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On Efficient Traffic Distribution for Disaster Area Communication Using Wireless Mesh Networks

Mostafa M. Fouda · Hiroki Nishiyama · Ryu Miura · Nei Kato

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Abstract In recent time, a great deal of research effort has been directed toward promptly facilitating post-disaster communication by using wireless mesh networks (WMNs). WMN technology has been considered to be effectively exploited for this purpose as it provides multi-hop communication through an access network comprising wireless mesh routers (MRs), which are connected to the Internet through gateways (GWs). One of the critical challenges in using WMNs for establishing disaster-recovery networks is the issue of distributing traffic among the users in a balanced manner in order to avoid congestion at the GWs. To overcome this issue, we envision a disaster zone WMN comprising a network management center (NMC). First, we thoroughly investigate the problem of traffic load balancing amongst the GWs in our considered disaster zone WMN. Then, we develop traffic load distribution techniques from two perspectives. Our proposal from the first perspective hinges upon a balanced distribution of the bandwidth to be allocated per user. On the other hand, our second perspective considers the dynamic (i.e., varying) bandwidth demands from the disaster zone users that requires a more practical and refined distribution of the available bandwidth by following an intelligent forecasting method. The effectiveness of our proposals is evaluated through computer-based simulations.

M. M. Fouda · H. Nishiyama · N. Kato
Graduate School of Information Sciences (GSIS), Tohoku University, Aramaki aza Aoba 6-3-09, Aoba-ku, Sendai-city, Miyagi-pref, 980-8579, Japan
E-mail: mfouda@ieee.org

H. Nishiyama
E-mail: bigtree@it.ecei.tohoku.ac.jp

N. Kato
E-mail: kato@it.ecei.tohoku.ac.jp

M. M. Fouda
Faculty of Engineering at Shoubra, Benha University, 108 Shoubra Street, Cairo, Egypt

R. Miura
National Institute of Information and Communications Technology (NICT), 3-4 Hikarino-oka, Yokosuka, Kanagawa 239-0847, Japan
E-mail: ryu@nict.go.jp

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1 Introduction

We live in a world where big disasters may strike suddenly. These disasters may come in the form of earthquakes, tsunamis, hurricanes, tornadoes, floods, fires, and so on. Some recent examples of such disasters include the 2010 earthquake in Haiti (which affected three million people and left one million homeless), the 2011 earthquake and tsunami that hit east Japan (leading to the toughest and the most difficult crisis for Japan since the end of World War II), and the 2012 Hurricane Sandy (which affected at least 24 states of the USA and left about 200,000 people homeless in Haiti).

While these sudden disasters result in deaths, injuries, and homeless people, a quick response from the corresponding governments may include different techniques for post-disaster recovery. One big challenge that arises with disasters is that the telecommunication services (e.g., cellular networks, third generation (3G), long term evolution (LTE) services, and Internet infrastructures) usually become interrupted or overwhelmed. This congestion can be, particularly, noticed immediately after the disaster because the inhabitants of the affected area might want to, at the same time, communicate with the rest of the world. In order to deal with this challenge, the topic of designing an efficient disaster resilient network has recently gained much interest.

A recent research work in [1] has indicated that disaster-recovery networks may be formulated with the aid of mobile ad hoc networks (MANETs). MANETs are exploited to promptly form disaster-recovery networks for collecting critical information on the conditions of the affected citizens. On the other hand, in [2], satellite communication network and a ballooned wireless ad hoc network have been considered to be the driving technology in this domain. However, the ad hoc communication technology poses a number of challenges, e.g., managing the variation in the population density of the affected areas, many sparse networks with intermittent connectivity, energy-limited resources, bandwidth constraint, and so forth. Also, the use of cognitive radio networks has been noted in the recent literature to establish disaster resilient communication networks [3]. But, cognitive radio technology, too, falls short in terms of constructing large scale post-disaster networks due to their limitations such as opportunistic spectrum use and bandwidth limitation for secondary users.

As a consequence, researchers have diverted attention toward an alternate technology, namely the wireless mesh networks (WMNs), in order to construct disaster zone networks [4–7]. The WMNs present an attractive choice for this purpose due to their multi-hop wireless communication feature, with a wireless backbone comprising wireless mesh routers (MRs), which provide more bandwidth resources in contrast with its basic ad hoc counterpart such as MANETs. Hence, WMNs can be exploited for the fast deployment of an urgently required communication infrastructure to combat the collapse in communication due to a disaster (e.g., earthquake, hurricane, and so on). However, the WMN technology still suffers from a major challenge concerning the traffic distribution amongst the nodes for avoiding bottleneck formation. In our work, we consider a practical disaster zone

WMN in which a network management center (NMC) coordinates the traffic load balancing decision to facilitate disaster resilient communication. Also, in our considered network, the problem of congested GWs is highlighted that occurs due to a large number of users demanding to connect to a GW from the disaster area (i.e., the spatially dense crowded areas attempting to connect with the Internet). Therefore, we argue the urgency of envisioning an adequate traffic distribution technique for effectively facilitating WMN-based disaster communication.

The problem of traffic load balancing amongst the GWs is addressed in our work from two perspectives. Our proposal from the first perspective hinges upon a balanced distribution of the bandwidth to be assigned/allocated per user. By proposing a heuristic, we perform traffic balancing at the gateways to ensure fairness amongst the users in the disaster area. On the other hand, our second perspective considers the dynamic (i.e., varying) bandwidth demands from the disaster zone users that require a more practical and refined distribution of the bandwidth demand by following an intelligent forecasting technique. With the aid of computer-based simulations, we demonstrate the effectiveness of our proposals from both these perspectives.

