A PRACTICAL ROUTE RECONSTRUCTION METHOD FOR WI-FI MESH NETWORKS IN DISASTER SITUATION WITH SPARE AP

Erdenetuya Dorj[1], Jovilyn Fajardo[2] and Kazuhiko Kinoshita[3]

[1]Department of Information Science and Intelligent Systems, Tokushima University, Japan
[2]Space-Time Engineering LLC, Japan
[3]Graduate School of Technology, Industrial and Social Science, Tokushima University, Japan

ABSTRACT

Computer networks comprise essential infrastructure in modern society and must function even in a disaster situation. Therefore, fault-tolerant networks are being actively studied. Disaster information systems, however, suffer from two main issues: lack of their utilization in peacetime and the difficulty for a non-expert to manage them should a disaster strike. Therefore, we place special emphasis on the development of a reliable network infrastructure that can function during both normal and disaster times, using a Wi-Fi-based wireless mesh network. In a large-scale disaster situation, our goal is to identify a way to reconstruct the mesh network by adding the minimum number of spare access points (APs) to ensure the reachability of all mesh routers to the backbone network. Furthermore, we consider that only public workers without any experience with wireless communication technologies must decide upon the adequate locations for spare APs and install them. Both of simulation experiments and field trial prove the effectiveness of the proposed methods.

KEYWORDS

Wi-Fi, wireless mesh network, disaster, rerouting

1. INTRODUCTION

Over the course of history, the world has endured natural disasters such as hurricanes, earthquakes, floods, and tsunamis, causing numerous casualties, damage to properties, and destruction of millions of homes and businesses. If the disaster-affected area had been accurately defined and information sharing in the vicinity was possible, recovery/response would likely have been much improved. Therefore, researchers have been studying the deployment of robust network infrastructure for disaster information systems for more than a century, the goal being to transmit information at all stages of an emergency, including disaster mitigation and citizen preparation for the same [1-2].

For this purpose, wireless mesh networks (WMNs) have become a key practical communication solution to provide higher reliable network infrastructure for numerous applications in emergency scenario. By adopting the key advantages of ad hoc networking, such as dynamic self-forming, self-healing, and self-organization, WMNs can accomplish flexible network architecture, easy deployment and configuration, network topology reliability and survivability as well as mesh connectivity [1-8]. Furthermore, in WMNs with multi-radio and multi-channel interfaces, using

DOI: 10.5121/ijwmn.2019.11301

directional antenna considerably improves the spatial reuse of wireless network and achieve high network throughput [9-10].

However, these kinds of ad-hoc mesh networks are considered to be unpractical infrastructure since the ad-hoc mode does not possess IEEE 802.11 control and encryption frames [17]. Further, as per [17], [11], and [12], smartphones do not support the 802.11 ad-hoc mode, and thus, additional mobile ad hoc network (MANET) protocols are preferred for routing and address resolution. Another significant problem in terms of the use of the ad-hoc mode is that mobile device vendors and operating system developers, especially Wi-Fi alliances, pay much attention to the development of 802.11 infrastructure mode-based devices, considering the ease of practical use and cost reduction. For these reasons, we focus on a Wi-Fi mesh network based on the IEEE 802.11 infrastructure mode as the base for a disaster information system.

When a large-scale disaster occurs, some mesh routers may become isolated from the backbone network. Thus, our goal is to identify an effective way to reconstruct the WMN. By interviewing public workers, we clarified the following requirements/constraints with regard to the mesh network recovery. (1) Spare APs and portable batteries are limited. (2) Firefighters and/or members of the self-defence forces surveying disaster-affected areas only can identify locations for spare AP placements. (3) Public workers, who may not be well-versed with wireless communications technologies, can nonetheless install the spare AP(s). Considering these requirements/constraints, we propose a practical method to reconstruct the network infrastructure using spare APs, allowing the unreachable routers to restore their connections to the wired network easily.

The remainder of this paper is organized as follows. In Section 2, we introduce some related works. In Section 3, we discuss the system architecture and discuss problematic issues. We also highlight the proposed reconstruction method using spare APs for the devised architecture in section 4. We evaluate the proposed method using simulation experiments in Section 5 and field trial experimentation in Section 6, respectively, to show its effectiveness. Finally, section 7 concludes the paper with a summary of our contributions and offers recommendations for future work.

2. RELATED WORK

Many previous works have made large contributions to the development of WMNs for use in the unlicensed spectrum and at low cost based on the IEEE 802.11 ad-hoc mode by considering multiple characteristics such as network design, scalability, quality of service, and fault tolerance. In particular, these features make the use of WMNs advantageous in terms of low upfront cost, easy network maintenance, robustness, and reliable service coverage. For example, [1] presented the results of a real mesh network infrastructure connected to the Internet via a wired backbone in test bed environment deployed on a campus to improve ad-hoc WMN survivability in a disaster scenario. [2] showed that a multi-channel and multi-radio ad-hoc WMN can achieve high capacity compared to dual- and single-radio WMNs. Previous studies on WMN design and its various uses not only discussed but also recommended various ways to build a robust city-wide WMN infrastructure by using ad-hoc mode-based network infrastructure for an urban area by studying a broad range of WMN characteristics such as coverage, connectivity, planning, multipath effect, and interference [3-8]. [4] addressed two issues, namely, channel assignment and load balancing in multi-channel WMN architecture based on the IEEE 802.11 ad-hoc mode. They suggested a distributed routing/channel assignment algorithm, which includes WMN recovery using the local recovery procedure without adding other backup nodes. [9] and [10] showed improvements in the performance of WMNs using directional antennas. Moreover, [10] reduced the total broadcast delay using multi-rate WMN, and presented improvements in dynamic antenna beams. However, the biggest challenge pertaining to the Wi-Fi mesh network based on the IEEE 802.11 infrastructure mode is resolving impracticalities such as the lack of 802.11 control frames and connectivity availability to unlicensed mobile devices (e.g., smartphones, laptops, and so on).

