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***Abstract*—Recently, the research community has paid much attention to Wireless Mesh Networks (WMNs) for rapidly formulating disaster zone networking infrastructures. These multi-hop WMNs, with almost stationary wireless Mesh Routers (MRs) as an access network, and gateways (GWs) connected to Internet, present an attractive choice for quickly establishing post-disaster recovery networks. However, one of the main challenges in such infrastructures consists in the traffic distribution among the users for avoiding congested GWs. In this paper, we focus on the issue of distributing and balancing the traffic load among the main GWs of the disaster zone WMN. We propose a novel method for controlling the handover of some of the MRs connected to the congested GWs. The performance of our method is evaluated by conducting computer-based simulations. The simulation-results demonstrate the effectiveness of our proposed method in keeping the number of network-configuration changes to minimal while resulting in a better Fairness Index compared with other conventional techniques.**

***Keywords*-Disaster zone network, traffic distribution, Wireless Mesh Networks (WMNs).**

I. Introduction

Recently, there has been a remarkable impact of natural disasters on our heavily technology-oriented life. Disaster events, such as earthquakes, tsunamis, floods, and tornadoes, interrupt telecommunication services such as cellular phone communication, third generation (3G) and Long Term Evolution (LTE) networks, and Internet infrastructures [1]–[4]. While the critical infrastructures, which essentially support our modern society, may escape physical damage due to the disaster, it is expected that they would be overwhelmed with heavy traffic from the users in the disaster zone. 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 alleviate such congestion, previous researches used Mobile Ad Hoc Networks (MANETs) [5], [6] to quickly formulate disaster zone networks to gather critical information about the inhabitants of the affected area, and to mobilize support for them [1]. Disaster zone networking, however, needs to address a number of challenges with ad hoc communication technology, such as densely managing the contrast of populated areas and a large number of sparse networks having intermittent connectivity, energy-constrained resources, and bandwidth limitations.

Instead of using ad hoc communication technology, the research community has, therefore, paid attention to Wireless Mesh Networks (WMNs) for formulating disaster zone networks [2]. The WMNs are multi-hop wireless networks, with a fixed wireless backbone composed of usually stationary wireless Mesh Routers (MRs), which provide more bandwidth resources compared to its basic ad hoc counterpart. Therefore, WMNs can be utilized for promptly setting-up a new communication infrastructure to recover network collapse following a disaster event (e.g., earthquake, tsunami, and so forth). However, one of the main challenges in WMN infrastructures is the traffic distribution among the nodes in order to avoid the formation of bottleneck(s). In this paper, we focus on the issue of distributing and balancing the traffic load among the main gateways (GWs) of WMNs used in a disaster area. In order to effectively manage traffic distribution in our considered network, a network management center is used to co-ordinate the traffic distribution in the disaster zone WMN. We highlight the problem of congested GWs in the considered WMN due to a large number of users demanding to connect to the gateway from the disaster area (i.e., the spatially dense crowded areas attempting to connect with the Internet). In order to address this problem, we propose a novel method for controlling the handover of some of the MRs connected to the congested GWs. Our proposed method, with the aid of computer-based simulations, demonstrate its effectiveness in keeping the number of network-configuration changes to minimal while achieving a better Fairness Index compared with some of the conventional techniques.

The remainder of the paper is structured as follows. Section II presents relevant research works on disaster zone networks. Section III describes our disaster zone network model. The section also highlights the key challenges in designing a robust network for disaster areas. To overcome some of the challenges, our novel heuristic-based traffic distribution method in the disaster zone network is proposed in Section IV. The performance of the proposed method is evaluated in Section V through computer-based simulations. The paper concludes in Section VI.

II. Related Work

Following the strong earthquake in Wenchuan, China, in May 2008, the importance of post-disaster network planning and construction, along with disaster countermeasures involving future networking technologies were taken into account in the work in [3]. This work describes how the worst hit areas became an “isolated information island” due to destruction of communication infrastructure, failure of timely power and logistics supply, and network congestion. Three schemes were used simultaneously to establish connection with the outside using very small aperture terminals, hand-held satellite phones, and optical cables, in order to provide disaster relief work. [3] also suggests studying future-oriented disaster countermeasures of network and technology.