The remainder of the paper is structured as follows. Section 2 presents a comprehensive literature review of disaster area networks. Section 3 discusses the problem statement and describes the major challenges in designing a robust post-disaster communication networks. In Section 4, our proposed traffic distribution strategies are presented. The performance of the proposed strategies is evaluated in Section 5 with the aid of computer-based simulations. Finally, the paper is concluded in Section 6.

2 Literature Review

After one of the strongest earthquakes shocking the Wenchuan region of China in May 2008, the research community realized the urgent need of post-disaster network planning [8]. The work in [8] demonstrates the importance and significance of constructing disaster resilient communication by involving future networking technologies. This work delineates how the worst hit areas turned into an "isolated information island" because of the large scale damage of the communication infrastructure, power failure, breakdown in the supply chain, and network congestion. At the same time, different schemes were utilized for communication to provide disaster-relief in the affected area by using very small aperture terminals, hand-held satellite phones, and optical cables. The work in [8] also indicates the need of further study on disaster countermeasures via advanced network and communication technologies.

A MANET-based emergency communication and information system for catastrophic natural disasters was suggested in [9]. The objective of the system is to support a large number of rescue volunteers. It comprises a peer-to-peer network by exploiting notebook computers to build the emergency communication infrastructure. However, the resource constraint of the nodes, due to the absence of localized data concentrators or aggregators (such as MRs), can be considered as a significant shortcoming of this work.

On the other hand, an effective and robust wireless network to provide post-disaster connectivity is presented in [10]. This work proposes a network composed

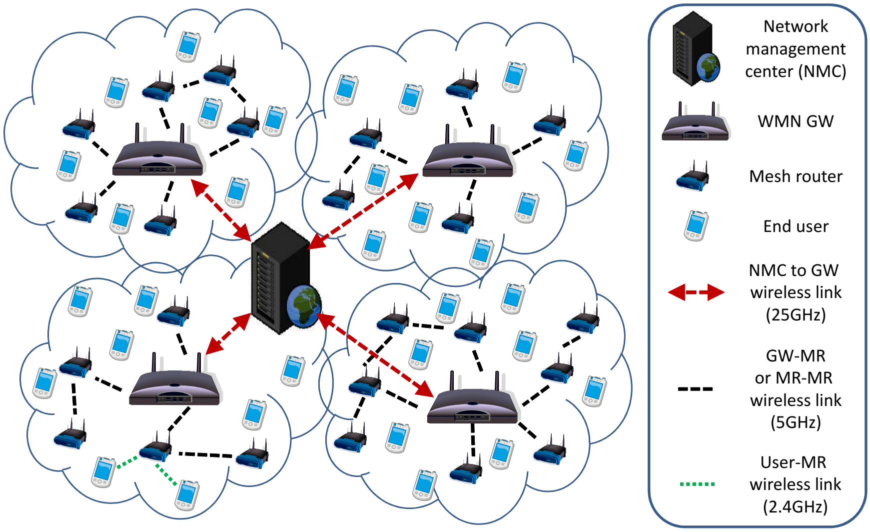


Fig. 1 An example of the considered disaster area network model.

of different wireless local area networks (WLANs) and mobile networks through a mobile router located on a roaming vehicle. By deploying a number of these mobile routers, a multi-hop communication path is constructed. While these mobile routers can be, to some extent, considered as entities similar to the MRs of a WMN, their mobility, distance from each other while roaming, transmission power and frequency, would make it hard to offer a practically effective disaster communication network.

WMN-based disaster resilient communication has raised a lot of research collaboration among the academia, industry, and government in Japan since the "great east earthquake" in March 2011. In the work in [11], a WMN-based architecture to combat the post-disaster communication impairment is proposed by effectively exploiting especially designed movable and deployable resource units (MDRUs). While the work serves as an inspiration in this research domain, it does not consider exploiting the surviving network resources in the disaster-stricken zone. In fact, our research work describes how it is possible to use the surviving network equipment as MRs to construct post-disaster communication networks.

To achieve load balancing in WMNs, Bedi *et al.* [12] proposed a geographic multipath routing protocol. In their proposal, each time a MR receives congestion information of any of its neighbors, it records it and changes the path for all its subsequent packets, until receiving a flag to indicate that the congested node is back to its normal load. This results in avoiding routing the traffic through the congested MRs. However, the case of balancing the load of the main gateways of the network is not studied extensively in this work.

3 Problem Formulation

In this section, we illustrate an example of our considered disaster area network model as shown in Fig. 1 whereby we envision a network management center

(NMC) to connect the disaster area network to the outside world (i.e., Internet). Assume that the disaster did not cause damage to all the electricity sources (i.e., main sources and backup power supplies) and that the existing network equipment (e.g., wireless routers and access points (APs)) in restaurants, stations, offices, and so forth, can still be utilized in the post-disaster situation. Also, it is assumed that those network equipment that usually operate using the wireless local area network (WLAN) technology will be utilized for public use as wireless MRs. Thus, we aim at effectively utilizing the network equipment, which were deployed before the disaster.

In our model, these MRs are exploited to connect the disaster-area residents with the communication network via a number of GWs, as shown in Fig. 1. Note that the NMC can assign the wireless MRs as the GWs, and establish a connection with each of the GWs by point-to-point with 25GHz frequency. The MRs compose the backbone disaster area network with 802.11a 5GHz technology. The users are considered as the mesh clients that may communicate with the MRs by using 802.11b/g/n with 2.4GHz technology. To avoid the channel interference in the communication between MRs, each MR is supposed to be equipped with multiple network interface cards (NICs). Through its NICs, each MR can communicate with its adjacent MRs without interference. Interested readers may refer to the work in [13, 14] for detailed information regarding the channel assignment issue. The bottleneck of the entire system may be identified by taking into account the amount of traffic along each wireless link. For the afore-mentioned network, the traffic congestion at the wireless interface (which is connected with the MRs) of each of the GWs means that the GW is the bottleneck in the network.

