outside a shelter.

5.1 Conditions of Measurement

We measure radio signal quality of an LTE link with a commercial smartphone because refugees may use their smartphones to retrieving data from the Internet. To measure radio signal quality of an LTE link, we develop an Android application that records statuses of an LTE link on changing the statuses, such as SNR (Signal to Noise Ratio). Since the current Android API does not support SINR measurements, we use SNR instead of SINR in this measurement.

For the measurements, we choose a non line of sight (NLOS) environment since many buildings in urban areas are located in NLOS environments. Since school buildings are used as shelters, we use an university building that is in an NLOS environment. The building is located 200 m away from an LTE BS. Assuming that refugees will be both inside/outside a shelter during disasters, we measure SNR values both inside/outside the building. According to the size of Japanese shelters and the number of people accommodated in the shelters [13], the distance between people in the shelters is typically 1.5–2 m. Thus, we divide the measurement areas into a grid formed by 2,m × 2 m squares and measure SNR values at the center of each square. The room inside the building and the measurement area outside the building are divided into 3 × 6 and 3 × 3 squares, respectively. We measure SNR values with putting the smartphone in an experimenter's pocket assuming that many refugees will do so in shelters.

5.2 Measurement Result

The time-series of SNR values measured inside the building is shown in Fig. 4. Due to effects of multipath fading, the SNR values are fluctuated. Furthermore, we observe that the average SNR at each square is different even if the measurements are performed in the same room, where the effects of shadowing might be the identical. To see the difference of the average SNR more clearly, we show that as a heat-map in Fig. 5. The average SNR around the center of the room is higher than other points in the same room.

Next, we analyze intervals between changes in measured SNR values. The average, the minimum, and the maximum of the intervals between changes in measured SNR values are 7.988, 0.021, and 382.470 seconds, respectively.

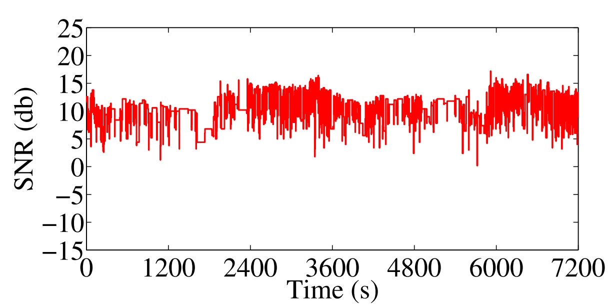

Fig. 4 An example of time-series of SNR inside the NLOS building.

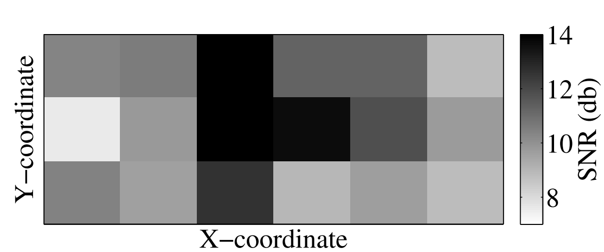

Fig. 5 The average SNR inside the NLOS building.

The results imply that it is desirable to complete communications via a representative within about 8 seconds after the selection of the representative. In the following section, we evaluate how the interval for selecting representative devices affects the radio resource reduction due to collaborative communication.

6. Evaluation of BS Radio Resource and Power Consumption

6.1 Conditions of Evaluation

In this section, we evaluate BS radio resource and power reduction due to collaborative communication from two perspectives: one is a simulation for evaluating how fluctuations in radio signal quality due to fading affects the consumed radio resources of a BS in a small area, e.g., a room in a shelter, and the other is an analysis with the model in Section 4 for evaluating how the collaborative communication reduces the power consumed by a BS in a highly dense and crowded large area covered by the BS.

For the simulation-based evaluation, we use a macro cell that has a BS with a proportional fair scheduler [9] and a 10 MHz LTE link. 18 devices are deployed in a NLOS room. We use radio signal quality generated with Rayleigh fading in addition to the measured one. Each device requests a data according to a Poisson process with mean rate 0.1. The data size is exponentially distributed with a mean size of 100 Kbyte assuming that refugees mainly send/receive text messages for notifying their families about their safety. A device with the best SNR value is selected as a representative device every T_I seconds. Other devices communicate via the representative devices until the next selection of representative devices.

