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Citation:

Thuan Ngo, Hiroki Nishiyama, Nei Kato, Toshikazu Sakano, and Atsushi Takahara, "A Spectrum- and Energy-Efficient Scheme for Improving the Utilization of MDRU-based Disaster Resilient Networks," IEEE Transactions on Vehicular Technology - Special Section on Green Mobile Multimedia Communications, vol. 63, no. 5, pp. 2027-2037, Jun. 2014.

URL:

http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6780991

A Spectrum- and Energy-Efficient Scheme for Improving the Utilization of MDRU-based Disaster Resilient Networks

Thuan Ngo, *Student Member, IEEE,* Hiroki Nishiyama, *Senior Member, IEEE,* Nei Kato, *Fellow, IEEE,* Toshikazu Sakano, *Member, IEEE,* and Atsushi Takahara, *Member, IEEE*

***Abstract*—The Movable and Deployable Resource Unit (MDRU)-based network provides communication services in disaster struck areas where the lack of spectrum and energy resources is intensified due to the high demand from users and the power outages after a disaster. The MDRU-based network attempts to apply spectrum- and energy-efficient methods to provide communications services to users. However, existing works in this field only consider spectrum efficiency or energy efficiency separately, in spite of the trade-off relationship between them. Thus, we propose a scheme to improve the utilization of both spectrum and energy resources for better system performance. The considered MDRU-based network is composed of gateways deployed in the disaster area, which can replenish their energy by using solar panels. Our proposed scheme constructs a topology based on the top k spectrum-efficient paths from each sender, and applies max flow algorithm with vertex capacities, which are the number of transmissions each gateway can send, referred to as transmission capability. The transmission capability of each gateway is determined by its energy resource and distances to its neighbors. Furthermore, we show that the proposal can be used for multi-sender multi-receiver topologies. A new metric named spectrum-energy efficiency to measure both spectrum and energy efficiencies of the network is defined. Through analyses, we prove that a value of k exists such that the spectrum-energy efficiency of a given topology is maximized. Furthermore, our simulation results show that by dynamically selecting appropriate value of k, the proposed scheme can provide better spectrum-energy efficiency than existing approaches. Also, our experimental results verify the analysis findings.**

I. Introduction

Providing information and communications technology (ICT) services in areas affected by disasters is a challenging issue for researchers and engineers because the ICT infrastructure in those areas can be damaged. In order to deal with such issue, the concept of MDRU-based networks has been introduced [1]. The idea of MDRU-based networks is to quickly deploy a resource unit, which has the ability to accommodate ICT services to the disaster site, and establish a wireless network in the site. The high demand from users and the power outage after disasters are fundamental problems in MDRU-based networks. In order to deal with the critical demand of ICT services, spectrum-efficient methods should be considered in MDRU-based networks. Furthermore, to solve the power supply problem, renewable energy functions should be used together with energy-efficient methods. Spectrum efficiency is a measure of how efficiently the limited frequency spectrum is utilized to transmit packets, i.e., how much throughput can be achieved with a limited frequency bandwidth. However, contemporary methods such as those in [2], [3] that aim to improve spectrum efficiency fail to consider the limited energy resources in practical MDRU-based networks. On the other hand, energy efficiency is a measure of how efficiently the energy is utilized to transmit packets, i.e., how many packets can be transmitted with a limited energy. However, energy-efficient methods such as those introduced in [4], [5] fail to consider the limited frequency spectrum. Although there are some investigations regarding multi-objective approaches [6], [7], the joint problem considering both spectrum and energy efficiencies has not received sufficient attention in literature. In this work, we propose a scheme that considers both spectrum and energy efficiencies in the MDRU-based network that is applied to the network between the gateways, shown in Fig. 1, deployed in a disaster area. We consider that each gateway has a limited battery that is replenished by a solar panel. The gateways can forward the packets from their surrounding users to the MDRU by using a special wireless band. Furthermore, each gateway can relay the data from other gateways to

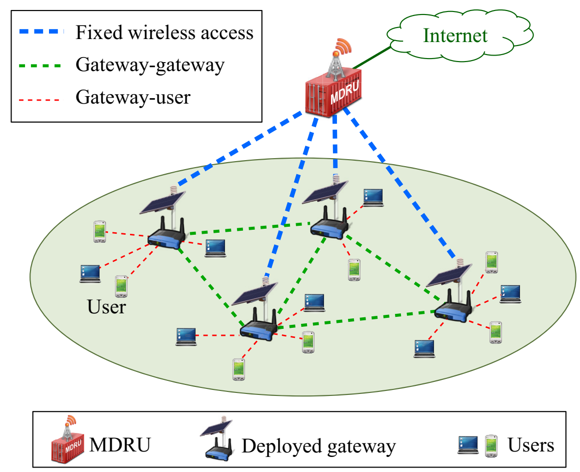

Fig. 1. Considered MDRU-based wireless network.

T. Ngo, H. Nishiyama, and N. Kato are with the Graduate School of Information Sciences, Tohoku University, Sendai, Japan. E-mails: {thuan, bigtree, kato}@it.ecei.tohoku.ac.jp.

T. Sakano and A. Takahara are with NTT Network Innovation Laboratories, NTT Corporation, Yokosuka, Japan. E-mails: {sakano.toshikazu, takahara.atsushi}@lab.ntt.co.jp.

Manuscript received August 21, 2013; revised January 20, 2014; accepted February 27, 2014.

either the MDRU or the next gateway in the path to the MDRU in the multi-hop manner. Based on the remaining energy of the gateways, MDRU will decide which gateway should transmit packets directly to the MDRU, and which gateway should use multi-hop paths to send its packets. We categorize the gateways into three groups, namely, senders, relays, and forwarders. Senders are the gateways that want to send packets via multi-hop paths. Relays are the gateways that can relay packets from its neighboring gateways to the next hop. Forwarders are the gateways that receive packets from its neighboring nodes and can directly transmit them to the MDRU. The proposed scheme is composed of two phases, namely, *topology formation* and *transmission division*. The topology formation phase creates a topology by using the top k spectrum-efficient disjoint paths from each sender. The gateways that are not in the resulting topology are not used. In the transmission division phase, we split the traffic from each gateway to the neighbors in the topology by using the *max flow with vertex capacities* algorithm, which maximizes the total number of transmissions that senders can transmit to the forwarders given the transmission capability of each gateway. Transmission capability is determined according to the energy resource of a gateway and the distances to the its neighbors. The main contributions of this article are summarized as follows:

- We propose a scheme that considers both spectrum and energy efficiencies to find routing paths from multiple senders to multiple forwarders in an MDRU-based network. The scheme composes the paths based on the top k spectrum-efficient paths and the transmission capabilities of the gateways. Additionally, we prove that the routing paths can be obtained in polynomial time.
- We analyze relationship between the value of k in the topology formation phase and the two objectives, namely, spectrum and energy efficiencies, and we show that a higher value of k decreases the average spectrum efficiencies of paths and increases the total number of transmissions that senders can send to the forwarders.
- We introduce a new metric, namely, spectrum-energy efficiency, to measure how many transmissions that can be carried out with a limited frequency band and limited energy resource. Furthermore, we prove that a value of k exists that leads to the maximum spectrum-energy efficiency of the MDRU-based network.
- By conducting extensive simulations, we validate the accuracy of our analyses. Moreover, the simulation results demonstrate that by dynamically selecting appropriate value of k, the proposed scheme can provide better spectrum-energy efficiency than the existing methods.