In our research, in order to increase the bandwidth utilization and to limit the end-to-end delay, we focus upon balancing the load amongst the existing GWs from the following directions.

A. Balanced distribution of the bandwidth to be allocated per user.
With this objective, it is possible to ascertain approximately the same bandwidth per user. In other words, the system can achieve communication bandwidth fairness for the users.
B. Balanced distribution of the bandwidth demand per GW.
This perspective considers the dynamic bandwidth demands from the disaster zone users because the demand per user should practically not be the same. In other words, some users may not be demanding/consuming any bandwidth while others may be in need for more bandwidth.

The basic idea behind those approaches is to transfer part of the load from the congested GWs to the non-congested ones. This can be done by performing handover of one or more of the MRs connecting through the congested GWs to be connected through the non-congested ones. However, a main challenge arises where the effect of users-mobility may result in a "reverse handover" of the MRs in a short period of time. Fig. 2 demonstrates a simple example of such a situation where after performing a handover of one MR from GW "i" to GW "j", the number of users in GW "j" increases in the next time-round and a reverse handover is required for the same MR. In order to avoid such scenario, we integrate some techniques to our approaches to carefully take a MR handover decision.

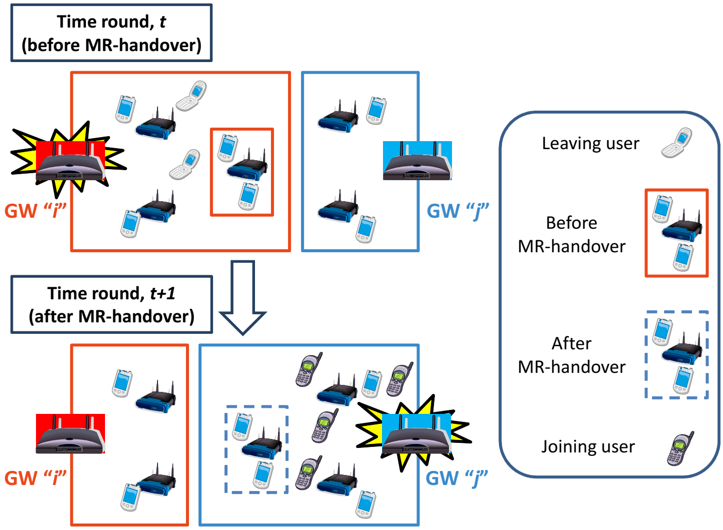


Fig. 2 An example of possible scenario where the MRs which performed handover may need to perform a "reverse handover" in the next time-round.

4 Proposed Traffic Distribution Methods in the Disaster Area

We segment our proposal from two perspectives as mentioned in Sec. 3 as follows.

4.1 Balanced distribution of the bandwidth to be allocated per user.

In this section, we propose a heuristic-based load distribution approach to achieve balanced distribution of the bandwidth to be allocated per user in the system. Part of the work can be referred back to our earlier work in [4]. Our heuristic has two objectives: to decrease the hop count between the GW and its MR(s), and to ensure fairness to the bandwidth to be allocated per user. Here, we assume that the bandwidth assigned per user in GW "g" is denoted by K_g, which is defined as the total bandwidth capacity of GW "g" divided by the total number of users serviced by GW "g" as in Eq. 1.

$$K_g = \frac{C_g}{\sum_{r=1}^{R_g} U_r}. \tag{1}$$

where C_g, R_g, and U_r denote the wireless link capacity of GW "g", the number of MRs in GW "g", and the number of users in MR "r", respectively.

Our heuristic aims at finding the most loaded GW and decrease its load by performing handover of one or more of its MRs to the least loaded GW. This process is repeated until the bandwidth to be allocated per user increases to its maximum level. The heuristic runs in time-rounds, simply referred to as "rounds" from hereon. In every round t, the following steps are repeatedly executed.

1. At first, using Eq. 1, the NMC computes K_g for all $g \in \mathcal{G}$ where $\mathcal{G}$ denotes the number of GWs in the system.
2. The NMC checks if K_g is the same for all the GWs. If yes, then this round finishes since the objective is achieved.
3. In case K_g is not the same for all $g \in \mathcal{G}$, then two GWs, i and j, are chosen such that i refer to the most loaded GW (where the bandwidth per user is minimum), and j refer to the least loaded GW (where the bandwidth per user is maximum). This can be shown by the following equations.

$$K_i = min\{K_g,\ g \in \mathcal{G}\}. \tag{2}$$

$$K_j = max\{K_g,\ g \in \mathcal{G}\}. \tag{3}$$

4. The NMC verifies whether each MR in GW "i", denoted by MR^i, has a neighboring MR in GW "j", denoted by MR^j. In case no MR^i detects any adjacent MR^j, then it is not possible to perform handover of MR^i from GW "i" to GW "j" and the current j is excluded and another j (i.e., a different GW) is to be chosen.
5. If MR^i successfully detects a neighboring MR^j, then the steps below are followed.
   (i) The NMC sorts the MR^is having neighboring MR^j(s) in a descending order of hop count (where the considered hop is from the respective MR^i to its current GW "i"). This is in order to perform the handover process to the MRs which have the highest hop count from their current GW.
   (ii) At the same time, the NMC calculates UHO, which denotes the required number of users belonging to GW "i" (i.e., belonging to a number of MR^is) in order to achieve a fair bandwidth per user in GWs "i" and "j" if those MR^is performed handover from GW "i" to GW "j". UHO is calculated using Eqs. 4 and 5.