For the analysis-based evaluation, we assume a shelter in Tokyo, which is one of the crowded cities in the world. We use a macro cell with the radius of 250 m and a BS with the bandwidth of 10 MHz. We set $\Delta_E = 188$ watt and $E_0 = 260$ watt for Eq. (13) according to [3]. We set the range of wireless local communication to 20 m assuming Wi-Fi. Devices are categorized into three radio quality classes, *Poor*, *Moderate*, and *Good*, wherein the radio signal quality of devices is poor, moderate, and good. Then, we set the average radio quality of devices as $\gamma_{\text{poor}} = 9.54$, $\gamma_{\text{moderate}} = 16.99$, and $\gamma_{\text{good}} = 23.87$ dB, so that the average data transfer rate is about 20%, 50%, and 80% compared with the best data transfer rate, i.e., in the case of the MCS index value of 28, in the same way as [2]. Radio signals to devices farther from the BS must be affected by shadowing more, we set the ratio of the radio quality classes according to distance from the BS as summarized in Table 1. We evaluate two scenarios; one is normal time and another is disaster time. For the normal time, 1,250 devices are deployed assuming the population density of Tokyo. For the disaster time, we deploy 40,000 devices since about 32,000 people in Tokyo will be accommodated in the Rikugien shelter of about 52,000 m^2 size [13] and 3 cellular carriers in Japan serve LTE to them.

Table 1 Ratio of devices belonging to the radio quality classes.

Parameter	Values of p_c for the distance from the BS		
	(0 m, 80 m]	(80 m, 160 m]	(160 m, 250 m]
p_{poor}	0.1	1/3	0.6
p_{moderate}	0.3	1/3	0.3
p_{good}	0.6	1/3	0.1

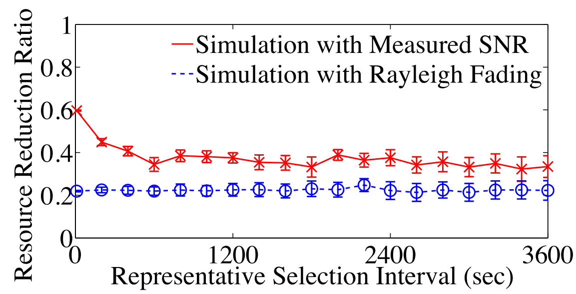

Fig. 6 The ratio of the consumed radio resources with and without collaborative communication.

6.2 Evaluation Result

First, we evaluate the reduction in the consumed radio resources through simulation experiments in Fig. 6. The vertical axis is the ratio of the radio resource consumption reduced by collaborative communication to the radio resource consumption without collaborative communication. We choose the representative selection interval for the horizontal axis to see the effects of fluctuations in radio signal quality on the radio resource consumption. Markers and error bars indicate the mean and the 95% confidence intervals of results of 50 simulation trials, respectively. The solid and dashed lines indicate results with the SNR values measured with commercial smartphones and generated by Rayleigh fading, respectively. We reveal the following two observations. First, under the situation where the measured SNR values are used, collaborative communication reduces up to 60% of the consumed radio resources compared with the case without collaborative communication in the case of the short representative selection interval. Even if the representative selection interval is long, it reduces about 30% of the consumed resources. However, under the situation where the SNR values are generated with Rayleigh fading, the reduction in the radio resource consumption does not change regardless of the representative selection interval. In contrast to Rayleigh fading, where the SNR values are stochastically independent random variables, the measured SNR values do not change within a certain intervals as we discussed in Sect. 5. That is, the SNR values of the selected representative devices are more likely to remain high in the case of the smaller representative selection interval and this results in the large reduction in the radio resource consumption. These results imply that the interval value should be carefully selected. Second, the reduction in the radio resource consumption under the measured SNR is higher than the SNR generated with Rayleigh fading since fluctuations in the measured SNR are smaller

IEICE TRANS. COMMUN., VOL.E99–B, NO.12 DECEMBER 2016

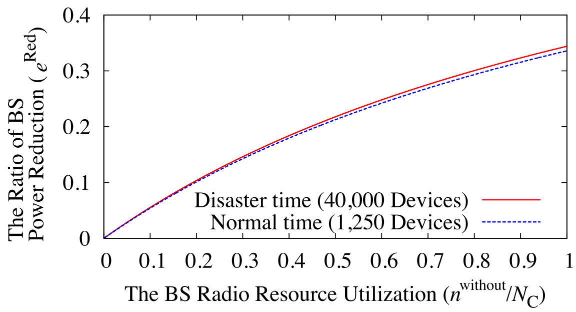

Fig. 7 The BS power reduction.

than those generated by Rayleigh fading. That is, intervals between changes in the measured SNR values are larger than that with Rayleigh fading.

