A Probabilistic Approach to Deploying Disaster Response Network

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***Abstract*—Disasters, in most cases, cause the breakdown of important structures, such as communication and Internet connection. This is concerning because victims need a way to communicate, either to contact family and loved ones for emotional support or those responsible for disaster relief in order to coordinate rescue and safety measures. Because these scenarios are characterized by a lack of infrastructure, one attractive solution is to bring in mobile communication units to provide connection as part of disaster relief. This is the basis behind moveable and deployable resource unit (MDRU) based wireless mesh networks (WMN), where the MDRU is a communication equipment, usually mounted on a vehicle, that is deployed into a disaster area to establish a WMN (i.e., a mostly static, highly interconnected network) with an Internet connection. Here, the MDRU is the one responsible for connecting victims to exterior networks. However, MDRU based WMNs are composed of different hierarchical levels, such as routers and gateways, as well as the MDRU and users themselves. Despite this, existing literature model it as a flat network. In this paper, we propose a hierarchical model of the MDRU based WMN, which is more realistic than conventional research. Additionally, our model exposes an interlevel tradeoff relationship between the number of routers and performance in this network, which proves that too little or too many routers both lead to low quality of experience. Our research, thus, analyzes this tradeoff and provides the optimal configuration that maximizes throughput.**

***Index Terms*—Wireless mesh networks, disaster response networks, moveable and deployable resource unit, probabilistic modeling.**

I. Introduction

A DRASTIC disaster such as an earthquake or a tsunami is known to cause damage in many aspects including human lives, household, transportation infrastructures, power infrastructures, and telecommunication infrastructures. After the Great East Japan Earthquake on March 11, 2011, the telecommunication infrastructures in the affected area suffered greatly. Even with the great effort from the Nippon Telegraph and Telephone (NTT) Corporation, it took approximately a month and a half to restore the telecommunication infrastructures in the affected area [1], [2].

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In these critical situations [3], rescue and recovery operations revolve around communication technologies for connecting different bodies of responders. Beyond that, it is also important to restore Internet connection as early as possible, to allow victims to be reached by these rescue responders and also allow the victims to contact family and friends to receive and provide emotional support in this difficult moment. For example, a survey from the University of San Francisco, School of Management [4] points out that social media services, such as Twitter and Facebook, are widely used as a tool to contact friends and inform loved ones of their situations and retrieve emergency. Thus, despite the loss of infrastructure, it is very important to somehow re-establish a long distance connection between the disaster area and the Internet as soon as possible, as part of the relief efforts. This can be done through the use of non-conventional connection equipment that relies less on infrastructure, such as unmanned aerial vehicle (UAV) networks [5], delay tolerant networks (DTNs) [6], and wireless mesh networks (WMNs) [7].

One of the most promising types of disaster relief network architectures used for reinstating Internet connection is the Moveable and Deployable Resource Unit (MDRU) based WMN [1] because it can promptly provide real-time communications to the disaster area. Here, MDRU is a mobile equipment, usually mounted on a vehicle, that has strong communication capabilities, with a large coverage of local equipment as well as the means of establishing connection to outside networks. After a disaster strikes, the MDRUs can be dispatched to the disaster area and establish a WMN based on the existing mesh routers (MRs) or MRs that are transported along with the MDRUs (in fact the only difference from regular WMNs is how the MDRU is the centralized point for connecting to external networks; just like normal WMNs, the MDRU based one is mostly static and has rich interconnection). Hence, the disaster victims in the evacuation centers will be able to establish communication services such as Internet connection with their common WiFi equipped communication devices. However, the MDRU based WMN architecture exhibits several problems; in particular, the network capacity will likely be exceeded as the evacuation center becomes increasingly crowded. This is a serious problem because the performance of 802.11 or WiFi devices drastically decreases with the number of users. Previous research [8] shows that multiple MRs can be used to improve the performance of wireless networks in a critical situation. Therefore, in order to ensure the successful deployment of MDRU based WMN, a method for choosing an appropriate number of MRs to provide the best connectivity services is necessary. However, the MDRU based WMN is made of multiple layers, as shown by Fig. 1, with many components each, so changing something as the number of routers may have positive or negative ramifications in the

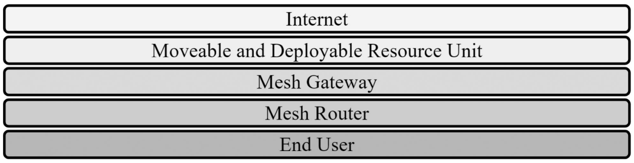

Fig. 1. The hierarchical layered architecture of the MDRU based WMN.