The remainder of this paper is organized as follows. Section II surveys current research on spectrum and energy efficiencies in wireless networks. In Section III, we outline the challenges for MDRU-based networks. Section IV describes the system assumptions, network model, and the definitions of transmission capability and spectrum-energy efficiency. Our proposed spectrum- and energy-efficient scheme is explained in Section V. In Section VI, we analyze the relationship between the value of k and the two objectives: spectrum and energy efficiencies. Furthermore, the complexity of our proposed algorithm is analyzed. We present the performance evaluation in Section VII and conclude the paper in Section VIII.

II. Related Work

Much research has been conducted on routing in multi-hop networks, where nodes can serve as relays. Most of the previous works on routing, such as those in [8], [9], focus on how to improve the network throughput by designing routing metrics and modifying the existing routing protocols to apply these new metrics. However, these models do not fully take into account the limitations of the physical layer. In contrast, routing with limited spectrum resource has drawn attention of the research community recently. Sikora *et. al.* analyzed the performance of some practical routing schemes for wireless networks and pointed out those that are most suitable for power-limited networks and those that are most acceptable for bandwidth-limited networks [6]. They also proposed a new information-theoretic scheme, referred to as multi-hop with recursive backward interference cancellation, to remove all interference from the multi-hop system with an arbitrarily small rate loss. However, they considered a one-dimensional linear network and assumed that the number of relays and their locations are design parameters. Chen *et. al.* considered a more flexible assumption with a linear network comprised of an arbitrary number of randomly located nodes and introduced the objective function for the optimal spectrum-efficient routing problem [2]. They note that the problem cannot be solved by using simple shortest path algorithms because the routing metric is neither isotonic nor monotone. Instead, they proposed two suboptimal solutions, which are Approximately Ideal-Path Routing (AIPR) and Distributed Spectrum Efficient Routing (DSER). AIPR, a location-assisted routing algorithm, aims to approximate the ideal routing path by calculating the optimum inter-relay distance D_{hop} and choosing the relay node with the distance to the source closest to D_{hop}. On the other hand, DSER modifies the objective function of the optimal spectrum-efficient routing problem so that the problem can be solved in a distributed way. In DSER, the weight function of a link l is calculated as $1 + \frac{\beta}{\rho_l}$, where β is the routing coefficient, ρ_l is the signal-to-noise ratio (SNR) of the link l, and 1 is the penalty for an additional hop. By using this weight function, DSER can find the routing path based on a shortest path routing algorithm. Furthermore, Saad [3] proposed two algorithms to solve the original problem of finding the maximum spectrum-efficient path in polynomial computation time. These algorithms rely on the iterative use of a shortest path procedure on a graph modified by removing unnecessary links. However, the above mentioned algorithms are based on the assumption that all nodes in the network are connected with abundant power supplies.

Energy efficiency is another important topic in wireless network and has attracted much attention [10]–[14]. For example, Srinivas and Modiano studied minimum energy disjoint path routing problem in wireless ad hoc networks [4]. Two optimal solutions for minimum energy 2 link-disjoint paths and minimum energy k node-disjoint paths were proposed in their research. Also, two heuristic algorithms were provided to reduce the complexity of the optimal algorithms. On the other hand, Miao *et. al.* focused on the energy-efficient link adaptation in [5]. They proved that a unique globally optimal link adaptation solution exists and proposed two iterative algorithms, namely, Gradient Assisted Binary Search (GABS) and Binary Search Assisted Ascent (BSAA), to obtain the optimum solution. However, the above mentioned algorithms for energy efficiency do not consider the limited spectrum resource as a co-objective in their method.

In this paper, we consider a network with the limitations of both frequency bandwidth and energy resources. To come up with the solution for the joint problem of finding both spectrum-efficient and energy-efficient routing paths, we propose a scheme composed of two phases: topology formation and transmission division. In the topology formation phase, we iteratively apply the optimal spectrum-efficient routing algorithm [3] k times to find the top k best disjoint paths in terms of spectrum efficiency. The resulting paths are used to construct a topology. After that, we split the transmissions based on the transmission capability of nodes from the constructed topology. The transmission capability of a node is calculated based on its remaining energy and the distances to its neighbors.

III. Challenges for MDRU-based Networks and Desired Solution

As mentioned in [1], right after the occurrence of a disaster, MDRU(s) will be transported to the disaster site to establish a network that provides Internet connectivity to users in the area. The current prototype MDRU is relatively big having dimensions of 9.0 meters width, 2.4 meters depth, and 2.7 meters height, and thus, can be transported only by large vehicles, which includes trucks and ships. However, more compact versions of MDRUs that can be carried by helicopters or other agile vehicles are being developed. An MDRU contains ICT equipment such as servers and storage devices, power supply, and cooling systems. After arriving to the area, the MDRU connects to the Internet by using the optical fiber cables installed under the ground, which are robust to earthquakes and tsunamis according to the experience of the great east Japan earthquake in 2011. The MDRU has the ability to provide Internet connectivity to approximately 5000 users within a coverage area of 500 meters radius. The total time for setting up the MDRU-based network, which includes MDRU transportation, gateway placement, configuration, and other preparation tasks, is expected to be one to three days after the disaster occurrence. Also, the configured network can be extended to cover a larger area by connecting multiple MDRUs.

After a disaster occurs, people will try to use ICT devices to confirm the safety of their family and friends. Additionally, disaster victims will likely attempt to use mobile applications such as [15] to inform their locations. Therefore, the number of users will increase sharply within a short period of time. Therefore, even though the MDRU only aims to provide basic services such as VoIP, e-mail, and Internet access, guaranteeing adequate network throughput is a major challenge in the MDRU-based network, where the following issues are very important.