For these reasons, we focus on the studies by [11] and [12], which presented experimental results on IEEE 802.11 infrastructure mode-based WMNs. [11] addressed client-side transparency characteristics in an IEEE 802.11 infrastructure mode-based mesh networking architecture called iMesh, in which APs not only build multi-hop interconnections between each other with wireless distribution system (WDS) links, but also provide seamless network connection clients. Specifically, typical mobile clients do not run in ad-hoc networks but perform in the 802.11 infrastructure mode. The experimental results prove that mobile client nodes create their optimal paths via handoffs between six AP nodes in the IEEE 802.11b-based mesh network. [12] proposed a mobile ad-hoc Wi-Fi (MA-Fi) architecture comprising a two-tier hierarchy of router nodes (RONs) and station nodes (STAs). RONs are responsible for assigning the access point (AP) mode and station (STA) mode to two virtual interfaces on the single physical radio interface. Furthermore, RONs such as notebooks or netbooks serve as APs for other station devices in the region by using their AP mode, whereas their STA mode also establishes association with other RONs to interconnect networks. The STA can only work as a client. Consequently, multi-hop mobile ad-hoc networks based on the 802.11 infrastructure mode can be formed by considering the mobility characteristics of the RONs and STAs. In the performance evaluation, MA-Fi outperforms ad-hoc mode communication and offers throughput comparable to Wi-Fi even over multiple hops.

According to the assumption of a practical rerouting method for a Wi-Fi mesh network based on the IEEE 802.11 infrastructure mode in a disaster situation, the investigations and implementation were conducted with reconstruction methods for WMNs working in either ad-hoc mode or infrastructure mode. Basically, a fault tolerant system has major three steps including fault detection, diagnosis and recovery in case of link and node failure. [13] and [14] showed reconfiguration of WMNs using the link recovery techniques by monitoring link quality, whereas another [15] reviewed fault tolerance issues, such as link failures in different types of WMNs. Additionally, [15] showed the fault tolerant base station planning algorithm in WMNs and placed base stations on adequate locations based on radio coverage information. For experiment studies, [16] and [18] showed that distributed wireless mesh network architecture in ad-hoc mode can be performed successfully in disaster situations and some isolated nodes were connected to the backbone network using the small unmanned aerial system (UAS). In [17], 802.11 infrastructure mode based MANET routers were designed and implemented for an emergency fire response system working in a disaster system.

Although past research revealed the many advantages of the WMN network infrastructure with regard to the capabilities of the 802.11 infrastructure mode, some vital capabilities of ad hoc mesh networking, such as dynamical self-forming and self-configuration, have not been implemented. Therefore, we propose practical implementation for reconstructing WMNs with a directional antenna using spare APs.

3. NETWORK MODEL

3.1. Assumed Network

In this section, we present the network model devised for this study. It consists of mesh routers equipped with two radio interfaces, which can connect to adjacent mesh routers using directional antenna with a beamwidth of 60°. Note that we assume the use of a kind of patch antenna due to cost constraints. Each radio interface supports the IEEE 802.11 infrastructure mode, and thus, it works in either the AP or the STA mode. While most mesh routers can be installed on traffic and street lights, a few of them can be installed in public facilities such as government offices, police stations, and hospitals, which are considered as gateways (GWs) for providing connectivity to the management server (MS) in the backbone network via wired connections, as shown in Figure 1.

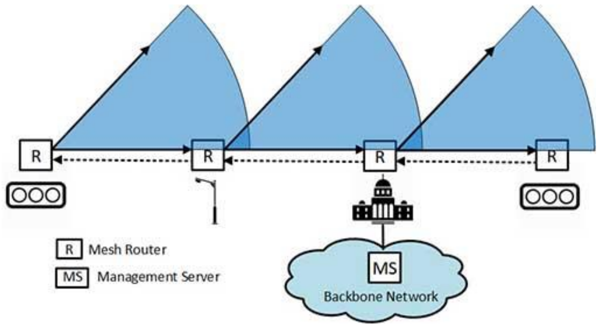


Figure 1. System architecture

More specifically, we show an assumed network model in Figure 2. It is a Wi-Fi multi-radio mesh network architecture based on the IEEE 802.11 infrastructure mode, consisting of multi-channel mesh routers which are connected to a wired backbone network through a set of GWs equipped with either wireless or wired network interface controllers [1-8]. The mesh routers maintain themselves autonomously and provide a Wi-Fi service for user terminals without any special configuration and software. There are multiple GWs, denoted by GW1 and GW2, which can transmit data packets between sets of mesh routers and the MS. All the mesh routers are placed at the same distance from each other. Each of them has two radio interfaces equipped one or two directional antennas. The red and blue arrows indicate the orientations of directional antennas at radio interfaces 1 and 2, respectively. The same coloured antennas are neighbours connected to the same interface. In addition, the number of channels each router uses simultaneously is equal to the number of equipped radio interfaces. Consequently, the network, as a whole, uses three different channels configured in constant conditions. In normal situations, all the mesh routers are reachable to the MS.