Asplund *et al.* [1] pointed out that the information dissemination in disaster zones needs timely and energy-efficient communication in the networks, which are intermittently connected. The work suggests the use of a manycast algorithm in a wireless mobile ad hoc network topology. However, it does not investigate how WMNs can be adopted to improve the resource limitations associated with conventional ad hoc networks.

A MANET-based emergency communication and information system for catastrophic natural disasters was presented in [4]. The system aims at supporting a large number of rescue volunteers, and comprises a peer-to-peer network using notebook computers to construct the emergency communication infrastructure. However, the resource constraint of the user-nodes, due to the absence of localized data concentrators or aggregators (such as MRs), can be considered as a significant shortcoming of this work.

Wishart *et al.* [2] provided a survey of client handoff approaches applicable to IEEE 802.11 WMN for public safety and disaster recovery networks. However, this work does not take into account the effect of having high number of users in some of the MRs, which can lead to heavy traffic to their respective GW. In our work, we address and solve this issue by proposing a heuristic-based method.

III. System Model & Problem Formulation

In this section, we describe our considered disaster zone network model. As depicted in Fig. 1, we consider a Network Management Center (NMC) with a ground station connected to a satellite. We assume utilizing the existing network equipment (e.g., wireless routers and Access Points (APs)) in restaurants, stations, offices, and so forth. We also assume that those network equipment (which usually operate in the normal Wireless Fidelity (WiFi) mode) are to be opened for public use as wireless MRs following a disaster. In other words, we are considering the simple yet effective utilization of the network equipment deployed prior to the disaster. Those MRs are used, in our model, to connect the inhabitants of the disaster area with the communication network through a number of GWs. In order to avoid interference in the communication channel between the MRs, every MR is assumed to be equipped with multiple Network Interface Cards (NICs) so that each MR can communicate with its adjacent MRs without interference. More details about channel assignment are described in [7], [8]. The bottleneck of the entire system can be identified by considering the amount of traffic in each wireless link. For the considered network model, the traffic congestion at the wireless interface (which is connected with the MRs) of a GW makes it the bottleneck of the network.

In our research, in order to increase the bandwidth utilization and to limit the end-to-end delay, we attempt at distributing the load equally amongst the existing GWs, and we define an optimization problem with the following objectives.

TABLE I
List of notations used in the paper.

Symbol	Notation
B_g	Bandwidth allocated to every user belonging to GW "g".
b_u	Bandwidth allocated to user $u \in \mathcal{U}$.
C_g	Wireless link capacity of GW "g".
$\mathcal{G}$	Number of GWs in the considered network.
f	Fairness index.
h_r	Number of hops from MR "r" to its belonging GW.
$\mathcal{R}_g$	Number of MRs in GW "g".
MR^g	MR belonging to GW "g".
$\mathcal{U}$	Total number of users in all GWs.
U_{ho}	Number of users required for MR-handover to a new GW.
U_r	Number of users in MR "r".
U_r^*	Maximum variation in U_r per time-round.

1) ***Balanced distribution of the number of users per GW.*** This can result in having approximately the same bandwidth per user (i.e., achieve communication bandwidth fairness for the users).
2) ***Minimization of the total number of hops in the WMN.*** The total number of hops represents the gross sum of the number of hops from every MR to its corresponding GW. As pointed out in [9], in the wireless multi-hop network, an increase in the number of hops results in an increase of the relay delay accompanied with other issues, e.g., interference and cross traffic.

By using the list of notations listed in Table I, the aforementioned objectives can be formulated as follows.

$$\max \min_{\forall g} \frac{C_g}{\sum_{r=1}^{\mathcal{R}_g} U_r}\ , \text{ where } (g \in \mathcal{G}). \quad (1)$$

$$\min \sum_{g=1}^{\mathcal{G}} \sum_{r=1}^{\mathcal{R}_g} h_r\ , \text{ where } (h_r \geq 1). \quad (2)$$

Eq. 1 represents the objective function for having almost the same bandwidth allocated to each user. The wireless link capacity of each GW is divided by the number of users of that GW, the minimal value is then maximized to improve the fairness. Eq. 2 represents the objective function for minimizing the total number of hops in the WMN. The summation of the number of hops from every MR and its corresponding GW is computed, and its minimization guarantees the quality of communication between a MR and its GW. Note that the hop count is always greater than (or equal to) one.