$$\frac{C_i}{\sum_{x=1}^{R_i} U_x - UHO} = \frac{C_j}{\sum_{y=1}^{R_j} U_y + UHO}. \tag{4}$$

$$UHO = \frac{C_j \sum_{x=1}^{R_i} U_x - C_i \sum_{y=1}^{R_j} U_y}{C_i + C_j}. \tag{5}$$

6. At this point, the NMC requires to determine an appropriate MR^i for performing handover.
7. The NMC verifies whether an "inversion" occurs between K_i and K_j. The term "inversion" refers to the situation when K_i becomes the maximum while K_j becomes the minimum in the case if the handover is performed.
8. If an "inversion" takes place between K_i and K_j, the NMC deems this situation unnecessary for performing handover of MR^i from its old GW "i" to the new GW "j". As a consequence, the current round t finishes since we have reached a steady state in the current round where there is no more possible improvement.
9. On the other hand, if the "inversion" does not take place, the NMC makes a final check called "reverse handover prevention check" (shortly, RHPC) before permitting MR^i to perform handover. This check is to ensure that MR^i will not need to perform a reverse handover in the next round even if the worst case variation in the number of users is encountered. The RHPC is described in more details later in this section.

10. If the MR^i passes the reverse handover prevention check, then the NMC permits MR^i to perform handover from GW "i" to GW "j"and the steps from 1 to 10 are repeated.

4.1.1 Reverse handover prevention check (RHPC) to deal with user mobility

Here, we explain the effect of the change in the number of users because of their mobility on our heuristic. Accordingly, we use the RHPC (early mentioned in *Step 9*) to combat the users-mobility effect.

Like other wireless networks, also in the disaster area WMN, users can move around to join, leave, or perform handover from one MR to another in a dynamic way. As a consequence, the number of users connected to each GW might change dynamically with time. To achieve fairness in the bandwidth to be allocated per user, it is necessary to regularly perform handover for some MRs from a GW to another one as the number of users varies. This leads to an increase in the control overhead, which affects the bandwidth available for communication.

Therefore, we integrate RHPC to our heuristic-based approach and consider the handover of MRs to be performed under certain conditions in order to decrease the communication overhead. The variation of the number of users is taken into account to avoid a reverse handover of the same MRs within a time-window. By assuming that there is a maximum limit for the change of the number of users per MR every round, we consider that the worst case scenario (i.e., when there is a maximum variation of the number of users per MR) may occur in the post-handover round. Based on this, the NMC calculates the difference of (K_i and K_j) in the current round and in the worst case post-handover round that are denoted by D_1 and D_2, respectively, and calculated by employing Eqs. 6 and 7, respectively.

$$D_1 = \frac{C_j}{\sum_{y=1}^{R_j} U_y} - \frac{C_i}{\sum_{x=1}^{R_i} U_x}. \tag{6}$$

$$D_2 = \frac{C_i}{\sum_{x=1}^{R_i} U_x - UHO - \sum_{x=1}^{R_i-1} {U_x}^*} - \frac{C_j}{\sum_{y=1}^{R_i} U_y + UHO + \sum_{y=1}^{R_j+1} {U_y}^*}. \tag{7}$$

$$\textit{Condition for MR-handover:}\ \ D_1 \geq D_2. \tag{8}$$

where U_x^* refers to the maximum variation in U_x per round.

The post-handover worst case scenario, reflected in Eq. 7, is the one where the number of users belonging to the MRs of GW "i" decreases to its minimum limit, while the number of users connected to the MRs of GW "j" increases to its maximum limit. The NMC takes the handover decision when the current difference in the bandwidth per user is greater than or equal to that in the post-handover worst case scenario. This is demonstrated in the inequality (8). This condition is necessary to ascertain that in the next round, the NMC will not make a decision to perform a reverse handover even if the worst case variation in the number of users is encountered. Our proposal with RHPC is able to decrease the number of MR-handover events as well as the control overhead.

4.2 Balanced distribution of the bandwidth demand per GW.

While our main objective is to balance the load amongst the GWs, the proposed method in Sec. 4.1 only deals with the balanced distribution of bandwidth per user while assuming that all users in the same GW are assigned the same bandwidth. This may be interesting to the system designers based on their design objectives. However, note that such design considerations do not reflect the fact that there may be variation in the bandwidth demanded by the users. In order to deal with the variation in the bandwidth demand of the users, in every round t, the following steps are repeatedly executed for distributing the bandwidth demand in a balanced manner.