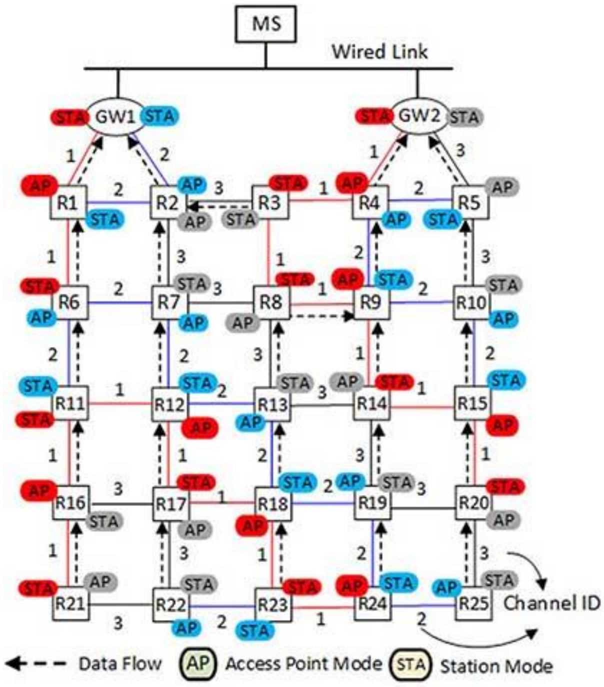


Figure 2. Assumed network model

One or more feasible paths must be suggested for each mesh router to reach one or multiple GWs. Weighted cumulative expected transmission time (WCETT) is proposed as a link metric for WMNs, which can be changed depending on the bandwidth, error rate, and channel diversity in a path [19]. Each mesh router could select a primary path with the lowest sum of the WCETT as its best route in its routing table, and others as feasible paths in the topology table. Thereafter, a mode selection procedure should be performed automatically in order to assign either the AP or the STA mode on their interfaces and then feasible interfaces. Consequently, each neighbour table is updated with the selected mode information and the convergence process is completed. Figure 2 also shows the selected mode for both primary and feasible links of each mesh router, denoted by the same colour as the link colour. The dashed lines denote data flows from a mesh router to a GW, so that we may confirm that the network topology has been converged.

3.2. Problem Formulation

Now, we have a Wi-Fi mesh network modelled as a connected graph $G(V, E)$ comprising a set of wireless routers $V = \{v_0, v_1, \ldots, v_N\}$, and $E = \{e_{ij}\}$ is a set of links. An edge $e_{ij} \in E$ between nodes $v_i, v_j \in V$ exists if and only if they are in their transmission area each other. Serving GWs, denoted as GW_l , can provide primary routes for a set of routers to reach the MS. Each node has r radio interfaces equipped with z directional antennas, which are used for establishing point-to-point communication with their neighbour nodes. Moreover, for the assumed network infrastructure, each directional antenna has a fixed beamwidth θ. Then, a beam can be uniquely described by two parameters: its transmitting node and its orientation [12]. In the case of a disaster event, a large number of mesh routers stop functioning and/or some directional antennas lose their original angle. Thus, we consider restoring a Wi-Fi mesh network where one or more mesh routers have lost their connectivity to the MS by using GWs. According to Figure 3, V is divided into three sets: C, U and F. Routers in C can communicate with the MS. U consists of a set of unreachable mesh routers that have lost their primary routes to their serving GWs. F is a set of failed nodes. U is divided into some isolated parts U_i.

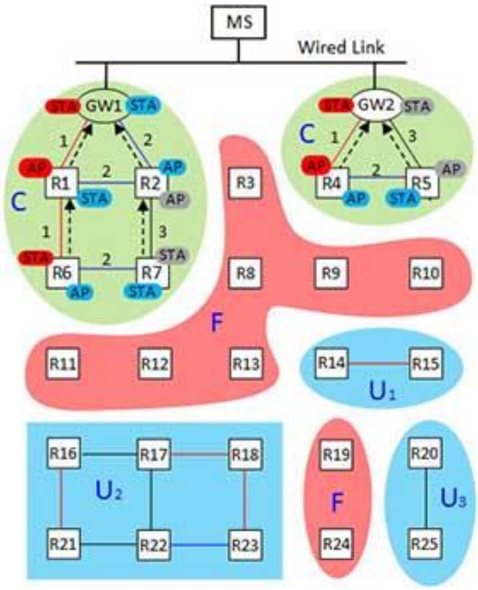


Figure 3. Failure situation

We assume that local recovery cannot be performed to provide communication for an unreachable router to reach a connected area. In other words, one or more unreachable routers cannot be connected to a router in a connected area. Therefore, we aim to restore the Wi-Fi mesh network by establishing network connectivity from unreachable mesh routers to their serving GWs using the minimum number of spare APs. Consequently, our core problem lies in making all the nodes in the set of $V \setminus F \cup U \cup B (= C \cup U \cup B)$ reachable, where B denotes the set of spare APs.

To achieve this goal, we need to overcome the following two main challenges. One is to determine optimal locations where spare APs can be installed. The other is to reconstruct a fully converged Wi-Fi mesh network in which each mesh router has at least one primary route to a serving GW with the automatic mode selection mechanism.

We also assume that the public workers are not experienced in wireless communication technology. Thus, they can only place a spare AP at the recommended location. This is a reasonable assumption as per the interviews conducted with public officers. Therefore, we do not use directional antennas with spare APs. In other words, a spare AP is not able to make neighbouring with any other spare APs, since their interfaces should work in the AP mode.