An objective function with multiple problems (as the one stated above) is referred to as a multi-objective function. Owing to the multiple criteria in the objective functions in Eqs. 1 and 2, there may be trade-offs between their objectives. As a consequence, it is quite difficult to derive a solution, which may achieve optimization for all the objectives simultaneously. In other words, it is impossible to improve the value of one objective function without worsening the value of the other objective function. Normally, the solution for such multi-objective optimization problem is called Pareto-optimal solution, and in general, multi-objective optimization problems

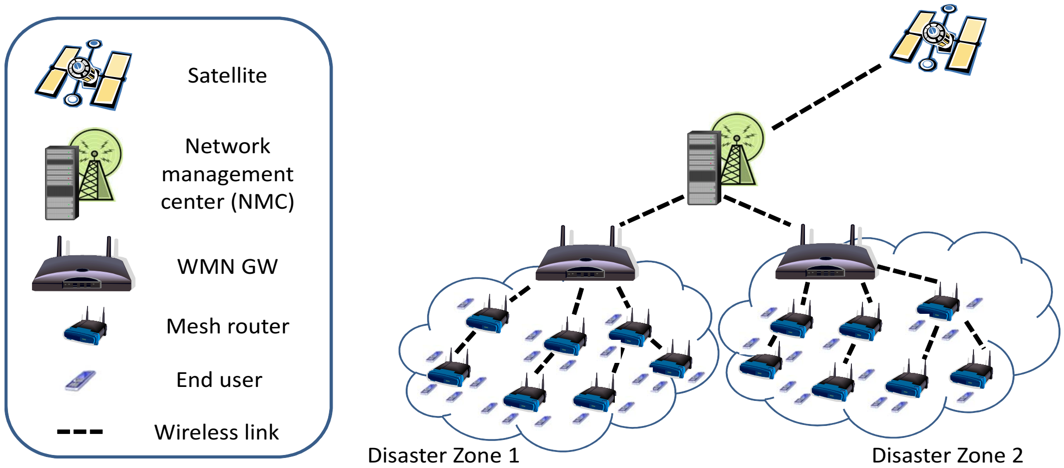

Fig. 1. Considered disaster area network model.

have many solutions. Therefore, even though it is necessary to explicitly define how to select only a single solution, achieving such a solution is usually difficult. In this paper, we solve this multi-objective optimization problem approximately through a heuristic-based method, which is presented in the next section.

IV. Envisioned Solution for Effective Traffic Distribution in Disaster Area WMN

In this section, we present our envisioned heuristic-based load distribution method, which has two objectives, namely (i) to decrease the hop count (it is worth reminding that the hop count refers to the number of hops between the GW and the MR servicing the users), and (ii) to achieve fairness to the bandwidth allocated to each user in the WMN. Our heuristic is repeated until the bandwidth allocated to the users reaches a steady state. In other words, the heuristic is executed up to the point when no further improvement (in terms of assigning higher bandwidth to the users in all the GWs) is possible. This section is divided into two parts. Our basic heuristic-based method for fairly assigning the bandwidth to the users in the disaster zone is proposed in Sec. IV-A. On the other hand, Sec. IV-B delineates how the heuristic-based approach may be enhanced to deal with the effect of mobility of the users.

A. Proposed heuristic-based method

Fig. 2 demonstrates our proposed heuristic-based method, which is executed in time-rounds (shortly referred to as "rounds" in the remainder of the paper). The figure shows a number of sequential steps performed in each round, t, which are described in the following. The notations used in these steps are mentioned in Table I.