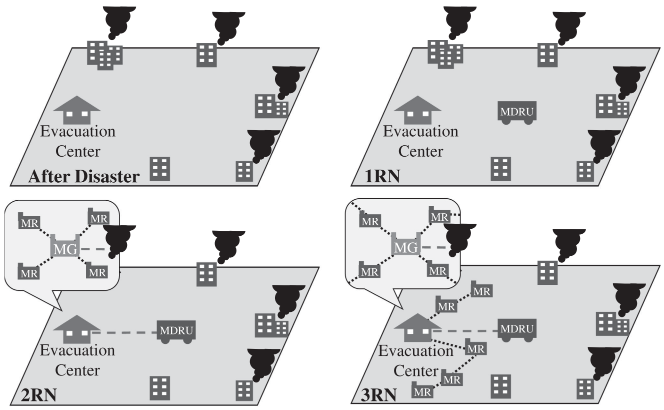

Fig. 2. An illustration of deployment framework of the MDRU based WMN.

other layers and the system as a whole. This characteristic referred to as the interlevel tradeoff exists in multi-level networks, such as the MDRU based WMN and it is why we must perform a thorough network analysis in order to determine the optimal configuration for this kind of change [9].

According to the framework illustrated in [10], the network for disaster situations can be classified based on the requirements and deployment complexity into the first response network (1RN), second response network (2RN), and third response network (3RN). For the MDRU based WMN, the framework can be divided in a similar manner such that the 1RN MDRUs are transported to the disaster areas to quickly establish a connection with outside networks using available means, such as remaining optical fiber infrastructures, satellites, or unmanned aerial vehicles networks. With the connectivity, the MDRUs will be able to satisfy the basic needs of operating personnel with their communication and computing utilities as illustrated in Fig. 2. During the 2RN deployment, MDRUs will try to extend their connectivity services to the disaster victims by establishing connectivity within places like evacuation centers and shelters by placing necessary MRs to facilitate WiFi enabled Internet connectivity for devices such as smartphones and tablets. Finally, during the 3RN deployment, the MDRU will extend their range of services even more by introducing additional MRs to the networks. The 2RN network is extremely critical because it is the first phase of the deployment framework that is open to the disaster victims. Many difficulties, such as high density of users and high demand for connectivity services, can deteriorate the network performance to the point of being unusable, which will further delay the deployment of future networks like 3RN.

In this paper, we take into account the interlevel tradeoff property of MDRU based WMN and propose a probability based disaster relief network planning scheme to optimize the number of MRs required to provide connectivity services in a given evacuation center during the 2RN deployment. Compared to the literature, our proposal is more realistic because it takes into account the hierarchical layers of the MDRU based WMN, while existing research models it as a flat network. The contribution of this paper can be summarized as follows:

- We illustrate the interlevel tradeoff property of the MDRU based WMN.
- Based on the interlevel tradeoff property, we formulate a mathematical model to estimate the performance of the MDRU based WMN.
- Using the formulated mathematical model, we derive the number of MRs that should be deployed in the evacuation center in order to maximize Quality of Experience given a tolerance condition.

The remainder of the paper is organized as follows. Section II provides a literature review on disaster relief networks. Section III illustrates the scenario assumptions and definitions. Section IV details our analytical model for analyzing the performance of the 2RN MDRU based WMN. Section V presents our results and discussion. Finally, we conclude this paper in Section VI.

II. Literature Review

A number of works on disaster relief networks [11], [12], especially MDRU based WMNs, has been conducted. Sakano *et al.* [1] explained the demand for disaster relief networks and described the MDRU based WMN network in details. They also provided a simple simulation result, which shows that one MDRU based WMN can provide Internet access to around 560 users, with each user provisioned with 24 kbps. Lin *et al.* [13] and Fu *et al.* [14] both investigated the highly related Machine to Machine paradigm, more specifically the impact of movement of the many users in the performance of the network and how to manage device mobility, while Fu *et al.* [15], in another work, further investigated the performance of Machine to Machine communications with the focus now on the tradeoff between energy utilization and data accuracy. Ngo *et al.* [16] provided a new performance metric called the spectrum-energy efficiency, in order to measure the spectrum efficiency and energy efficiency of the MDRU based WMN while also providing a method to maximize said metric.