Formally, each spare AP must connect to at least one router in C and at least one router in U. We aim to not only determine the adjacent nodes and their routing paths to the wired network, but also to assign either the AP mode or the STA mode, as far as possible, at their primary links. On the other hand, we do not focus on channel assignment. Thus, all interfaces are supposed to use the same channel hereafter.

4. Proposed Method

In this section, we propose a route reconstruction method for restoring Wi-Fi mesh networks. It has two phases; the connectivity restoration phase and the rerouting phase. Fault management approaches for WMNs are deployed in order to recover link or node failures [13-15]. Thus, we assume three major steps of the fault management approach such as fault detection, diagnosis and recovery in the proposed method. connectivity restoration phase is responsible for fault detection and diagnosis. A spare AP is installed at an adequate point in the connectivity restoration phase. Finally, in the rerouting phase, one or more routes are reconstructed from isolated routers to the MS.

4.1. Connectivity Restoration Phase

For fault detection in connectivity restoration phase, public workers, typically firefighters, trace RSSI information from unreachable routers using their smartphones while going through a disaster area for investigation and/or rescue [14]. The place where RSSI information is collected is defined as an *anchor point*. For the node $v_i \in (C \cup U)$, several anchor points $a_{ix}(x = 1,2, \dots)$ are assumed to be obtained. In other words, we aim at detecting whether routers in an isolated area are alive or not. All the collected RSSI information is directly sent to the MS and then first step finishes.

In the next step for fault diagnosis, the MS only executes an RSSI-based ranging and localization algorithm based on the collected data. Consequently, we estimate the transmission range of the routers and find overlapping transmission ranges between unreachable and reachable routers in order to determine adequate locations for spare APs.

The RSSI ranging and localization algorithm uses a database which mainly contains RSSI values of the unreachable routers and their known location information. Equation (4.1) shows a path loss model. In this equation, $P_L(d)$ indicates the path loss of the receiving signal when the measuring distance is d [m]. It indicates the absolute power in dBm. d_0 [m] is the reference distance at which the reference loss is calculated. β is the path loss exponent. In a free space environment, β is set at 2 [20-22]. δ is the random shadowing effect in dB, which may have a different value for each anchor point.

$$P_L(d) = P_L(d_0) + 10\beta \log\left(\frac{d}{d_0}\right) + \delta \quad (4.1)$$

Equation (4.2) shows the manner of calculation for the path loss for anchor point x.

$$P_L(d_x) = P_L(d_0) + 10\beta \log\left(\frac{d_x}{d_0}\right) + \delta_x \quad (4.2)$$

In Equation (4.3), P_x and P_t refer to the signal strength at anchor point x and the signal transmission power, respectively.

$$P_t - P_L(d_x) = P_x \quad (4.3)$$

Using the measured RSSI values of each anchor point and P_t (which is assumed to be given), $P_L(d_x)$ can be calculated. As a result, δ_x can be estimated using Equation (4.4).

$$P_L(d_x) - P_L(d_0) - 10\beta \log\left(\frac{d_x}{d_0}\right) = \delta_x \quad (4.4)$$

Equation (4.5) shows the path loss at the maximum transmission range, denoted as $P_L(d_{max})$ in case P_{min} denotes the minimum signal strength for reliable packet delivery, which can be considered to be constant.

$$P_t - P_L(d_{max}) = P_{min} \quad (4.5)$$

Consequently, we can also calculate d_{max_x}, as follows.

$$d_{max_x} = \frac{10^{(\frac{P_L(d_{max}) - P_L(d_0) - \delta_x}{10\beta})}}{d_0} \quad (4.6)$$

Figure 4 demonstrates the manner of estimation of the sector area of a radio interface r of a router v_i using the collected RSSI values, denoted as $w_x^{i_r}$ and measured at anchor point x. Since the coordinates of locations (X_i, Y_i) and (X_x, Y_x) of router v_i and anchor point x are given, the distance between them is defined as Equation (4.7), denoted by d_{ix}.

$$d_{ix} = \sqrt{(X_i - X_x)^2 + (Y_i - Y_x)^2} \quad (4.7)$$

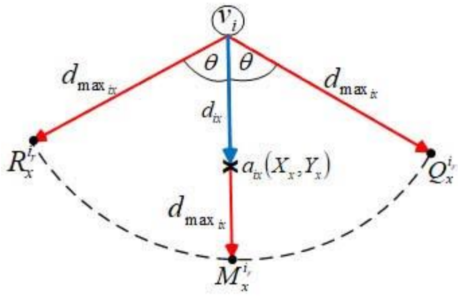


Figure 4. Estimated sector area of an anchor point xth at the radio interface rth of router v_i

Consequently, we compute the coordinates of locations (X_M, Y_M) of a point denoted by $M_x^{i_r}$ at $d_{max_{ix}}$ using Equation (4.8).

$$X_M, Y_M = \begin{cases} d^2{}_{max_{ix}} = (X_M - X_i)^2 + (Y_M - Y_i)^2 \\ \left(d_{max_{ix}} - d_{ix}\right)^2 = (X_M - X_x)^2 + (Y_M - Y_x)^2 \end{cases} \quad (4.8)$$

Then, we create a sector area with double θ degree, containing two endpoints $R_x^{i_r}$ and $Q_x^{i_r}$ as well as the interior point $M_x^{i_r}$. Furthermore, the coordinates of locations (X_R, Y_R) of the endpoint $R_x^{i_r}$ and the coordinates of locations (X_Q, Y_Q) of another endpoint $Q_x^{i_r}$ are calculated using Equation (4.9).