1. The NMC computes the sum of the bandwidth demand for each GW. This is done through the aggregate bandwidth demands originating from the users belonging to the MRs connected to each GW.
2. The NMC computes $\Delta\mathcal{B}_t = (\mathcal{B}_{max} - \mathcal{B}_{min})$, where $\mathcal{B}_{max}$ and $\mathcal{B}_{min}$ denote the maximum and minimum bandwidth demands, which are experienced at the most and least congested gateways, respectively. $\Delta\mathcal{B}_t$ denotes the difference between $\mathcal{B}_{max}$ and $\mathcal{B}_{min}$ in the current round, t. In the next steps, we investigate the possibility of performing MRs-handover from the GW which has $\mathcal{B}_{max}$ to the GW which has $\mathcal{B}_{min}$.
3. The NMC estimates $\Delta\mathcal{B'}_{t+1} = (\mathcal{B}_{min} * (1+\eta) - \mathcal{B}_{max} * (1-\eta))$. Here, η is a percent denoting the worst case variation in the bandwidth demanded per gateway per round. $\Delta\mathcal{B'}_{t+1}$ denotes the difference between $\mathcal{B}_{max}$ and $\mathcal{B}_{min}$, which are *expected* in the worst case scenario in the next round, $t+1$.
4. If $\Delta\mathcal{B'}_{t+1} > \Delta\mathcal{B}_t$, then there is no need for performing MR-handover.
5. At this stage, the NMC sorts the MRs, belonging to the GW experiencing $\mathcal{B}_{max}$, in descending order based on the bandwidth demands occurred at the MRs.
6. For each MR in the sorted list, if $\Delta\mathcal{B}_t > (\theta \cdot MR_{demand})$, this MR performs handover to the GW with $\mathcal{B}_{min}$. Here, MR_{demand} denotes the aggregate bandwidth demand of the MR, and θ refers to a factor, value of which lies between one to two, in order to prevent the recurrence of the handover of the same MR in round t. Then, $\Delta\mathcal{B}_t$ is recomputed for performing the same step with other MRs in the GW with $\mathcal{B}_{max}$.
7. The above steps are executed until all the GWs have been checked, and no further MR-handover can be performed.

This proposed method, as described above, balances the bandwidth demand of the users per GW by performing handover of the MRs from one GW to another. In each time-round, the system re-executes the above steps to assure that none of the GWs experiences excess bandwidth requests from the users.

Note that *Steps 3* and *4* of our bandwidth demand based traffic distribution method "intelligently" prevents the reverse MR-handover within a period of time. Indeed, in order to prevent such kind of reverse MR-handover situations, it is critical to forecast an expected situation of the GWs in the next round. This is estimated by the NMC in *Step 3*. Also, our proposed notion of intelligence is based on the expected worst case scenario of the next time round. If in the next round, the bandwidth demands in the GWs flip (e.g., if the GW currently experiencing the maximum bandwidth demands becomes the least requested one, and vice versa), then there is no need to perform any MR-handover, as indicated in *Step 4*.

5 Performance Evaluation

The performance of our proposed methods is verified through extensive simulations in this section. First, the effectiveness of our proposed balanced distribution of the bandwidth (BW) to be allocated per user (shortly, BW/user based) is elucidated. Then, the performance of the proposed balanced distribution of the bandwidth demand per GW (shortly, BW demand based) is evaluated in the remainder of the section.

5.1 Balanced distribution of the bandwidth to be allocated per user.

In this section, we present the performance evaluation of the proposed heuristic-based load distribution, which depends on balancing the bandwidth to be allocated per user. The computer-based simulations used in the evaluation are conducted using MATLAB [15]. The considered simulation parameters are as follows. There are 21 MRs serviced by three GWs, each of which has a wireless link capacity of 100 Mbps. Initially, the 21 MRs are equally distributed among the three GWs (i.e., 7 MRs per GW). Also, the initial numbers of users connected to the corresponding MRs of the three GWs are arbitrarily considered to be 10, 20, and 25, respectively. Therefore, there are 385 users in the considered simulations. It is worth stressing on the fact that this arbitrary assignment does not interfere with the fundamental observations of the simulation results. For simplicity, the maximum variation in the number of these users per MR in a round is set to two. From the fairness point, there should be an upper boundary for the number of users per MR to ensure that excessive users are not assigned to a given MR. Hence, the maximum numbers of users per MR are considered to be 20, 25, and 25 in the three GWs, respectively. Furthermore, it is also necessary to consider a lower bound for the number of users per MR for the MRs not to remain under-utilized. Therefore, we assume that the minimum numbers of users per MR are set to 10, 20, and 10 for the MRs belonging to the three considered GWs, respectively. The number of rounds in our simulations is set to 100. The simulations are conducted 300 times, and the average values are used as results.

Three performance metrics are taken into account, namely (*i*) Fairness Index (FI) for estimating how fairly the bandwidth is assigned to the users, (*ii*) the average hop count, and (*iii*) the number of MR-handover events. Using those three metrics, the performance of the proposed heuristic-based approach (described in Sec. 4.1) is evaluated with and without the reverse handover prevention check. Also, the conventional Hybrid Wireless Mesh Protocol (HWMP) scheme [16] is used for comparison.

For the first performance metric (i.e., FI), we utilize Jain's FI as expressed in Eq. 9 [17].

$$f = \frac{\left(\sum_{u=1}^{\mathcal{U}} k_u\right)^2}{\mathcal{U} \cdot \sum_{u=1}^{\mathcal{U}} {k_u}^2}. \tag{9}$$

We adopted Jain's FI because it rates the fairness of a set of values, where there are $\mathcal{U}$ users and k_u is the bandwidth assigned to user u ($\in \mathcal{U}$). It is worth noting that $k_u = K_g$ in case the user u is served by the GW "g" (since we are assuming that the GW bandwidth capacity is distributed among the users equally). The FI value in Eq. 9 ranges from the worst case value of $\frac{1}{\mathcal{U}}$ to the best case value of one. The FI value becomes the maximum in case that all the users in the network obtain the same bandwidth allocation from their respective GWs.

As indicated in Table 1, our proposed distribution of BW/user (with and without RHPC) outperform the HWMP scheme by a substantial margin in the estimated FI. Indeed, the FI resulted in the proposed method is over 0.99. In contrast, HWMP is able to distribute the bandwidth amongst the users with a slightly low FI value of approximately 0.95. On the other hand, Table 1 also indicates that the proposed methods exhibits only a slight increase in the average hop count compared to HWMP.