While MDRU based networks are designed specifically for disaster recoveries, they do deploy 802.11 technologies. Therefore, it is essential for us to be aware of the performance of 802.11 based networks. Tickoo and Sikdar [17] presented an analytical model using G/G/1 queuing to estimate contention delays and collisions. Huang *et al.* [18] derived an analytical framework for ring-based wireless mesh network and proposed a method to maximize the throughput by adjusting the number of rings and the radius of each ring. The connectivity and capacity of wireless networks are estimated analytically by [19]. The findings concluded that higher node density increases connectivity while reducing the cumulative throughput. It is understandable that more nodes would increase connectivity. However, the results that more nodes reduce the throughput may come from the fact that only MRs and one mesh gateway (MG) are considered. As mentioned earlier, Jun *et al.* [20] derived a simple but effective method for computing the upper-bound throughput of a WMN under the assumptions that the MAC layer is fair and that the MRs in the network have the same offered load. Additionally, there are many works that focus on the performance of 802.11 technologies. Bianchi [20] provided an accurate

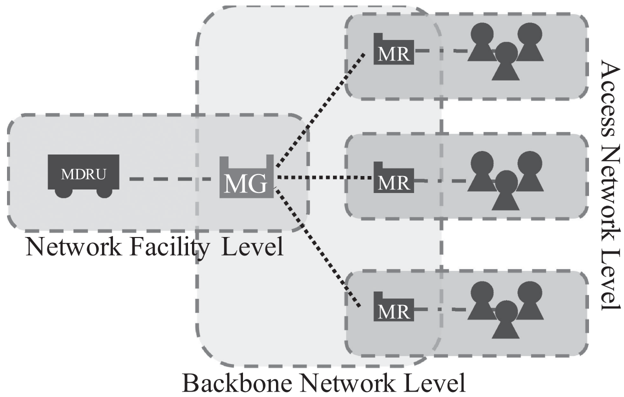

Fig. 3. An overview of the MDRU based WMN architecture.

analytical model based on Markov's chain to compute the throughput of 802.11 in the DCF mode. Wang and Aceves [22] came up with a similar analytical model for Ad-Hoc networks where they took into account the problem of hidden terminals.

Although there is plenty of research on both the MDRU based disaster recovery network and general 802.11 based networks, it is notable how the majority of these works focus on "flat" networks where the nodes considered are the only category of nodes within the network. Since MDRU based WMNs have a hierarchical architecture in which different levels are affected by one another, we aim to determine an analytical model and provide detailed insight of the deployment of this type of network.

III. System Definitions and Assumption

In this section, we define and introduce our network model and scenario while stating any assumptions made in this work. First, the unique characteristics of MDRU based WMNs along with the 3-level architecture will be introduced. Second, the assumed scenario will be explained.

A. 3-Level Architecture of MDRU based WMN

MDRU based WMN, as shown in Fig. 3, is a unique disaster relief network. In contrast with a rather flat network commonly found in other WMNs, wireless ad hoc networks, or sensors networks [20], [23], MDRU based WMN is hierarchical, consisting of three different levels as follows:

1) Network Facility Level: The network facility level (NFL) facilitates the connection between the MDRU and MG that are both equipped with fixed wireless access (FWA) transmitters and receivers. FWA permits the MDRU and the MGs to communicate by using the Quasi-Millimeter wave operated at 26 GHz. The MGs will forward the uplink traffic received from the backbone network level (BNL) to the MDRU while forwarding the downlink traffic from the MDRU to other MRs in the BNL. Detailed information regarding NFL and FWA transmitters and receivers can be found in [24] and [25].

2) Backbone Network Level: The backbone network level interconnects MRs and MGs to form a WMN that acts as a backbone network carrying traffic between the mesh clients (MCs) and the NFL.

3) Access Network Level: The access network level (ANL) is the level where each MR acts as a wireless access point to provide connectivity service to MCs within the MR's vicinity. Since the MRs operate based on the well-adopted standard 802.11, the MCs, such as smartphones, laptops, or commercial tablets, will be able to join the network without needing any special equipment or setting.

Regardless of the different levels, NFL, BNL, and ANL are not entirely unrelated. Since the NFL communications are conducted by using the high-performance FWA transmitters and receivers, the performance is assumed to be high. Hence, in this work, we focus on the BNL and ANL. From our assumption, it was mentioned that the MRs do not send any data frames of their own. Therefore, the number of data frames that can arrive at the MGs, which will be forwarded to the MDRU, will depend on both the performance of the BNL and ANL. When the performance in the ANL is low, fewer data frames will reach the MRs to be forwarded to the MG. On the other hand, if the performance in the BNL is low, fewer data frames being forwarded from the MRs will be able to reach the MGs. Hence, the performance of each level is heavily reliant on one another.