$$\begin{cases} X_R = \cos(\theta) * d_{max_{ix}} + X_i; \\ Y_R = \sin(\theta) * d_{max_{ix}} + Y_i; \\ X_Q = \cos(-\theta) * d_{max_{ix}} + X_i; \\ Y_Q = \sin(-\theta) * d_{max_{ix}} + Y_i; \end{cases} \quad (4.9)$$

However, the transmission range is likely to be smaller due to some obstacles. Therefore, we propose estimating the real transmission range using several anchor points as follows. Figure 5 shows four anchor points for router v_1. For each anchor point, δ_x can be obtained using Equation (4.4). As a result, the interior point $M_x^{1_0}$ as well as the endpoints in terms of $R_x^{1_0}$ and $Q_x^{1_0}$ for each anchor point x of the router v_1 are also computed as shown in Figure 4. By connecting all the interior points and two endpoints, the transmission range, denoted as T^{1_0} separated by blue solid lines for the radio interface zero of router v_1, can be obtained. The transmission ranges, denoted by T^{0_0} and T^{2_0}, are also obtained in the same manner for the radio interface zero of both routers v_0

and v_2. The area, denoted by S, which is covered by the transmission ranges of the maximum number of routers is selected as the adequate location for setting a spare AP. Note that at least one of the routers must be in C.

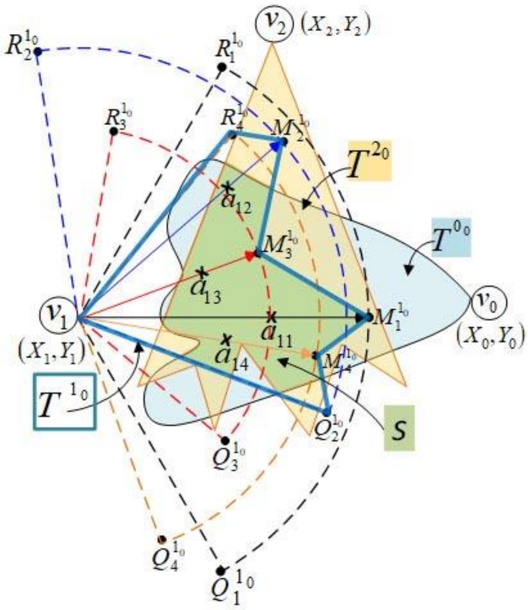
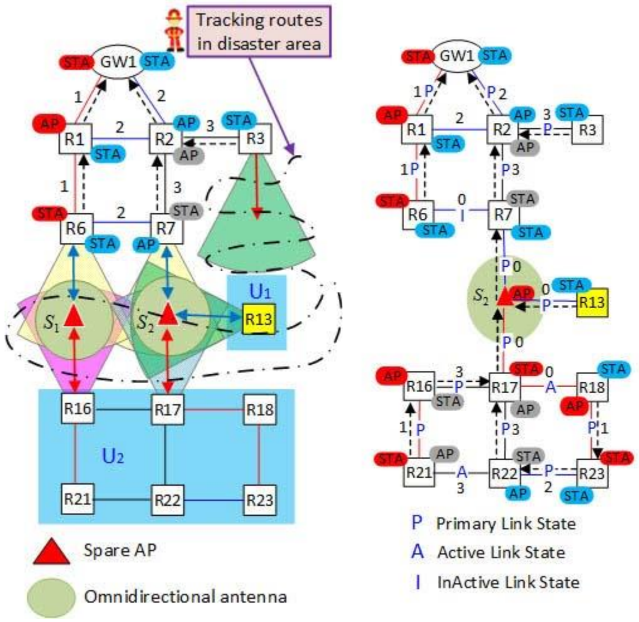


Figure 5. Discovering adequate locations for installing spare Aps

4.2. Rerouting Phase

We first discuss rerouting procedure. Note that before rerouting, first of all, while public workers working in the disaster area are going along tracking routes, an application software on their smartphones automatically measure RSSI levels of all the unreachable routers at anchor points [23]. For example, as shown in Figure 6(a), receiving all the information from the public workers, MS can estimate the communication range of each router. since some routers are supposed to get down and R13 has been changed its antenna orientation, overlapping communication ranges of the unreachable routers and the closest routers is derived as candidate locations for spare APs. Before installing spare APs, rerouting technique should be simulated for each candidate location area S_1 and S_2 on MS, respectively. In this demonstration, spare APs at S_1 location only provide route for the unreachable routers in the area U and spare AP at S_2 location can provide routes for all the unreachable routers in both U_1 and U_2.



a) Initial routing b) Rerouting

Figure 6. Route reconstruction procedure in Disaster situation

In Figure 6(b), when the installed spare AP is turned on, it must first discover a route to a proper GW. For this purpose, it performs active scanning on all channels to maintain a neighbour and routing table. In this case, the spare AP is considered as a root, since it has a single radio interface with an omnidirectional antenna (denoted as the green circle). In addition, it must work in the AP mode. After the scanning process, if the spare AP first discovers its parent node (such as R7) as its neighbour, as shown in Figure 6(b), the link between them is considered as a primary link.

The best route is a chain of the primary links for each router. In addition, if there is no neighbouring connection with any node, a router takes STA mode and Active state by default. Each mesh router selects a primary path with the lowest WCETT as its best route in its routing table and others as feasible paths in the topology table. Note that each link must have one of the following statuses: Primary, Active, or Inactive. Both the Primary and Active statuses indicate that this link is available. The Primary and Active links are used for the main and backup routes, respectively. Inactive indicates that this link is not available since the connected interfaces works in the same mode [19].