Next, we present the number of MR-handover events for the proposed BW/user based heuristic (with and without RHPC) over 100 rounds in the plot depicted in Fig. 3. As evident from the results, using RHPC achieves a lower number of MR-handover events compared to the proposal without using RHPC. This helps the stability of the network and reduces the communication overhead while performing the handover of the MRs. Simply put, this result demonstrates the effectiveness of our proposed heuristic-based approach using the RHPC to deal with the mobility of the users.

5.2 Balanced distribution of the bandwidth demand per GW

To evaluate the performance of our proposed BW demand based method, we carry out new simulations using MATLAB [15]. Here, we consider a larger topology where there are four GWs covering the disaster area and providing Internet connection to all the users inside the disaster zone. The bandwidth per GW is set to 100Mbps. Also, we consider 60 MRs that already exist in the disaster area (in shopping malls, restaurants, and so on). Initially, each GW is connected to 15 MRs in one-hop/multi-hop fashion. The total number of users inside the disaster zone is considered to be up to 4000 users. The bandwidth demand per user is gradually

Table 1 Comparison of our proposed BW/user based heuristic and HWMP.

Approach	Fairness Index	Average number of hops
BW/user based (with RHPC)	0.9933	2.5208
BW/user based (without RHPC)	0.9965	2.6309
HWMP	0.9465	2.4286

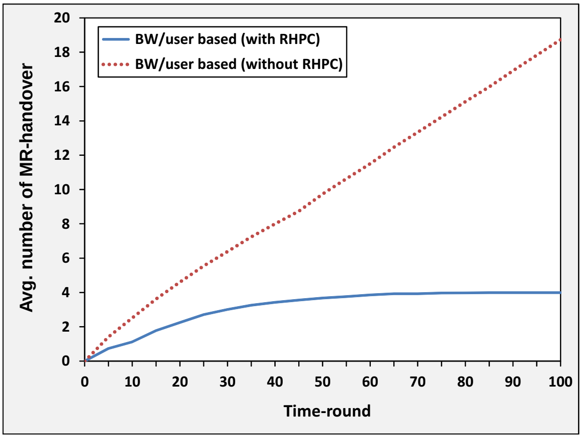
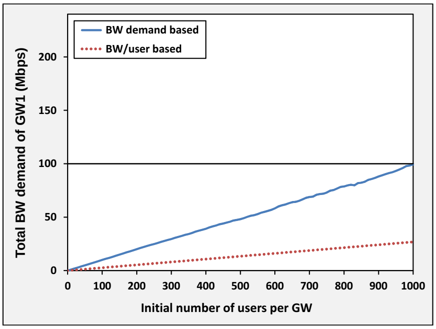


Fig. 3 Average number of MR-handover events of our proposed BW/user based heuristic with and without RHPC.

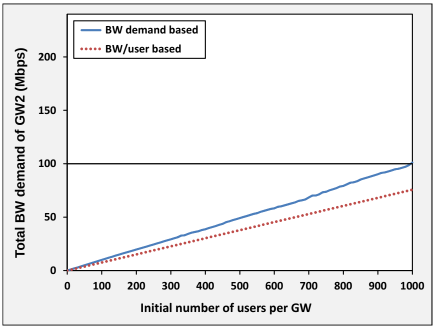
set with its minimum at the users initially connected to GW1 and its maximum at the users initially connected to GW4, respectively. The upper limit of bandwidth demand per user is set to 200Kbps. The values of θ and η are set to 1.5 and 0.1, respectively. Note that this simulation was repeated ten times, and the average values are presented as result.

To discuss the performance of our bandwidth demand based method, we compare it with the BW/user based method. Fig. 4 presents the total bandwidth demanded from each GW after applying both methods. In this scenario, we vary the initial number of users per GW from 10 to 1000. It is worth noting that the number of users per GW can be changed while applying the proposed methods since some of the MRs may perform a handover to balance the load amongst the GWs. As we observe from Fig. 4, the proposed BW demand based method shows a better performance in balancing the bandwidth demand per GW. This utilizes the bandwidth capacity of the GWs (which is 100 Mbps in this simulation as demonstrated in Fig. 4 with the black horizontal line) and also fulfills the users' bandwidth demand in the same time. On the other hand, the BW/user based method is not able to fulfill the bandwidth demands of the users since it is designed to allocate same bandwidth per user. As a result of this, the users in the disaster zone will be serviced in a better way (if they are allowed to request different bandwidth demands) with our bandwidth demand based method.

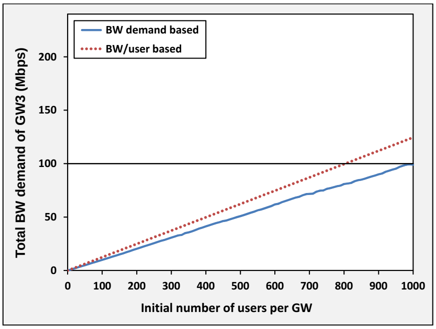
Fig. 5 shows the average bandwidth utilization for all the GWs in the considered scenario while varying the initial number of users per GW. As we can notice from the figure, when the initial number of users is small, both of our proposals give similar performance. This happens because there is not much demand on the GWs; so both strategies may similarly serve the users-demand. On the other hand, when the number of users increases, the average bandwidth utilization of the BW demand based method results in a better performance than the BW/user based strategy. For example, when the initial number of users per GW reaches 1000, the average bandwidth utilization reaches almost 100% for the BW demand based method. But, the BW/user based method suffers from under utilization of the bandwidth since the utilization is around 76%. In other words, the BW demand



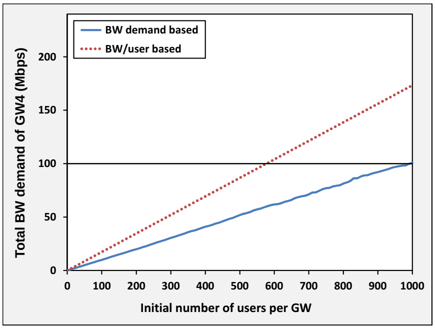
(a) The bandwidth demand at $GW1$.