- *Spectrum efficiency:* due to the extremely high demand from users, wide frequency bandwidth is required to achieve good throughput. However, the spectrum resource is limited. Thus, it is necessary to use spectrum-efficient methods for the MDRU-based network to increase the number of users that can be satisfied with the available throughput.
- *Energy efficiency:* in a disaster struck area, one of the most critical issues is the power supply because the infrastructure for power supply is not available due to damage, safety reasons, and so forth. Hence, the network has to operate in an area where energy is very limited, which renders using energy-efficient methods for MDRU-based network to be of utmost importance.

However, the approaches about spectrum efficiency alone or energy efficiency alone, which are widely discussed in literature, cannot be used in this kind of network because there is a tradeoff relationship between the two. Therefore, the desired solution for the aforementioned challenges is a method that considers both spectrum and energy efficiencies to maintain high throughput for the MDRU-based network, which is limited in energy and spectrum resources. This objective is referred to as spectrum-energy efficiency in this paper.

IV. System Assumptions and Definitions

In this section, we describe the assumptions for our considered MDRU-based network, define the network model, and introduce the metrics of transmission capability and spectrum-energy efficiency. Transmission capability is used to measure the number of transmissions that a gateway can transmit given the limited energy resource and the distances to its neighbors. Spectrum-energy efficiency is used to measure both spectrum and energy efficiencies, which is calculated as the number of transmissions that can be achieved given the limited frequency and energy resources.

A. System Assumptions

Fig. 1 shows the considered MDRU-based network. Gateways are deployed within the service area radius, i.e., 500 meters, to create an infrastructure to facilitate Internet connectivity to the users in the disaster area. In order to alleviate the power outage in the disaster area, the gateways are equipped with batteries, which are rechargeable with solar panels. All gateways can directly connect to the MDRU by using the Fixed Wireless Access (FWA) [1]. Each gateway can forward packets from its surrounding users to the MDRU. Also, they can connect to other gateways to form a multi-hop network among themselves. The connections between gateways equally share the frequency bandwidth, which is a widely accepted assumption [2], [3], [6]. Since the available energy can be different time to time and between gateways, the MDRU needs to decide which gateway should send packets directly

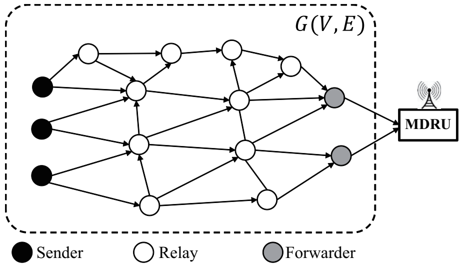

Fig. 2. The categories of nodes in the network $G(V, E)$. In the real network, the forwarders are the gateways that have direct connections with the MDRU in the routing paths.

to the MDRU and which gateway has to send packets by using the multi-hop gateway network in order to efficiently utilize the remaining energy of the gateways. The MDRU uses 920MHz frequency band for controlling gateways, which is different from frequency band for data transmission, to reduce the influence of the controlling transmissions on network performance.

B. Network Model

For the multi-hop network composed of gateways, we define the directed graph $G(V, E)$, where V is the set of gateways and E is the set of directed links between gateways. For a given link $l \in E$, we use $t(l)$ and $r(l)$ to represent the transmitting node and receiving node, respectively. A path L from node s to node d in the network can be defined in two ways:

1) It can be defined as an ordered sequence of nodes $u_1, u_2, u_3, ..., u_n \in V$, where $u_1 = s$ and $u_n = d$.
2) It can be defined as an ordered sequence of links $l_1, l_2, l_3, ..., l_n \in E$, where $t(l_1) = s$, $r(l_n) = d$, and for each $1 \leq i \leq n-1$, $r(l_i) = t(l_{i+1})$.

Also, we use $t(L)$ and $r(L)$ to represent the starting node and the ending node of a path L, respectively.

As shown in Fig. 2, the nodes in the graph are categorized into the following sets:

- Senders (S): the set of nodes that collect data from users and transmit over the multi-hop network.
- Forwarders (F): the set of nodes that receive data from other nodes and directly send the data to the MDRU.
- Relays (R): the set of nodes that do not exists in S or F and are able to relay data from other nodes in S or R.

The three sets satisfy the following equation:

$$S \cup F \cup R = V. \tag{1}$$

We define $\mathcal{L}$, the set of all paths from any sender in S to any forwarder in F:

$$\mathcal{L} = \{L | t(L) \in S, r(L) \in F\} \tag{2}$$

C. Metrics

1) Spectrum Efficiency: Spectrum efficiency of a path L, $\Re_L$, has been defined as the bandwidth-normalized end-to-end rate [6]. It can be calculated as follows:

$$\Re_L = \frac{C_L}{B}, \tag{3}$$

where C_L is the end-to-end achievable rate of path L, and B is the given bandwidth constraint of path L. The unit of $\Re$ is bit per second per hertz (b/s/Hz). With the assumption of equal bandwidth sharing [2], $\Re_L$ can be calculated based on the SNR of links as follows:

$$\Re_L = \min_{l \in L} \frac{1}{|L|} \log(1 + SNR_l). \tag{4}$$

Here, we define the spectrum efficiency of a network $G(V, E)$, $\Re_G$, as the average spectrum efficiency of the paths from the senders to the forwarders.

$$\Re_G = \frac{\sum_{L \in \mathcal{L}} \Re_L}{|\mathcal{L}|}. \tag{5}$$

2) Transmission Capability: In this article, we introduce a metric named transmission capability in order to measure the amount of transmissions given a specific amount of energy. The transmission capability of a node u, Γ_u, is the number of transmissions that node u can transmit to its next hop v with its remaining energy:

$$\Gamma_u = \frac{E_u}{e_{(u,v)}}, \tag{6}$$

where E_u is the remaining energy of node u and $e_{(u,v)}$ is the energy needed to carry out a transmission from node u to node v. In a network with constant transmission power, which is similar to the consideration in [2], [3], [6], Γ_u can be derived as follows:

$$\Gamma_u = \frac{E_u}{e}, \tag{7}$$

where e is the energy for a single transmission.