The main constraint is that the router R7 cannot allow its parent route or feasible route to be used for connection with the spare AP via its interface. R7, R13, and R17 must set the STA mode at their interfaces to connect to the spare AP, and then, their channels must be assigned. After R17 becomes reachable, it is able to receive primary route requests from other unreachable routers (such as R16, R18, and R22) in a neighbour relationship. The main constraint is that a router must first create a neighbouring connection with its parent node, and then, with its child nodes. We consider nodeID for each node. Thus, a router with the lowest node ID takes AP mode at its radio interface. Since R17 provides a primary route for two neighbours (R16 and R22) connected via the same interface, both of R16 and R22, will take the STA mode. Thus, both will become reachable nodes. R21 can be recommended a primary route with the same WCETT by either R16 or R22 and will choose R16 with the lower nodeID as its parent node. R16 and R21 have no child node at the interface, and thus, the parent node R16 can take the AP mode. However, the link between R21 and R22 is not used as the best route for both, and thus, the status is Active. Thereafter, since R17 has already used the interface connected to R18 for its own primary route to the spare AP, R18 will connect to the backbone network through R23. Finally, the rerouting process is complete when all the unreachable routers have their own primary route to the MS.

5. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the proposed methods via simulation experiments using ns-3.26. The WMN topology in Figure 2 was built as a simulation model. All the nodes were placed at the same distance (380 [m]) from each other and had directional antennas oriented to their neighbour nodes. The evaluation parameters in the simulation environment is shown in Table 1.

Table 1. Evaluation parameters

Parameter	**Value**
Signal transmission power	16 dBm
Total number of routers	25
Propagation model	Log Distance Propagation Loss Model
MAC interface	802.11g
Wi-Fi type	Infrastructure mode
Gain of directional antenna	9 dBi
Gain of omni-directional antenna	2 dBi
Transport Layer Protocol	TCP
Application Protocol	FTP

In normal situations, all the routers are reachable to the MS. To create a disaster situation, *n* random routers were assumed to be down. Also, another *n* routers' antenna orientation changed randomly, shown at the horizontal axis in Figure 7.

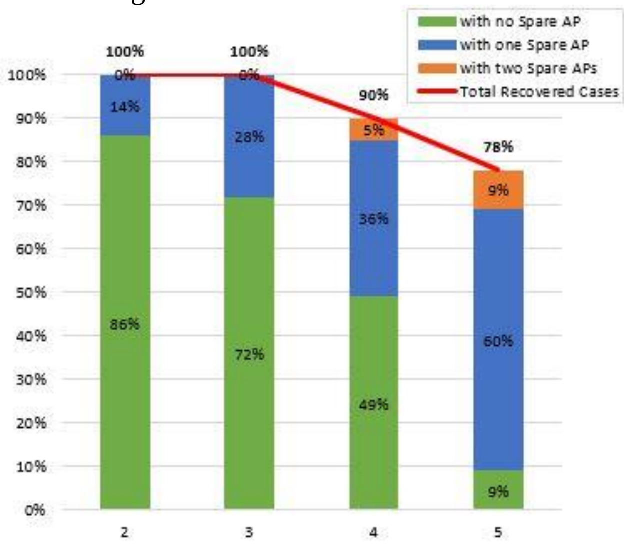


Figure 7. Successful recovery probability

Their interface numbers were selected randomly. We changed *n* from 2 to 5, and tested 100 different failure cases for each *n*. To recover any failure situations, the number of spare APs is equal to or less than a half of the number of down routers was used. Moreover, only one spare AP was used to recover in the cases of *n*=2,3 scenarios, whereas one or two spare APs were used for recovering in the cases of *n*=4,5. Figure 7 shows successful recovery probability using the proposed route reconstruction method. “Recover” means that all the active routers became reachable to the MS after the reconstruction process. Given that at most four routers remained in the failed state, the proposed method could recover routers with a high enough probability. Even if five routers went down and the antenna orientations of another five routers changed in the case of *n*=5 scenario, in about 78% of the cases, one or two spare APs could restore the whole reachability. Consequently, the proposed method is practical.

6. IMPLEMENTATION

We implemented the proposed methods and got field trial to confirm their feasibility.

6.1. Applications For Collecting AP Information

We developed a mobile application for firefighters or other first responders to collect radio wave conditions within the disaster area. We also developed a Web application to visualize and analyse the collected RSSI information using our mobile application.

We applied the radio wave collection system described in [24] for network recovery. The system is composed of three main parts: (1) mobile application, (2) Web application, and (3) data manager (Scenargie® Scene Manager [25]). The mobile application is mainly used for data acquisition. The Web application is used for data visualization and analysis of the aggregated data. The data manager, Scenargie® Scene Manager, is used for aggregation and synchronization of the measured and calculated data from both the mobile and Web applications. The mobile application was run on Android, wherein it measures the Wi-Fi radio waves at frequencies of 2.4 GHz and 5 GHz. The user's activity (such as rescuing) is not inhibited since the application requires no special operations. Figure 8 shows a snapshot of the developed mobile application.

Figure 8. Mobile application

Based on the collected data, a Wi-Fi radio map is then constructed. The collected Wi-Fi beacon data consist of the RSSI, service set identifier, channel frequency, and channel bandwidth at a certain location and time. These values are then uploaded to the data manager, and using the acquired RSSI value and position information, the radio wave status is displayed as a heat map chart on the mobile device.