1. The first step comprises the NMC performing the computation of B_g, the bandwidth allocated to every user belonging to GW "g" as in Eq. 3 (where $g \in \mathcal{G}$ and $\mathcal{G}$ refers to the number of GWs in the system).

$$B_g = \frac{C_g}{\sum\limits_{r=1}^{\mathcal{R}_g} U_r}. \quad (3)$$

2. In the second step, it is verified whether B_g for each gateway in $\mathcal{G}$ is the same. If so, the round does not need to continue. The next round may then commence in which the NMC computes new B_g values for $\forall g \in \mathcal{G}$.
3. If B_g is not the same for $\forall g \in \mathcal{G}$, then two GWs, i and j, are selected such that the following conditions hold.

$$B_i = max\{B_g,\ g \in \mathcal{G}\}. \quad (4)$$

$$B_j = min\{B_g,\ g \in \mathcal{G}\}. \quad (5)$$

4. Next, the system checks if each MR in GW "j", denoted by MR^j, has an adjacent Mesh Router in GW "i", denoted by MR^i. If no MR^j finds any adjacent MR^i, then the current i is excluded and another i (i.e., a different GW) is to be selected.
5. In case that MR^j successfully finds an adjacent MR^i, the NMC performs the following.
(i) The NMC sorts the MR^js having adjacent MR^i(s) in an descending order of hop count (where the considered hop is from the respective MR^j to its current GW "j").
(ii) The NMC, at the same time, computes the required number of users for MR^j handover to have a fair bandwidth per user in GWs "i" and "j". This number is denoted by U_{ho} as shown in Eqs. 6 and 7.

$$\frac{C_i}{\sum_{x=1}^{\mathcal{R}_i} U_x + U_{ho}} = \frac{C_j}{\sum_{y=1}^{\mathcal{R}_j} U_y - U_{ho}}. \quad (6)$$

$$U_{ho} = \frac{C_i \sum_{y=1}^{\mathcal{R}_j} U_y - C_j \sum_{x=1}^{\mathcal{R}_i} U_x}{C_i + C_j}. \quad (7)$$

6. Next, the NMC needs to decide an appropriate MR^j for handover.
7. Then, the NMC checks if "inversion" occurs between B_i and B_j. By "inversion", we refer to the situation when B_i becomes the minimum and B_j becomes the maximum.

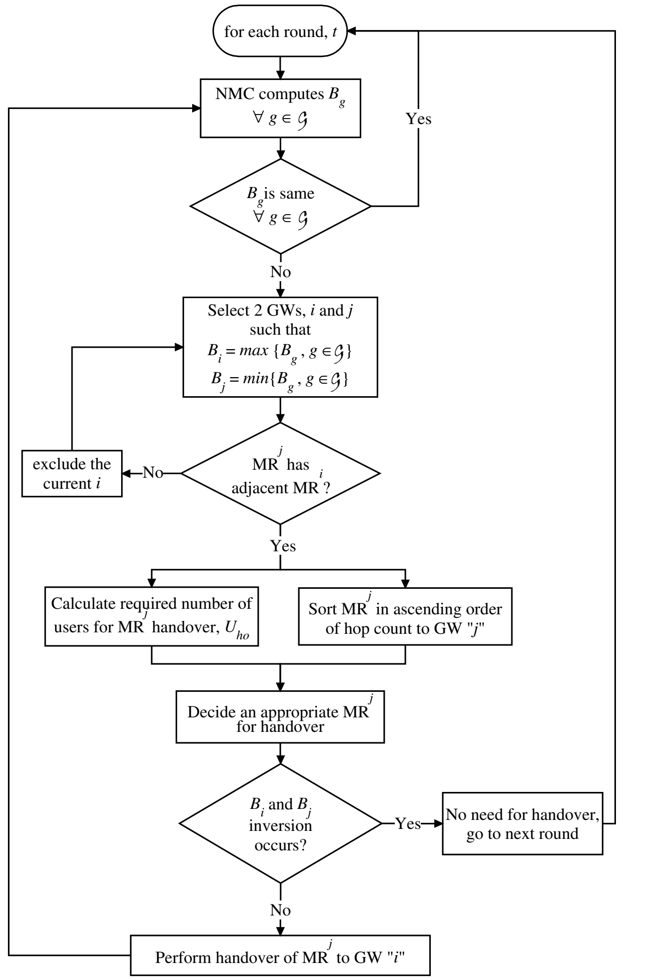

Fig. 2. The steps of the proposed heuristic-based method for effectively distributing the traffic load in the disaster area WMN.