B. Assumed Scenario

We assume that after a disaster the MDRU will be deployed to the affected area to set up a communication network for disaster relief. The assumed network scenario is composed of an MDRU, an MG, multiple MRs, and a certain number of clients. After the lifetime of 1RN has ended, a BNL composed of an MG and some MRs will be set up at locations where disaster victims gather, such as shelters and evacuation centers. To establish the BNL, the MDRU communicates with the MG via FWA transmitters and receivers, which are assumed to be high-performance while the MG and MRs are implemented with 802.11a equipment for BNL communications. Because disaster response networks need to be deployed quickly, in our considered scenario we assume that 2RN utilizes the flexible wireless network 802.11, which allows for simple installation and utilization. Since an evacuation center is assumed to have a maximum number of evacuees that it can accommodate, the number of clients can be deduced. Finally, each MR is also equipped with another 802.11a interface to provide the access network or ANL to the clients within its vicinity. Due to the limitation of the number of network interfaces of the MG and MRs (two network interfaces, one for BNL communications and the other for ANL communications), it is assumed that all MRs share the same channel when communicating with the MG or, in other words, the communications in BFL share the same communications medium. However, since the 802.11a standard (with 802.11h revision) specifies over 23 orthogonal channels, each MR operates its own access network or communications in ANL in an orthogonal channel. It is assumed that the clients will always have traffic to send, while the MRs will only forward traffic and do not generate their own data traffic.

IV. MDRU Based WMN Performance Analysis

In this section, we present a numerical analysis on analyzing the performance of a given MDRU based WMN. In this work, a probability-based approach is used to determine the average throughput of a given network scenario.

A. Channel Transmission Markov Chain

First, to model the behavior of a wireless channel, we use the channel transmission Markov chain, which is given in Fig. 4.

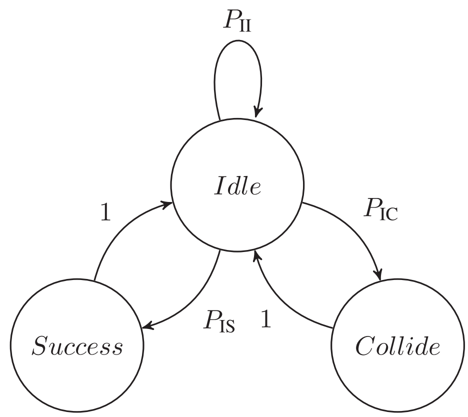

Fig. 4. The channel transmission Markov chain.

Markov chain models have been used to represent 802.11 channel access before [21] due to how the network nodes operate in states with nearly deterministic probabilities between them [26]. This Markov chain characterizes a scenario where multiple child nodes are trying to transmit a data frame to the parent node using a shared medium. The child nodes and parent node can vary depending on the level that is currently in focus. For example, in ANL, the parent node is the MR acting as an access point and the child nodes are the clients that are trying to transmit data frames. It is composed of three states, which are defined as follows:

- Success: when any given data frame successfully arrives at the destination node or, in other words, when only one node transmits during this time interval.
- Idle: the channel is idle because no node is transmitting during this time interval.
- Collision: there is more than one node transmitting during this time interval, thus resulting in a collision.

P_{II}, P_{IS} and P_{IC} are different state transition probabilities. P_{II} is the probability of transitioning from the idle state to the idle state or in other words the probability that no node will transmit during this time interval, and hence can be mathematically defined as

$$P_{II} = (1 - P_t)^n, \tag{1}$$

where P_t is the probability of a node transmitting within a time interval while n is the total number of child nodes (clients or MRs) within the destination node (MRs or MG) vicinity. The probability that the node will transmit within this time step takes into account the backoff probability, P_t, derived by [21] under the assumption that there is no exponential backoff, where

$$P_t = \frac{2}{W + 1} \tag{2}$$

and W is the backoff window of the child nodes. P_{IS} is the probability of transitioning from the idle state to the success state or when there is only one node transmitting during this time interval, defined as

$$P_{IS} = P_t(1 - P_t)^{n-1}. \tag{3}$$

Finally, P_{IC}, which is the probability of transitioning from the idle state to the collision state, or when there are more than one child nodes transmitting within this time interval. When more than one child node transmits within the same time interval, a collision will occur. Since our sample space is composed of three states, P_{IC} can be easily determined as

$$P_{IC} = 1 - P_{II} - P_{IS} \tag{4}$$

The Markov chain in Fig. 4 can be written as the following state transition matrix

$$\boldsymbol{P} = \begin{pmatrix} P_{II} & 1 & 1 \\ P_{IS} & 0 & 0 \\ P_{IC} & 0 & 0 \end{pmatrix}. \tag{5}$$