Next, we evaluate the power consumption of a BS in a highly dense area by using the analytical model. The y-axis in Fig. 7 is the ratio of the BS power reduction. The x-axis indicates the load on the BS in the case without collaborative communication. The density of devices does not dominate the BS power reduction. The existence of representative devices with the higher MCS index values is one of the imporant factors for collaborative communication to reduce the power consumption of the BS. The probability that a representative device with the higher MCS index value exist within the distances of Wi-Fi one-hop becomes high enough if the density of devices d_c is sufficiently high, as shown in Eqs. (9), (10) and (11). In both the disaster and normal cases, the number of devices is sufficiently high such that representative devices with higher MCS index values would exist. Therefore, collaborative communication reduces the power consumption of the BS similarly in both the cases. In contrast, the load on the BS is a dominant factor in reducing the power consumption of the BS, as shown in Eq. (13), i.e., the ratio of reduction becomes higher as the load on the BS increases. Since the traffic load in a disaster time is generally higher than that in a normal time [1], our architecture based on collaborative communication would be effective for reducing the BS power consumption in disasters. We should note that the reduction in the BS power consumption in Fig. 7 is slightly overestimated since the analytical model assumes that the radio signal quality of representative devices does not change after their selection. In contrast, the simulation experiments with radio signal quality generated by Rayleigh fading may underestimate the BS power consumption as discussed in Fig. 6 since the fluctuations in the radio signal quality generated with Rayleigh fading is larger than the measured one. The measurement-based simulation experiments for an entire macro cell are not reasonable. Thus, we have to see the both results in Figs. 6 and 7 and conclude that our messages delivery protocol reduces at most 30% of the BS power consumption if representative devices are carefully selected so that communications via a representative are completed within about 8 seconds after the selection of representative devices, as we discussed in Sect. 5.

Finally, we discuss the power consumed by representative devices. Collaborative communication may increase the power consumed by Wi-Fi communications of representative devices for transmitting messages to delegating devices though it reduces the BS power consumption. However, the power consumed by Wi-Fi interfaces of representative devices is a few orders of magnitude smaller than the power consumed by the BS. For instance, a currently available smartphone, Nexus One, consumes 0.0012 [joule/packet] for sending a packet via its Wi-Fi interface [14]. From these results, we conclude that message delivery with collaborative communication is effective for reducing the power consumed by BSs in a disaster time.

7. Related Work

We employ NDN/CCN and COPSS [6] as a basis of our message delivery protocol. With the asynchronous message delivery of COPSS, devices need not to be online when messages are published. They can asynchronously receive the messages by sending just one subscribe message to the broker when they become online. Although retrieving multiple Data packets by issuing one Interest packet is supported by Interest aggregation [15], it aims at solving the link underutilization problem originated from CCN's one-for-one relation between Interest and Data packets and furthermore it implicitly requires devices to be online. In contrast, the asynchronous message delivery of COPSS is one of useful features for the message delivery during a disaster time, where devices might often be turned off to save their battery lives.

Collaborative communication is effective to improve efficiency of cellular frequency resource usage [2]. Asadi and Mancuso propose collaborative communication and quantitatively analyze how it improves throughput with the same radio resources. This paper follows their approach but the differences to their study are summarized as follows: First, this paper focuses on reduction in radio resources with the same throughput. Second, mapping between SINR and MCS values are carefully decided to precisely model an LTE-compliant BS. Third, we empirically measure radio signal quality of an LTE link and validate that collaborative communication reduces radio resources around the NLOS environments, where the measurements are performed.

In disaster communications, a number of emergency alert systems (emergency warning systems) are developed for communication between refugees and rescue teams focusing on the "golden 72 hours" [16]. These systems focus on how to provide communication without relying on cellular networks assuming that a communication infrastructure is severely damaged. In contrast, we focus on a situation that a communication infrastructure is not severely damaged but that an infrastructure for power supply is damaged.

8. Conclusion

In this paper, we propose to apply collaborative communication into disaster communication to prolong battery-operated

BSs' life. Collaborative communication reduces power consumed by BSs by making devices with better radio signal quality forward messages of other neighboring devices. The author designs a message delivery architecture focusing on disaster communication. We empirically and analytically validate that the architecture reduces both radio resources and power consumed by a BS. Investigating the energy-reduction effects in the case that collaborative communication is used in conjunction with BS-side energy-reduction approaches, such as cell-zooming, is one of our future research directions.

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