8. If "inversion" occurs between B_i and B_j, the NMC considers it unnecessary for performing handover of MR^j from its old GW "j" to new GW "i". The current round t ends, and the next one may begin.
9. On the other hand, if the "inversion" does not occur, the NMC allows the MR^j to perform handover to GW "i". Following this, the NMC repeats the steps from 1 to 9.

B. Adjustments made to the proposed heuristic to deal with the user mobility

In this section, we describe the effect of the variation of the number of users due to their mobility on the proposed heuristic. Accordingly, we also describe how the heuristic-based proposal may be enhanced to counter the effect of this issue.

Due to the wireless nature of the WMN, the users are expected to move freely. The users are free to join, leave, or perform handover from one MR to another in a dynamic way (i.e., the number of users of each GW changes dynamically with time). In order to achieve fairness in the bandwidth allocated for each user, we have to regularly perform handover for some MRs from a GW to another as the number of users changes. However, in order to do that, and due to excessive management, the control overhead will increase and affect the communication bandwidth.

To deal with this issue, we modify our proposed heuristic-based method and take into account that the handover of MRs should only be performed under certain circumstances in order to decrease the control overhead. This can be achieved by taking into account the variation of the number of users in order to avoid a reverse handover of the same MRs within a time-window. In this paper, we assume an estimation of the maximum change of the number of users per round. By using this, a simple example is demonstrated in Fig. 3 to illustrate a situation, where the GW "j" has more users than those in GW "i" that results in performing a handover of a MR from GW "j" to GW "i". In the next round, due to the dynamic variation in the number of users, the situation is reversed, and the same MR requires a reverse handover to go back to GW "j".

To overcome this problem, we compute the difference of B_i and B_j. If this difference is lower than a certain threshold, the MR need not perform any handover. Otherwise, the MR performs the handover. By doing so, the number of network-configuration changes is reduced.

In order to take into account the worst case scenario, we may consider the maximum variation of the number of users per MR in the post-handover round. The difference of the bandwidth per user in the current round and that in the worst case post-handover round are computed by using Eqs. 8 and 9, respectively.

$$D_1 = \frac{C_i}{\sum_{x=1}^{\mathcal{R}_i} U_x} - \frac{C_j}{\sum_{y=1}^{\mathcal{R}_j} U_y}. \tag{8}$$

$$D_2 = \frac{C_j}{\sum_{y=1}^{\mathcal{R}_j} U_y - U_{ho} - \sum_{y=1}^{\mathcal{R}_j - 1} {U_y}^*} - \frac{C_i}{\sum_{x=1}^{\mathcal{R}_i} U_x + U_{ho} + \sum_{x=1}^{\mathcal{R}_i + 1} {U_x}^*}. \tag{9}$$

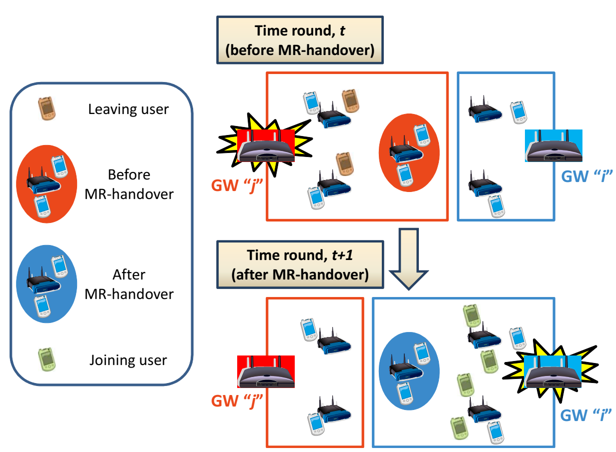

Fig. 3. A simple example explaining the worst case scenario.

$$\textit{Condition for MR-handover:} \quad D_1 \geq D_2. \tag{10}$$

The considered post-handover worst case scenario, formulated in Eq. 9, is the one where the number of users belonging to the MRs of GW "i" increases to its maximum limit, while the number of users connected to the MRs of GW "j" decreases to its minimum limit. The handover decision is taken when the current difference in the bandwidth per user is greater than or equal to that in the post-handover worst case scenario (as shown in inequality (10)). This is in order to assure that in the next round, we will not need to perform a reverse handover even if a worst case variation in the number of users occurred. Thus, this proposed enhancement to our heuristic-based approach decreases the number of network-configuration changes along with the control overhead.