The transmission capability of a path L, Γ_L, is the minimum transmission capability of nodes in the path:

$$\Gamma_L = \min_{u \in L} \Gamma_u. \tag{8}$$

Here, we define the transmission capability of a network $G(V, E)$, Γ_G, as the total of the transmission capability of paths from senders to forwarders:

$$\Gamma_G = \sum_{L \in \mathcal{L}} \Gamma_L. \tag{9}$$

Based on the transmission capability, the energy efficiency of the network $G(V, E)$, $\mathcal{E}_G$, can be calculated as follows:

$$\mathcal{E}_G = \frac{\Gamma_G}{\sum_{L \in \mathcal{L}} \sum_{u \in L} E_u}, \tag{10}$$

where E_u is the remaining energy of node u. $\mathcal{E}$ is measured in 1 over joule (1/J).

3) Spectrum-Energy Efficiency: In order to measure both spectrum efficiency and energy efficiency of a network, we introduce a metric named spectrum-energy efficiency. The idea of this metric is to measure the energy-normalized spectrum efficiency of a network. The spectrum-energy efficiency of a network $G(V, E)$, Ω_G, can be calculated as the product of spectrum efficiency and energy efficiency of the network:

$$\Omega_G = \Re_G \times \mathcal{E}_G. \tag{11}$$

Since $\Re$ is measured in b/s/Hz and $\mathcal{E}$ is measured in 1/J, the unit of Ω is b/s/Hz/J.

V. Proposed Spectrum- and Energy-Efficient Scheme

Based on the metrics mentioned in the previous section, the problem statement can be defined as follows: *given a gateway network $G(V, E)$, the set of senders S, the set of forwarders F, and the set of relays R, find the routing paths from the senders to the forwarders such that the spectrum-energy efficiency of the network, Ω_G, is maximum.* In order to solve the problem, we proposed a spectrum- and energy-efficient scheme. From each sender, we find k disjoint paths with the highest spectrum efficiency, $\Re$, by iteratively applying the optimal spectrum-efficient routing algorithm [3]. The nodes and links of the resulting paths are used to construct a topology. Then, the max flow algorithm with vertex capacities is applied to the constructed topology, where the capacity of a node u is its transmission capability, Γ_u. Finally, the transmissions from nodes are split according to the result of the max flow algorithm.

The proposed scheme is composed of two phases: topology formation and transmission division. The topology formation phase has two steps:

- From each sender, find the top k spectrum-efficient disjoint paths to the forwarders.
- Construct a new topology using nodes and links of the paths found in the previous step.

After the topology formation phase, transmission division phase carries out following steps:

- Calculate the transmission capabilities of nodes in the topology created from topology formation phase.
- Carry out the max flow algorithm with vertex capacities, where the capacities are the transmission capabilities of nodes.
- Split the transmissions from nodes following the result of max flow algorithm.

The following sub-sections present the details of the above mentioned phases, and the algorithm is described in Procedures 1 and 2.

A. Topology Formation

In our proposal, we first attempt to find top k disjoint paths from each sender to the forwarders in terms of spectrum efficiency. Then, we construct a new topology, $\hat{G}(\hat{V}, \hat{E})$, based on all nodes and links of the resulting paths. Finding one best spectrum-efficient routing path from a sender s to a forwarder d can be formulated as finding the solution for following optimization problem [2].

$$\max_{L \in \mathcal{L}} \Re_L. \tag{12}$$

In order to transfer the problem of finding paths from senders to the forwarders into a one-source one-destination problem, we create an extended graph $G'(V', E')$ from $G(V, E)$. $G'(V', E')$ is created by adding a virtual destination d' to V and adding links from the forwarders to d'. The SNR of the links from the forwarders to d' are set to infinity.

$$V' = V \cup \{d'\} \tag{13}$$

$$E' = E \cup \{l | t(l) \in F, r(l) = d', SNR_l = \infty\} \tag{14}$$

Now the problem becomes finding top k spectrum-efficient disjoint paths from a sender s to the virtual destination d'. The process is carried out as follows. For each routine, we find the most spectrum-efficient path from sender s to the d' in the graph G' by using the optimal algorithm proposed in [3]. All the nodes and links of the resulting path are added to the topology $\hat{G}$. After that, all nodes (except s and d') and links of the resulting path are removed from G'. The routine is repeated until we find k paths or no more path from s to d' can be found. The resulting $\hat{G}$ is the topology we need to find.

Procedure 1 Topology formation

Input: The original gateway network $G(V, E)$, set of senders S, set of forwarders F, and the value of k.
Output: The topology $\hat{G}(\hat{V}, \hat{E})$.

Create a graph $\hat{G}(\hat{V}, \hat{E})$ with $\hat{V} = V$ and $\hat{E} = \{\}$.
Create a graph $G'(V', E')$ with $V' = V$ and $E' = E$.
Add a virtual destination d' to V'.
for all $f \in F$ **do**
  Add link $l_{(f,d')}$ to E' with $SNR_l = \infty$.
end for
for all $s \in S$ **do**
  for $i = 1$ **to** k **do**
    In G', find the best spectrum-efficient path L from s to d' by using the optimal algorithm proposed in [3].
    Add all links of L to $\hat{E}$ except the links from forwarders to d'.
    Remove from E' all links and nodes that belong to L except nodes s and d'.
  end for
end for
return $\hat{G}(\hat{V}, \hat{E})$.

B. Transmission Division

In order to have the best transmission strategy from senders to the forwarders, we apply a *max flow algorithm with vertex capacities* [16] for the topology $\hat{G}$ where the *capacities* are the nodes' transmission capabilities. Therefore, we need to transform the topology $\hat{G}(\hat{V}, \hat{E})$ to a one-source one-destination topology with links' capacities, $G^*(V^*, E^*)$, as shown in Fig. 3. G^* is the extended graph of $\hat{G}$ with a virtual source s^* and virtual destination d^*. Every node v in $\hat{G}$ is transformed to two nodes, v_{in} and v_{out}, in G^*. The set of nodes of G^* can be calculated as follows:

$$V^* = \{s^*, d^*\} \cup \{v_{in}, v_{out} | \forall v \in \hat{V}\}. \tag{15}$$

The set of links in G^*, E^*, has all the links of $\hat{G}$. The capacities of these links are set to infinity. E^* also has links from s^* to all senders S and links from all forwarders F to d^*

Procedure 2 Transmission division

Input: The topology $\hat{G}(\hat{V},\hat{E})$, set of senders S, and set of forwarders F.