(b) The bandwidth demand at $GW2$.



(c) The bandwidth demand at $GW3$.



(d) The bandwidth demand at $GW4$.

Fig. 4 The bandwidth demand observed for varying the initial number of users per GW for the BW demand based and the BW/user based approaches.

based strategy outperform the BW/user strategy by around 24% in the bandwidth utilization.

Fig. 6 demonstrates the average user satisfaction ratio versus the initial number of users per GW. The user satisfaction ratio can be defined as the bandwidth received divided by the bandwidth demanded for each user. As the figure shows, almost all the bandwidth demanded from the users could be satisfied with our BW demand based strategy, while the other strategy faces lower user satisfaction with increasing the number of users.

Next, we construct an additional simulation to evaluate the effect of the dynamic variation in the bandwidth demanded by the users. In this scenario comprising 4 GWs, 60 MRs, and 4000 users, we assume that the bandwidth demanded by each user dynamically varies in a range from -10% to 10% of its current value. The simulation period is set to 10000 rounds. Also, as consistent with the earlier simulation scenarios, the simuation is repeated ten times and the average values are used as result.

With this scenario, we compare the average system bandwidth utilization (%) for the proposed methods. The result of our simulation demonstrates that the BW demand based approach, is able to utilize, on average, approximately 93.4% of the available bandwidth in the four GWs. On the other hand, the BW/user based method can utilize only up to 74.7% of the system bandwidth capacity.

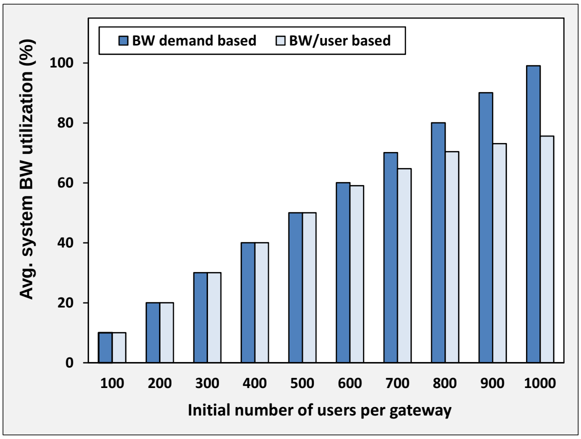


Fig. 5 Average system bandwidth (BW) utilization.

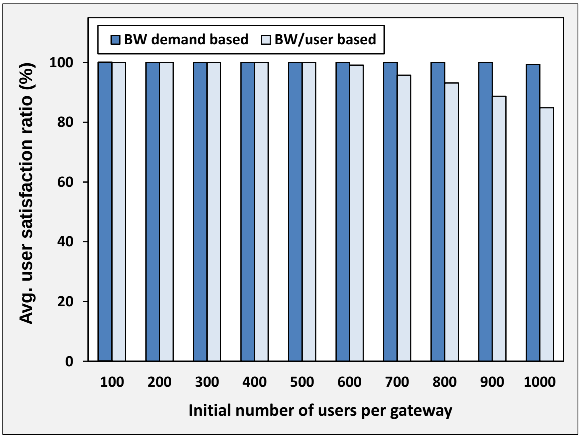


Fig. 6 Average user satisfaction ratio.

Finally, in Fig. 7, we investigate the benefit of intelligence incorporation in the BW demand based traffic distribution method. Here, the average number of MR-handover events over rounds is plotted for the bandwidth demand based method with and without intelligence. The result in this figure clearly demonstrates that without the notion of intelligence, the average number of MR-handover events increases gradually over time. As the number of time rounds approaches 10000, the number of MR-handover events exceeds 200. On the other hand, the average number of MR-handover events remains quite low for the entire course of simulation in case of the proposal with intelligence. For example, for the last time-round considered in this simulation, i.e., during the 10000^{th} time-round, the average number of MR-handover events is only approximately 40.

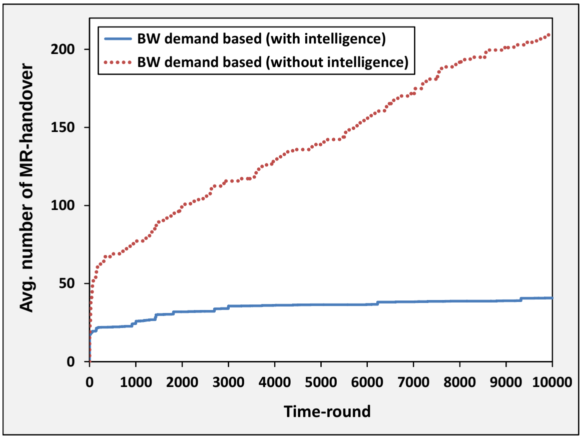


Fig. 7 Average number of MR-handover events over time-rounds for the BW demand based traffic distribution method with and without intelligence.

6 Conclusion

The research objective of our research work is to quickly construct disaster zone WMNs by utilizing the surviving network equipment such as wireless routers and access points in the affected area. One of the critical challenges in such networks consists in the traffic distribution issue among the users for avoiding congested GWs and unfair allocation of bandwidth. In this paper, we considered a disaster area WMN comprising a network management center, referred to as NMC, and investigated the problem of traffic load balancing amongst the GWs in the considered network. To overcome this problem, effective traffic load distribution techniques were proposed from two perspectives. Our proposal from the first perspective adopts a balanced distribution of the bandwidth to be allocated per user. On the other hand, our second perspective considers the dynamic bandwidth demands originating from the disaster zone users. The latter needs a more practical and intelligent distribution of the bandwidth demand per GW. The effectiveness of our proposals is evaluated and compared with existing and basic techniques through extensive computer-based simulations.