V. Performance Evaluation

In this section, we evaluate the performance of the proposed method through computer-based simulations conducted in MATLAB [10]. The considered simulation parameters are listed in Table II. As shown in the table, 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 amongst the three GWs (i.e., 7 MRs per GW), and the initial numbers of users connected to the corresponding MRs of the three GWs are arbitrarily considered to be 10, 20, and 25, respectively. Thus, in total we have 385 users in the considered simulations. It is worth mentioning that this arbitrary assignment does not affect the fundamental observations of the simulation results. The maximum variation in the number of these users per MR in a time interval is set to two. From the fairness point of view, we also consider that there should be an upper boundary for the number of users per MR in order to ensure that excessive users are not assigned to a given MR. The maximum numbers of users per MR, thus, are considered to be 20, 25, and 25 in the three GWs, respectively. On the other hand, it is also necessary to have a lower bound for the number of users per MR so that the MRs do not remain under-utilized and the precious bandwidth is not wasted in the disaster zone. Therefore, we set the minimum numbers of users per MR to 10, 20, and 10 belonging to the three considered GWs, respectively. The number of rounds considered in the simulations is set to 100. The simulations are repeated for 300 times, and the average values are obtained as results.

In the remainder of this section, for the sake of clarity, the proposed heuristic-based method without the users mobility consideration (described in Sec. IV-A) and that enhancing the heuristic-based approach to deal with the effect of the variation of the roaming users (presented in Sec. IV-B) are referred to as the "basic" and "enhanced" proposals, respectively. Also, three performance metrics are taken into account, namely (i) the average hop count, (ii) Fairness Index for estimating how fairly the bandwidth is allocated amongst the users, (iii) the number of network-configuration changes. The performances of the basic and enhanced proposals are illustrated through these metrics in the following.

TABLE II
Simulation environment.

Parameter	Value
Number of GWs, $\mathcal{G}$	3
Number of MRs, $\sum \mathcal{R}$	21
Number of users, $\mathcal{U}$	385
GW wireless link capacity	100 Mbps
Initial number of users per MR	10, 20, 25
Maximum number of users per MR	20, 25, 25
Minimum number of users per MR	10, 20, 10
Maximum variation in the number of users per MR per one time interval	2
Number of time-rounds	100
Number of simulation runs	300

The average number of hops for the basic and enhanced proposals, the conventional Hybrid Wireless Mesh Protocol (HWMP) scheme [11], and the maxmin solution (i.e., solution to Eq. 1) are compared in Fig. 4. The results demonstrate that the average number of hops in the maxmin solution suffers from the worst performance, reaching just over four. This means that, on average, the MRs (and the users connected to them) require four hops to connect to their respective GWs, thereby increasing transmission delay. This happens because the maxmin solution does not consider minimizing the number of hops. On the other hand, the basic and enhanced proposals, and HWMP exhibit average hop count of approximately 2.5.

Next, we compare the Fairness Index (FI) achieved using each of the considered methods. Here, Jain's FI, as shown in Eq. 11 [12], is used.

$$f = \frac{\left(\sum_{u=1}^{\mathcal{U}} b_u\right)^2}{\mathcal{U} \cdot \sum_{u=1}^{\mathcal{U}} {b_u}^2} \tag{11}$$

The reason behind using Jain's FI is that it rates the fairness of a set of values, where there are $\mathcal{U}$ users and b_u is the bandwidth allocated to user u $(\in \mathcal{U})$. Note that $b_u = B_g$ if the user u is served by the GW "g". The FI value in Eq. 11 ranges from the worst case value of $\frac{1}{\mathcal{U}}$ to the best case of value one. FI becomes the maximum when all the users receive the same bandwidth allocation from their respective GWs. As Fig. 5 demonstrates, our basic and enhanced proposals outperform the HWMP scheme by a significant margin. In fact, the FI achieved by the proposed heuristic-based method (both basic and enhanced) is over 0.99, i.e., very close to the maximum. On the other hand, the HWMP is able to distribute the bandwidth among the users with a Fairness Index of approximately 0.94. It is also worth noticing that the FI of the maxmin solution is even closer to the maximum value of one. This indicates that there is a trade-off between the average hop count and FI, while using the proposed heuristic-based method (both basic and enhanced) and the maxmin solution.