Output: The transmission division strategy from the senders to the forwarders.

```
Create a graph G*(V*, E*) with V* = {} and E* = {}.
Add a virtual source s* and a virtual destination d* to V*.
for all v ∈ V̂ do
    Calculate the transmission capability of node v, Γ_v, by using Eq. 7.
    Add two nodes v_in and v_out to V*.
    Add link l_(v_in,v_out) to E* with the capacity of the link cap(l_(v_in,v_out)) = Γ_v.
end for
for all l_(u,v) ∈ Ê do
    Add link l_(u_out,v_in) to E* with the capacity of the link cap(l_(u_out,v_in)) = ∞.
end for
for all u ∈ S do
    Add link l_(s*,u_in) to E* with the capacity of the link cap(l_(s*,u_in)) = ∞.
end for
for all v ∈ F do
    Add link l_(v_out,d*) to E* with the capacity of the link cap(l_(v_out,d*)) = ∞.
end for
Carry out a max flow algorithm for the graph G*(V*, E*) with sender is s* and destination is d*.
return The flow passing through the links of G*(V*, E*).
```

with the capacities of links are infinity. Furthermore, for any corresponding node v of $\hat{G}$, there is a link from v_{in} to v_{out} in G^*, with the capacity is v's transmission capability. The set of links E^* can be calculated as follows:

$$\begin{aligned} E^* = \{&l_{(u_{out},v_{in})} | l_{(u,v)} \in \hat{E}, cap(l_{(u_{out},v_{in})}) = \infty\} \\ &\cup \{l_{(s^*,u_{in})} | u \in S, cap(l_{(s^*,u_{in})}) = \infty\} \\ &\cup \{l_{(v_{out},d^*)} | v \in F, cap(l_{(v_{out},d^*)}) = \infty\} \\ &\cup \{l_{(v_{in},v_{out})} | v \in \hat{V}, cap(l_{(v_{in},v_{out})}) = \Gamma_v\}, \end{aligned} \tag{16}$$

where $cap(l_{(u,v)})$ is the capacity of link $l_{(u,v)}$.

By applying a max flow algorithm for the extended graph G^*, we can calculate the maximum total number of transmissions that the virtual source s^* can send to the virtual destination d^*. This value is exactly equal to the maximum total number of transmissions that senders S can send to the forwarders F. Since the transmission division phase uses only nodes' transmission capabilities, the max flow algorithm is carried out regardless the status of network traffic. After knowing the result of the max flow algorithm, the nodes can split their transmissions following the algorithm's result.

VI. Optimality of k and Scheme Complexity

In this section, we prove that a value of k exists to maximize the spectrum-energy efficiency of a network. Also, the complexity of the proposed algorithm is discussed.

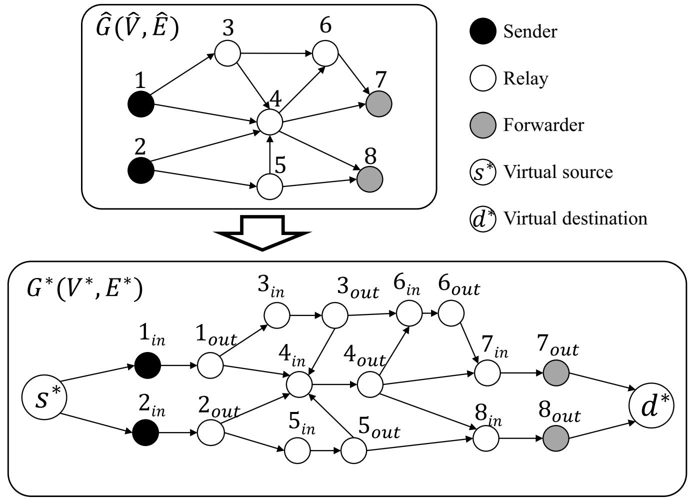

Fig. 3. Transforming the topology $\hat{G}(\hat{V},\hat{E})$ to an extended graph $G^*(V^*,E^*)$. Every node v in $\hat{G}$ is transformed to two nodes, v_{in} and v_{out}, in G^*. A virtual source s^* and a virtual destination d^* are added to G^*.

A. Relationship between k and Spectrum-Energy Efficiency

In order to analyze the relationship between the value of k and the spectrum-energy efficiency, we first analyze the relationship between k and the two metrics, spectrum efficiency and transmission capability.

Lemma 1: Given a network $G(V,E)$, the average spectrum efficiency of k paths from a sender to the forwarders is monotonically decreasing along with the increase of k.

Proof: Assume that $\{L_1, L_2, ..., L_i, ..., L_k\}$ are the top k spectrum-efficient paths from a sender s to the virtual destination d', which are found by using the Procedure 1. Since in every loop i, $1 \le i \le k$, we find the ith best routing path from s to d' in the current graph and after that remove all nodes and links of path L_i, the spectrum efficiency of the paths will satisfy $\Re_{L_1} \ge \Re_{L_2} \ge ... \ge \Re_{L_k}$. Thus,

$$\sum_{i=1}^{k} \Re_{L_i} \ge k\Re_{L_{k+1}} \tag{17}$$

$$k\sum_{i=1}^{k} \Re_{L_i} + \sum_{i=1}^{k} \Re_{L_i} \ge k\sum_{i=1}^{k} \Re_{L_i} + k\Re_{L_{k+1}} \tag{18}$$

$$(k+1)\sum_{i=1}^{k} \Re_{L_i} \ge k\sum_{i=1}^{k+1} \Re_{L_i} \tag{19}$$

$$\frac{1}{k}\sum_{i=1}^{k} \Re_{L_i} \ge \frac{1}{k+1}\sum_{i=1}^{k+1} \Re_{L_i}. \tag{20}$$

Therefore, the average spectrum efficiency of the paths will monotonically decrease when k increases. ■

Lemma 2: Given a network and the information about the energy level of nodes, the total number of transmissions that the senders can transmit to the forwarders is monotonically increasing along with the increase of k in the topology formation phase.

Proof: Assume that $\hat{G}_k(\hat{V}_k, \hat{E}_k)$ is the topology formed by using the Procedure 1 with a given value of k. Since in

TABLE I
EVALUATION SETTINGS

Parameter	Value
MDRU's coverage radius	500 m
Number of gateways	100
Gateway distribution	Uniform
Number of senders	5
Number of forwarders	5
Number of disjoint paths (k)	$1 \sim 5$
Network SNR	$30 \sim 40$ dB
Pathloss exponent	2
Energy consumed per transmission	20 mJ
Average gateways' remaining energy	$1000 \sim 2000$ mJ
Number of different network realizations	1000

every loop, we attempt to find one more path from s to d' and add the nodes and links from the path to the topology, $\hat{V}_k \subseteq \hat{V}_{k+1}$ and $\hat{E}_k \subseteq \hat{E}_{k+1}$. Accordingly, in the transmission division phase, G^*_{k+1} will have more nodes and links than G^*_k: $V^*_k \subseteq V^*_{k+1}$ and $E^*_k \subseteq E^*_{k+1}$. The total number of transmissions that senders can transmit to the forwarders is the flow that the virtual source s^* can send to the destination d^* in Procedure 2. Therefore, the flow calculated from G^*_{k+1} will be greater or equal the value calculated from G^*_k. In other words, the total number of transmissions that the senders can transmit to the forwarders monotonically increases when the value of k increases. ■

Theorem 1: Given a network $G(V, E)$, set of senders S, set of forwarders F, and the information about the energy level of nodes, there exists a value of k that maximizes the spectrum-energy efficiency of the network.