The Web application displays a summary or aggregate of measurement values gathered using the mobile app from multiple users on the screen. The application also displays a radio wave intensity graph, a heat map (wherein radio wave intensity data at each point are displayed on the map), and a time series display function. All values may be outputted in CSV format. Moreover, a router can be selected on the map display, and the heat map displays the reach of the radio waves. The Web visualization on the aggregated data serves as an aid for decision-making regarding target areas for equipment deployment, so that the wireless mesh network is restored throughout the affected area.

6.2. Field Trial

In order to demonstrate the effectivity of the system for disaster mesh network recovery, the system was deployed in-field in a small area near Hiwasa Station in Tokushima Prefecture, Japan. As mentioned before, we were able to determine the suitable targets for equipment deployment with the aggregated information and the RSSI ranging and localization algorithm described above. Three routers equipped with directional antennas with their gain 9dBi were installed at locations shown in Figure 9. They were not being able to communicate each other before installing a spare AP.

First, we collected the RSSI information using the mobile application in Figure 8. Then, the RSSI ranging and localization algorithm was executed based on the collected database. Table 2 shows the calculated maximum distance for each anchor point measured.

Table 2. Measured anchor points for each router

Router	**Latitude and Longitude of Anchor points**	**Measured RSSI level [dBm]**	**The maximum distance [m]**
R1	14976129.53, 3992580.745	-76	324.447
	14976130.93, 3992552.974	-74	395.426
	14976151.16, 3992528.87	-73	480.466
	14976108.32, 3992580.196	-73	411.773
	14976169.69, 3992539.888	-77	331.406
	14976111.27, 3992586.474	-79	212.153
	14976169.75, 3992541.126	-76	372.081
	14976118.75, 3992524.394	-69	647.163
	14976027.96, 3992520.433	-68	363.675
R2	14976274.86, 3992318.037	-65	365.489
	14976136.37, 3992559.73	-89	120.531
	14976015.41, 3992256.352	-87	119.718
	14976151.16, 3992528.87	-82	242.48
	14976129.53, 3992580.745	-78	454.787
	14976264.19, 3992320.674	-70	220.988
R3	14976174.81, 3992499.515	-84	156.321
	14976170.73, 3992536.529	-83	149.242
	14976167.16, 3992733.671	-46	813.175
	14976118.28, 3992544.232	-79	236.884

Consequently, the dashed circle shown in Figure 9 shows the adequate area for a spare AP, which was obtained by the proposed methods with 19 anchor points in Table 2. Moreover, the green, red, and yellow points are depicted as the measured anchor points R_1, R_2, and R_3, respectively. A triangle means a point where we installed a spare AP actually. When we put the spare AP at a point indicated by blue triangle, all routers had been reachable each other. On the other hand, however, when we set the spare AP at a point indicated by red triangle, one of 3 routers had been still isolated. In other words, the obtained area includes a few meters of estimation error.

Consequently, however, even if there are some obstacles such as houses, cars, and trees, the proposed method works well and successfully recovers a connection between at least two routers. It is sufficiently practical.

Figure 9. Router and Spare AP locations

7. CONCLUSIONS

In this paper, we proposed a practical route reconstruction method for Wi-Fi mesh networks in disaster situations by using spare APs. In order to obtain adequate locations for spare APs, we formulated an RSSI-based ranging and location as well as a rerouting algorithm in order to build a converged network.

Simulation results showed that the proposed method achieved the satisfaction degree of successful recovery for each failure scenarios using the minimum number of spare APs. In addition, as a result of the field trial, the location points of the adequate area for installing spare AP were successfully defined.

As a future work, we will demonstrate the automatic mode selection algorithm in real world.

ACKNOWLEDGEMENTS

This work is supported by MIC/SCOPE No. 175009002.

REFERENCES

[1] R. B. Dilmaghani, & R. R. Rao (2008) “Hybrid Wireless Mesh Network with Application to Emergency Scenario”, Journal of Software, Vol. 3, No.2, pp52-60.

[2] A. Yarali, B. Ahsant & S. Rahman (2009) “Wireless Mesh Networking: Key Solution for Emergency & Rural Applications”, Second International Conference on Advances in Mesh networks.

[3] I. F. Akyildiz, X. Wang, & W. Wang (2005) “Wireless mesh networks: a survey”, Computer Network ISDN Systems, Vol. 47, No. 4, pp445—487.

[4] A. Raniwala & T. Chiueh (2005) “Architecture and Algorithms for an IEEE 802.11-based Multi-Channel Wireless Mesh Network”, Annual Joint Conference of the IEEE Computer and Communications Societies.

[5] A. Le, D. Kum, Y. Cho & C. Toh (2009) “Routing with Load-Balancing in Multi-Radio Wireless Mesh Networks”, IEICE Transactions on Communications, Vol.E92-B, No.3, pp700—708.

[6] Parth H. Pathak & Rudra Dutta (2011) “A Survey of Network Design Problems and Joint Design Approaches in Wireless”, IEEE Communications Surveys & Tutorials.

[7] D. Benyamina, A. Hafid & M. Gendreau (2012) “Wireless Mesh Networks Design - A Survey”, IEEE Communications Survey & Tutorials, Vol. 14, No.2, pp445-487.

[8] S. Vural, D. Wei & K. Moessner (2013) “Survey of Experimental Evaluation Studies for Wireless Mesh Network Deployments in Urban Areas towards Ubiquitous Internet”, IEEE Communications Surveys Tutorials, Vol. 15, No.1, pp223-239.

[9] K. Umesh, G. Himanshu & R.D. Samir (2006) “A Topology Control Approach to Using Directional Antennas in Wireless Mesh Network”, IEEE International Conference on Communications.