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Author Biographies

Mostafa M. Fouda received his Ph.D. degree in Information Sciences in 2011 from Graduate School of Information Sciences (GSIS), Tohoku University, Japan. He received B.Sc. degree with honors in Electrical Engineering (Electronics & Telecommunications) in 2002, and M.Sc. degree in Electrical Communications in 2007, both from Faculty of Engineering at Shoubra, Benha University, Egypt. He is currently serving as an Assistant Professor at Tohoku University. Also, he has held a number of faculty positions at Benha University, as Teaching Assistant from 2002 to 2007, as an Assistant Lecturer from 2007 to 2011, and as an Assistant Professor (referred to as Lecturer position in the Egyptian academic system) from 2011 to date. He has a noteworthy contribution toward research community through his technical papers in scholarly journals, magazines, and international conferences in various areas of networking and communications. He is an associate editor of the International Journal on Internet and Distributed Systems (IJIDS) and a guest editor of the Special Issue (SI) on Wireless Network Intrusion in Journal of Computer and System Sciences, Elsevier (2012-2013). He served as a Session Chair at IEEE ICCC'12. He has been serving as Technical Program Committee (TPC) member in several IEEE international conferences like Globecom, ICC, PIMRC, etc. He also serves as a reviewer of a number of renowned IEEE journals and magazines such as COMST, TPDS, TWC, TSG, TWireless, TETC, etc. His research interests include cognitive radio networks, disaster resilient networks, wireless mesh networks, smart grid communications, network security, peer-to-peer applications, and multimedia streaming. He was a recipient of the prestigious First Place Award from the Faculty of Engineering at Shoubra in 2002. He is a member of IEEE.

Hiroki Nishiyama received his M.S. and Ph.D. in Information Science from Tohoku University, Japan, in 2007 and 2008, respectively. During his PhD, he was a Research Fellow of the prestigious Japan Society for the Promotion of Science (JSPS). Following his graduation, he became an Assistant Professor at the Graduate School of Information Sciences (GSIS) at Tohoku

University. He was promoted to his current position of an Associate Professor at GSIS in 2012, when he was only 29 years old. He is a young yet already prominent researcher in his field as evident from his valuable contributions in terms of more than 100 peer-reviewed papers including many quality publications in prestigious IEEE journals and conferences. He was awarded with the Best Paper Awards from many international conferences including many IEEE's flagship events, namely the IEEE Wireless Communications and Networking Conference in 2012 (WCNC'12) and the IEEE Global Communications Conference in 2010 (GLOBECOM'10). He currently serves as the Secretary of IEEE ComSoc Sendai Chapter and a SAC Symposium Co-chair of IEEE ICC'14. He was also a recipient of the IEICE Communications Society Academic Encouragement Award 2011 and the 2009 FUNAI Foundation's Research Incentive Award for Information Technology. He received the Best Student Award and Excellent Research Award from Tohoku University for his phenomenal achievement during his undergraduate and master course study, respectively. His research interests cover a wide range of areas including traffic engineering, congestion control, satellite communications, ad hoc and sensor networks, and network security. He is a member of the Institute of Electronics, Information and Communication Engineers (IEICE), and he is also an IEEE senior member.

Ryu Miura received the B.E., M.E., and PhD degrees in Electrical Engineering from Yokohama National University, Yokohama, Japan, in 1982, 1984, and 2000, respectively. He joined Radio Research Laboratory, Tokyo, Japan in 1984, which was reorganized to National Institute of Information and Communications Technology (NICT) in 2004. Now he is a director of Dependable Wireless Lab, Wireless Netowork Research Institute, NICT, Yokosuka, Japan, where he works on disaster-resilient wireless networks and the application of unmanned aircraft wireless relay networks. Dr. Miura is a member of 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, Japan, in 1988 and 1991, respectively. He joined Computer Center of Tohoku University at 1991, and has been a full professor with the Graduate School of Information Sciences since 2003. He became Strategic adviser to the President of Tohoku University since 2013. He has been engaged in research on satellite communications, computer networking, wireless mobile communications, smart grid, image processing, and pattern recognition. He has published more than 300 papers in peer-reviewed journals and conference proceedings. He will serve as elected Member-at-Large (2014-2017) on the Board of Governors, IEEE Communications Society. He currently serves as the Vice Chair of IEEE Ad Hoc & Sensor Networks Technical Committee, the Chair of IEEE ComSoc Sendai Chapter, the steering committee member of WCNC and a voting member of GITC, an editor of IEEE Wireless Communications (2006-), IEEE Wireless Communications (2006-), IEEE Network Magazine (2012-), IEEE Transactions on Wireless Communications (2008-), IEEE Transactions on Vehicular Technology (2010-), and IEEE Trans. on Parallel and Distributed Systems (TPDS, 2011-). From 2013, he also serves as an Associate Editor-in-Chief of TPDS and IEEE Internet of Things Journal. He has served as the Chair of IEEE 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, a symposium co-chair of GLOBECOM'07, ICC'10, ICC'11, ICC'12, Vice Chair of IEEE WCNC'10, WCNC'11, ChinaCom'08, ChinaCom'09, Symposia co-chair of GLOBECOM'12, TPC Vice chair of ICC'14, 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 Communications Society, 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), IEEE GLOBECOM/WCNC/VTC Best Paper Awards, 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 (2012-2014) and the co-PI of A3 Foresight Program (2011-2014) 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.