Proof: Let $\Re(k)$ be the average spectrum efficiency of the paths from the senders to the forwarders, $\Gamma(k)$ is the total number of transmissions that the senders can send to the forwarders, and $\mathcal{E}(k)$ is the network energy efficiency, the spectrum-energy efficiency of the network is calculated as follows:

$$\begin{aligned}\Omega(k) &= \Re(k) \times \mathcal{E}(k) \\ &= \Re(k) \times \frac{\Gamma(k)}{\sum_{L \in \mathcal{L}} \sum_{u \in L} E_u},\end{aligned} \tag{21}$$

where E_u is the remaining energy of node u and $\mathcal{L}$ is the set of all paths from senders to forwarders. When k increases, the total number of paths from senders to forwarders increases. Thus, $\sum_{L\in\mathcal{L}} \sum_{u\in L} E_u$ monotonically increases with the increase of k. According to Lemmas 1 and 2, $\Re(k)$ monotonically decreases and $\Gamma(k)$ monotonically increases with the increase of k. Also, k is bounded by $|F|$. Therefore, there exists a value of k that maximizes the value of $\Omega(k)$. ■

B. Complexity

In Procedure 1 at line 9, we use the optimal routing algorithm proposed in [3] which has the complexity of $O(|V|^2|E|)$, where V and E are the set of nodes and the set of links in the network, respectively. Therefore, the complexity of the topology formation phase is $O(k|S||V|^2|E|)$, where S is the set of senders and k is the number of paths we want to find from each sender to the forwarders. As shown in Procedure 2, we use a max flow algorithm for the extended graph. The complexity of the max flow algorithm is $O(|V|^2|E|)$ when using *Dinitz blocking flow algorithm* [17], or $O(|V|^3)$ in case of *push-relabel maximum flow algorithm* [18]. Hence, the complexity of our proposed spectrum- and energy-efficient scheme is $O(k|S||V|^2|E|)$.

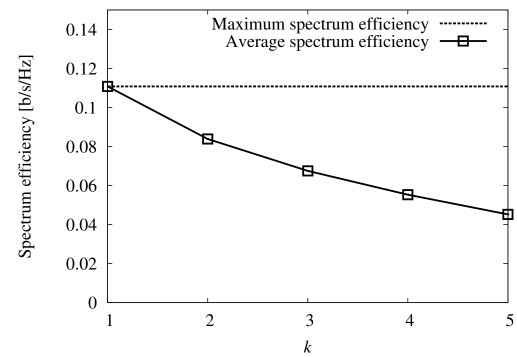

Fig. 4. Average spectrum efficiency of the network ($\Re_G$) with different values of k.

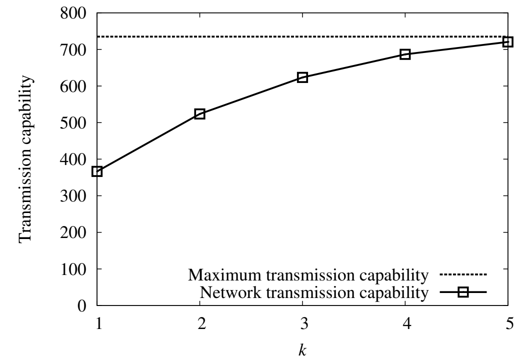

Fig. 5. Transmission capability of the network (Γ_G) with different values of k.

VII. Performance Evaluation

In this section, we evaluate the performance of our proposed spectrum- and energy-efficient scheme in an MDRU-based network by using extensive computer simulations. In order to validate the analysis results, we confirm the relationship between the value of k and the three metrics of the network, namely, spectrum efficiency, transmission capability, and spectrum-energy efficiency. Furthermore, the proposed scheme is compared with the optimal spectrum efficiency and the optimal transmission capability methods.

A. Simulation Settings

Table I describes the settings of our simulation. In the coverage area of the MDRU, which has a radius of 500 meters, 100 gateways are uniformly distributed. This is a large number of gateways because with 100 gateways, approximately 4000 users can be serviced (given that each gateway can provide

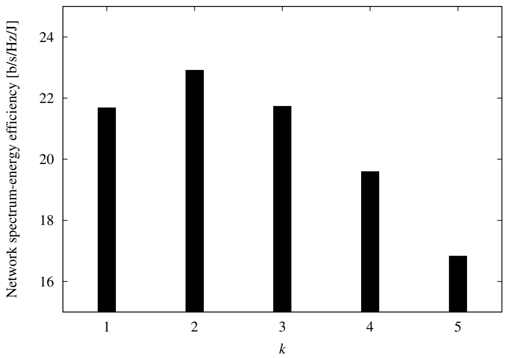

Fig. 6. The optimal value of k to maximize spectrum-energy efficiency (Ω_G) in simulated topologies.

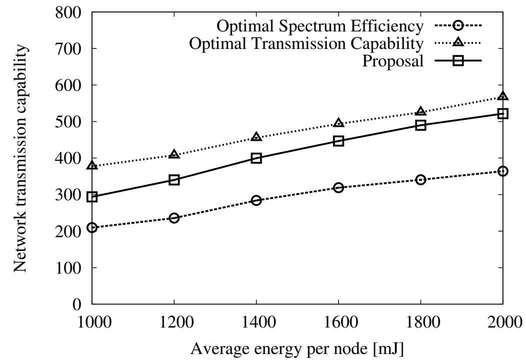

Fig. 8. Transmission capability of the network (Γ_G) with different values of the average energy per node.

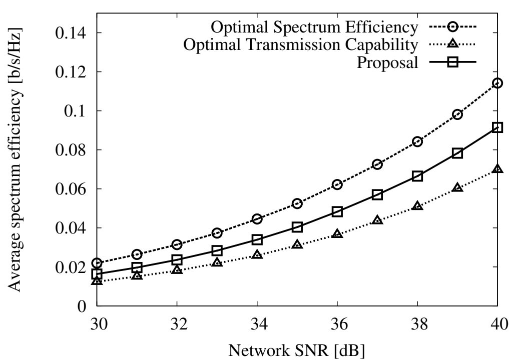

Fig. 7. Average spectrum efficiency of the network ($\Re_G$) with different values of network SNR.