[10] M. Rajesh & J. M. Gnanasekar (2015) “Routing and Broadcast Development for Minimizing Transmission Interruption in Multirate Wireless Mesh Networks using Directional Antennas”, Innovative Systems Design and Engineering, Vol. 6, No.7, pp30—42.

[11] V. Navda, A. Kashyap & S. R. Das (2005) “Design and Evaluation of iMesh: An Infrastructure-mode Wireless Mesh Network”, Sixth IEEE International Symposium on a World of Wireless Mobile and Multimedia Networks.

[12] H. Wirtz, T. Heer, T. Backhaus & K. Wehrle (2011) “Establishing Mobile Ad-Hoc Networks in 802.11 Infrastructure Mode”, 6th ACM workshop on Challenged networks, pp49—52.

[13] P. Sharnya & J. S. Raj (2013) “Self Organizing Wireless Mesh Network”, International Journal of Innovation and Applied Studies, ISSN 2028-9324, Vol. 3 No 2, pp486-492.

[14] K. Pendke & S. U. Nimbhorkar (2013) “Reconfiguring Wireless Mesh Network Using Link Recovery Technique”, IRACST - International Journal of Computer Networks and Wireless Communications, ISSN:2250-3501, Vol. 3, No.3, pp257-260.

[15] S. K. Singh & P. K. Manjhi (2016) “Fault Tolerance Issue in Wireless Mesh Network”, Imperial Journal of Interdisciplinary Research (IJIR), Vol. 2, Issue. 5, pp874-885.

[16] R. Miura, M. Inoue, Y. Owada, K. Takizawa, F. Ono, M. Suzuki, H. Tsuji & K. Hamaguchi (2013) “Disaster-Resilient Wireless Mesh Network - Experimental Test-bed and Demonstration”, 16th International Symposium on Wireless Personal Multimedia Communications.

[17] Y. Owada, B. Jeong, N. Katayama, K. Hattori, K. Hamaguchi, M. Inoue, K. Takanashi, M. Hosokawa, & A. Jamalipour (2016) “An Implementation of Multichannel Multi-Interface MANET for Fire Engines and Experiments with WINDS Satellite Mobile Earth Station”, IEEE Wireless Communications and Networking Conference.

[18] Y. Owada, J. Byonpyo, H. Kumagai, Y. Takahashi, M. Inoue, G. Sato, K. Temma, & T. Kuri (2018) “Resilient Mesh Network System Utilized in Areas Affected by the Kumamoto Earthquakes”, 5th International Conference on Information and Communication Technologies for Disaster Management (ICT-DM).

[19] E. Dorj & K. Kinoshita (2018) “A route reconstruction method with spare AP for wireless mesh networks in disaster situation”, 2nd International Conference on Vision, Image and Signal Processing (ICVISP 2018).

[20] H. Wang, J. Wan & R. Liu (2011) “A Novel Ranging Method based on RSSI”, Proceedings of the International Conference on Smart Grid and Clean Energy Technologies, Vol.12, pp230—235.

[21] A. Shojaifar (2015) “Evaluation and Improvement of the RSSI-based Location Algorithm”, Doctoral Thesis, Faculty of Computing Institute, Blekinge Institute of Technology, Karlskrona, Sweden.

[22] M. Yassin & E. Rachid (2015) “A Survey of Positioning Techniques and Location based Services in Wireless Network”, IEEE International Conference on Signal Processing, Informatics, Communication and Energy Systems (SPICES).

[23] J. Fajardo, T. Maeno & K. Kinoshita (2018) “A Radio Wave Condition Collection System for Mesh Network Recovery During Disasters”, IPSJ Multimedia, Distributed, Cooperative, and Mobile Symposium (DOCOMO 2018), pp1752—1755.

[24] J. Fajardo & K. Kinoshita (2018) “Implementation of a Radio Wave Condition Collection System for Disaster Mesh Network Recovery”, IEICE General Conference.

[25] “Scenargie”, http://www.spacetime-eng.com/.

AUTHORS

Erdenetuya Dorj

She received her B.Sc. and M.Sc. degrees in Information Network from Mongolian University of Science and Technology, Mongolia, in 2007, and 2008, respectively. She is currently pursuing a Ph.D. degree in Information Science and Intelligent Systems at Tokushima University, Jap an. Her academic interests include wireless multi-hop mesh network, QoS in Internet of Things.

Jovilyn Therese B. Fajardo

She received her B.S. degrees in Chemistry and Computer Engineering from Ateneo de Mani la University, Philippines in 2006 and 2007, respectively. She also received her M.S. in Electronics Engineering from the same university in 2010. She then received her D.Eng degree in Information Science from Nara Institute of Science and Technology in 2013, and joined Nagoya University as a Designated Assistant Professor from 2014 to 2017. Currently, she is working as an engineer at Space-Time Engineering Japan.

Kazuhiko Kinoshita

He received the B. E., M. E. and Ph. D degrees in information systems engineering from Osaka University, Osaka, Japan, in 1996, 1997 and 2003, respectively. From April 1998 to March 2002, he was an Assistant Professor at the Department of Information Systems Engineering, Graduate School of Engineering, Osaka University. From April 2002 to March 2008, he was an Assistant Professor at the Department of Information Networking, Graduate School of Information Science and Technology, Osaka University. From April 2008 to January 2015, he was an Associate Professor at the same University. Since February 2015, he has been a Professor at Tokushima University. His research interests include mobile networks, network management, and agent communications. Dr. Kinoshita is a member of IEEE and a senior member of IEICE.