In Fig. 6, the number of network-configuration changes for the basic and enhanced proposals and the maxmin solution are plotted over 100 rounds. As demonstrated by the figure, the

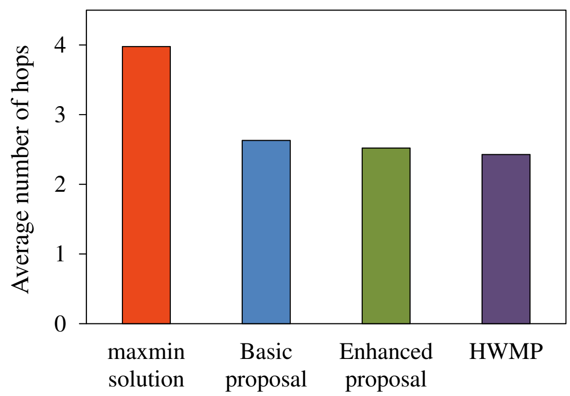

Fig. 4. Average number of hops for different approaches.

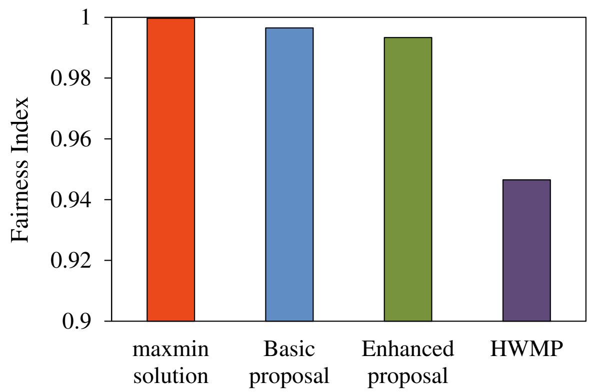

Fig. 5. Fairness Index for different approaches.

number of network-configuration changes increases almost linearly for all the considered approaches. The maxmin solution, however, exhibits the most drastic rate of network changes. In contrast with the maxmin solution, the basic proposal results in much lower network changes rate. The enhanced proposal, on the other hand, lowers this rate even further which helps stability of the network and reduces the overhead associated with the handover of MRs. In particular, the latter indicates the effectiveness of our proposed heuristic-based method with the appropriate enhancement to deal with the mobility of the users.

VI. Conclusion

In this paper, we focused on quickly constructing disaster zone WMNs by utilizing the network equipment such as wireless routers and access points that were already deployed in the affected area. One of the key challenges in such networks is the traffic distribution among the users for avoiding congested GWs and unfair allocation of bandwidth. By addressing this issue in the paper, we proposed a novel heuristic-based method for controlling the handover of some of the MRs connected to the congested GWs. The heuristic-based proposal was further enhanced to cope with the traffic variation due to users mobility. Simulation-results demonstrate the effectiveness of our proposed method, in contrast with conventional techniques, in keeping the number of network-

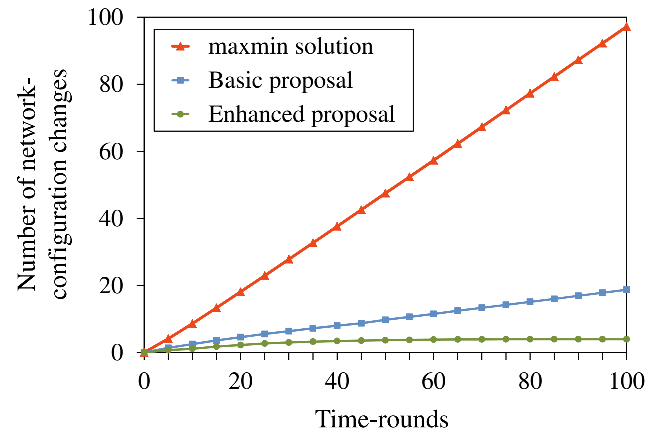

Fig. 6. Number of network-configuration changes for different approaches.

configuration changes to minimal while resulting in a better Fairness Index and a reasonable hop count.

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