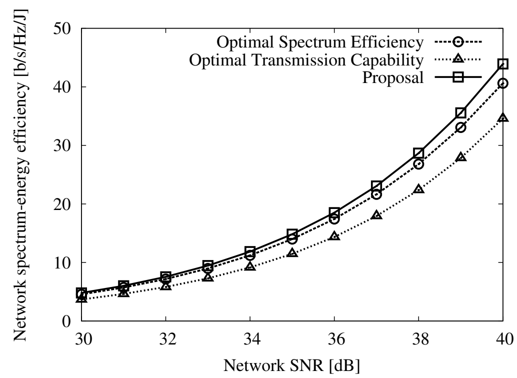

Fig. 9. Network spectrum-energy efficiency (Ω_G) with different values of network SNR.

service for up to 40 users). Each gateway has a battery with the average remaining energy varying from 1000 to 2000 mJ. The energy consumed per transmission is set to 20 mJ. Similar to the works in [2], [3], [6], the additive white Gaussian noise (AWGN) channel model is used in our simulation to calculate the spectrum efficiency of paths and the network. As mentioned in Section IV-A, the MDRU can determine the role of each gateway, which can be either a sender, a relay, or a forwarder, in the gateway network. Categorizing the nodes into senders, forwarders, and relays is outside the scope of this paper. For the simulation, we choose five gateways with the smallest amount of remaining energy to be senders and five gateways with the highest amount of remaining energy to be forwarders. The packets from senders go through the gateway network to the forwarders before arriving the MDRU. Since we find k disjoint paths from each sender to the MDRU to build a topology, the value of k is bounded by the number of forwarders, which is 5 in the simulation settings. The remaining energy of gateways are randomly uniform. The experiment simulations are executed 1000 times, each with a different topology.

B. The Relationship among k, Spectrum Efficiency, Transmission Capability, and Spectrum-Energy Efficiency

Fig. 4 demonstrates the relationship between the value of k and the average spectrum efficiency of the network. Note that $k = 1$ means that we try to find only the optimal path from each sender, which has the maximum spectrum efficiency. Therefore, when $k = 1$, our result in terms of spectrum efficiency is the same as the maximum possible value. The figure shows that when k increases, the average spectrum efficiency decreases. The reason behind this phenomenon is that paths with lower value of spectrum efficiency are used in the transmission division phase of the proposed scheme. The result of this figure validates the conclusion of Lemma 1.

Fig. 5 shows how the transmission capability of the MDRU-based network changes with different values of k. As demonstrated in the figure, the optimal spectrum-efficient method, which can be considered as the case $k = 1$, achieves only about 50 percent of the maximum transmission capability. When k increases to 5, the network transmission capability becomes close to the maximum value. As be clearly seen from the result, the transmission capability improves as k increases. The reason is that the number of paths participating in transferring data from the senders to the forwarders increases, which results in a higher total number of transmissions that can be conducted. This result validates the conclusion of Lemma 2. Figs. 4 and 5 prove that when k changes, the average spectrum efficiency and the transmission capability of the network change with opposite trends. Therefore, when we consider both spectrum efficiency and transmission capability of the network, the optimal value of k exists.

Fig. 6 shows the change of the network spectrum-energy efficiency when the value of k changes in simulated topologies.

The figure indicates that the optimal value of k that maximizes the spectrum-energy efficiency is 2. Note that the optimal value of k in this figure is the average value after simulating many topologies by using considered parameters. Different realizations of the network can have different optimal values of k.

C. Evaluating the Improvement in Spectrum-Energy Efficiency

In order to conduct comparisons with traditional methods, i.e., the methods that optimize spectrum efficiency and transmission capability, respectively, we dynamically choose the value of k for our proposed scheme to optimize the spectrum-energy efficiency of each specific topology. Fig. 7 demonstrates the change of network spectrum efficiency when the network SNR changes for our proposed scheme compared to the traditional methods. According to the results, the spectrum efficiency of our proposal is less than that of the optimal spectrum-efficient method but more than that of the optimal transmission capability method. This occurs due to the fact that our proposed scheme employs the top k spectrum-efficient paths that have a lower average spectrum efficiency compared with the one optimal spectrum efficient path.

Fig. 8 shows the network transmission capability of the network for different values of average remaining energy per node. The figure demonstrates that the transmission capability of proposed scheme is between the two traditional methods. The reason is the optimal transmission capability method only considers transmission capability of nodes while our proposal considers both transmission capability and spectrum efficiency.

Regarding the most important metric in this paper, spectrum-energy efficiency, Fig. 9 indicates performance of the proposed scheme compared to traditional methods. According to the result, our proposal achieves highest spectrum-energy efficiency compared to the optimal spectrum efficiency and optimal transmission capability methods.

In conclusion, the results of the computer simulations show that our method can improve the spectrum-energy efficiency of the MDRU-based network by choosing top k spectrum-efficient paths.

VIII. Conclusion

The lack of spectrum and energy resources is a major problem in MDRU-based networks, where the throughput requirement is very high. Current works in literature only consider the problems of spectrum and energy efficiencies separately, despite the fact that they are conflicting objectives. Hence, we proposed a scheme to improve the utilization of both spectrum and energy resources to increase performance in the gateway portion of the MDRU-based network. The proposal consists of two phases, namely, topology formation and transmission division. The topology formation phase constructs a topology composed of gateways and links that belong to the top k spectrum-efficient disjoint paths. The resulting topology is used by the transmission division phase to split the transmissions from the sender gateways to the MDRU through the forwarder gateways. The splitting is conducted via the max flow algorithm with vertex capacities, which are the transmission capabilities of the gateways in the resulting topology. Unlike the previous works in spectrum efficiency, the proposal can be used for multi-sender multi-receiver topologies. We defined a new metric, spectrum-energy efficiency, that reflects both spectrum and energy efficiencies of the network. Through analyses, we proved that there exists a value of k such that the spectrum-energy efficiency of a given topology is maximized. Our experimental results confirmed our analyses' findings. Furthermore, simulations showed that by appropriately selecting a value of k, the proposal can improve the spectrum-energy efficiency compared to traditional approaches.

Acknowledgement

Part of this work was conducted under the national project, "Research and development of "Movable ICT-Units" for emergency transportation into disaster-affected areas and multi-unit connection" supported by the Ministry of Internal Affairs and Communications (MIC), Japan.

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Thuan Ngo received his B.E. degree with honors in information technology from Hanoi University of Science and Technology, Vietnam, in 2008, and his M.S. degree in information sciences from Tohoku University, Japan, in 2011. He is currently pursuing a PhD in information sciences at the Tohoku University. His research interests include mobile ad hoc networks, wireless mesh networks, disaster resilient networks, spectrum efficiency, and energy efficiency. He received the Gold Medal of World Intellectual Property Organization for Best Young Inventor in 2009 and the IEEE VTS Japan Paper Award in 2010.

Hiroki Nishiyama is an Associate Professor at the Graduate School of Information Sciences (GSIS), Tohoku University, Japan. He received his M.S. and PhD in Information Science from Tohoku University, Japan, in 2007 and 2008, respectively. He has published more than 100 peer-reviewed papers including many high quality publications in prestigious IEEE journals and conferences. He was awarded Best Paper Awards from many international conferences including IEEE's flagship events, such as the IEEE Global Communications Conference in 2013 (GLOBECOM'13), GLOBECOM'10, and the IEEE Wireless Communications and Networking Conference in 2012 (WCNC'12). He was also a recipient of the IEEE Communications Society Asia-Pacific Board Outstanding Young Researcher Award 2013, the IEICE Communications Society Academic Encouragement Award 2011, and the 2009 FUNAI Foundation's Research Incentive Award for Information Technology. He has served as a Co-chair for Cognitive Radio and Networks Symposium of IEEE International Conference on Communications 2015 (ICC'15), a Co-chair for Selected Areas in Communications Symposium of IEEE ICC'14, an Associate Editor for IEEE Transactions on Vehicular Technology, an Associate Editor for Springer Journal of Peer-to-Peer Networking and Applications, and the Secretary of IEEE ComSoc Sendai Chapter. His research interests cover a wide range of areas including satellite communications, unmanned aircraft system (UAS) networks, wireless and mobile networks, ad hoc and sensor networks, green networking, and network security. One of his outstanding achievements is Relay-by-Smartphone, which makes it possible to share information among many people by using only WiFi functionality of smartphones. He is a Senior Member of the IEEE, as well as a member of Institute of Electronics, Information and Communication Engineers (IEICE).

Nei Kato received his Bachelor Degree from Polytechnic University, Japan, in 1986, M.S. and Ph.D. Degrees in information engineering from Tohoku University, in 1988 and 1991 respectively. He joined Computer Center of Tohoku University as an assistant professor in 1991, and was promoted to full professor position with Graduate School of Information Sciences, Tohoku University, in 2003. He became a Strategic Adviser to the President of Tohoku University in 2013. He has been engaged in research on computer networking, wireless mobile communications, satellite communications, ad hoc & sensor & mesh networks, smart grid, and pattern recognition. He has published more than 300 papers in peer-reviewed journals and conference proceedings. He currently serves as a Member-at-Large on the Board of Governors, IEEE Communications Society, the Chair of IEEE Ad Hoc & Sensor Networks Technical Committee, the Chair of IEEE ComSoc Sendai Chapter, the Associate Editor-in-Chief of IEEE Internet of Things Journal, an Area Editor of IEEE Transactions on Vehicular Technology, an editor of IEEE Wireless Communications Magazine and IEEE Network Magazine. He has served as the Chair of IEEE ComSoc Satellite and Space Communications Technical Committee(2010-2012), the Chair of IEICE Satellite Communications Technical Committee(2011-2012), guest-editor of many IEEE transactions/journals/magazines, symposium co-chair of GLOBECOM07, ICC10, ICC11, ICC12, Vice Chair of IEEE WCNC10, WCNC11, ChinaCom08, ChinaCom09, Symposia co-chair of GLOBECOM12, TPC Vice chair of ICC14, and workshop co-chair of VTC2010. His awards include Minoru Ishida Foundation Research Encouragement Prize(2003), Distinguished Contributions to Satellite Communications Award from the IEEE ComSoc, Satellite and Space Communications Technical Committee(2005), the FUNAI information Science Award(2007), the TELCOM System Technology Award from Foundation for Electrical Communications Diffusion(2008), the IEICE Network System Research Award(2009), the IEICE Satellite Communications Research Award(2011), the KDDI Foundation Excellent Research Award(2012), IEICE Communications Society Distinguished Service Award(2012), five Best Paper Awards from IEEE GLOBECOM/WCNC/VTC, and IEICE Communications Society Best Paper Award(2012). Besides his academic activities, he also serves on the expert committee of Telecommunications Council, Ministry of Internal Affairs and Communications, and as the chairperson of ITU-R SG4 and SG7, Japan. Nei Kato is a Distinguished Lecturer of IEEE Communications Society and a co-PI of A3 Foresight Program funded by Japan Society for the Promotion of Sciences(JSPS), NSFC of China, and NRF of Korea. He is a fellow of IEEE and IEICE.

Toshikazu Sakano received his B.E., M.E. and Ph.D. degrees in electronics engineering from Tohoku University, Sendai, Japan, in 1985, 1987 and 1998, respectively. In 1987, he joined Nippon Telegraph and Telephone Corporation (NTT) Laboratories, Yokosuka, Japan, and is now a Senior Research Engineer and Supervisor there. Since joining NTT Labs., he has been active in the several research and development fields including optical signal processing for high-performance computer systems, Super-High-Definition (SHD) imaging system, photonic network architectures, and large capacity optical transmission systems. After the Great East Japan Earthquake in March, 2011, he has engaged in the R&D on resilient ICT infrastructure available in disaster situations. He received the Young Engineer Award from IEICE of Japan in 1995. He is a member of IEEE, senior members of OSA and IEICE.

Atsushi Takahara received the B.S., M.S., and Dr. of Engineering degrees from Tokyo Institute of Technology in 1983, 1985, and 1988, respectively. He joined NTT LSI Laboratories in 1988 and has been researching formal methods of VLSI design, reconfigurable architectures, and IP processing. From 2003 to 2008, he was the director of Service Development & Operations Department, Visual Communications Division, NTT Bizlink Inc to develop and operate an IP-based visual communication service. From 2008 to 2011, he was the Executive Manager of Media Innovation Laboratory in NTT Network Innovation Laboratories. Since 2011, he has been the Director of NTT Network Innovation Laboratories. His current research interests are in IP networking for real time communication applications and IP infrastructure technologies. He is a member of IEEE, ACM, IEICE, and IPSJ.