Since this transition matrix, P, does not have any special structure and is small in size, we can solve it by using the direct technique. We start with the equilibrium equation

$$\boldsymbol{P}s = s, \tag{6}$$

which can be written as

$$\boldsymbol{A}s = 0, \tag{7}$$

where s is the vector

$$s = (\, s_i \quad s_s \quad s_c.\,)^T \tag{8}$$

s_i, s_s, and s_c are the steady state probabilities of the idle, success, and collision states, respectively, and matrix $A = P - I$, where I is the identity matrix. Thus,

$$\boldsymbol{A} = \begin{pmatrix} P_{II} - 1 & 1 & 1 \\ P_{IS} & -1 & 0 \\ P_{IC} & 0 & -1 \end{pmatrix}. \tag{9}$$

There are many solutions to this system, and hence we have to introduce an additional equation to obtain a unique solution. The elements in vector s are probabilities and sum to one, i.e.,

$$s_i + s_s + s_c = 1. \tag{10}$$

Therefore, we can replace any row in Eq. (9) with 1 resulting in

$$\begin{pmatrix} 1 & 1 & 1 \\ P_{IS} & -1 & 0 \\ P_{IC} & 0 & -1 \end{pmatrix} \begin{pmatrix} s_i \\ s_s \\ s_c \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}. \tag{11}$$

Therefore,

$$\begin{aligned} s_i + s_s + s_c &= 1, \\ s_i P_{IS} - s_s &= 0, \\ s_i P_{IC} - s_c &= 0. \end{aligned}$$

The elements in vector s can be easily solved by manipulations and the steady state probability of each state can be derived as

$$s_i = \frac{1}{2 - P_{II}}, \tag{12}$$

$$s_s = \frac{P_{IS}}{2 - P_{II}}, \tag{13}$$

$$s_c = \frac{P_{IC}}{2 - P_{II}}. \tag{14}$$

Eq. (12), (13), and (14) will be used in both ANL and BNL models with different notations to represent different levels.

Throughout the remainder of the paper, subindex c will correspond to the ANL and m will corresponde to the BNL.

B. ANL Successful Transmission Probability

In this section, we determine the probability of a successful transmission in an ANL. In other words, the ANL successful transmission probability is the probability that a data frame is successfully sent from clients to the MR within a given time interval. From now on, we will be referring to the ANL successful transmission probability as s_{s_c}, which can be determined by using the channel transmission Markov chain introduced in the previous section where the child nodes are the clients and the parent node is the MR. The probability that we are currently interested in is the ANL successful transmission probability or s_{s_c}. Therefore, by substituting Eq. (1), Eq. (3) and Eq. (4) into Eq. (12), Eq. (13) and Eq. (14), with simple manipulation, s_{i_c}, s_{s_c} and s_{c_c} are obtained as follows:

$$s_{i_c} = \frac{1}{2 - (1 - P_{t_c})^{n_c}}, \tag{15}$$

$$s_{s_c} = \frac{P_{t_c}(1 - P_{t_c})^{n_c - 1}}{2 - (1 - P_{t_c})^{n_c}}, \tag{16}$$

$$s_{c_c} = \frac{1 - (1 - P_{t_c})^{n_c - 1}}{2 - (1 - P_{t_c})^{n_c}}. \tag{17}$$

where n_c is the number of clients that are within the MR vicinity and P_{t_c} is the probability that a client will transmit within this time interval (given by Eq. (2)).

C. MRs Transmission Probability

Since the MRs do not generate any data frame but instead forward the traffic from the ANL, they do not always have data frames to send. In order to determine the probability that each MR will transmit in a given time interval, the probability that the queue or the buffer of the MR will be empty is derived. From here on, we will be using the terms queue and buffer interchangeably. The buffer of the MRs is modeled by an M/M/1/B queue, which is considered because of its simplicity and its suitability in modeling a First-in First-out queue with limited queue size. Hence, the probability that the buffer will be empty is given by queuing theory to be

$$P_{\text{empty}} = \frac{1 - \rho}{1 - \rho^{B+1}} \tag{18}$$

where B is the buffer size and

$$\rho = \frac{\lambda}{\mu}. \tag{19}$$

Here, λ is the arrival intensity (i.e., how many packets arrive per unit of time at the MR) and μ is the inverse of the average service time (i.e., how long on average it takes for the MR to send the packet on top of its queue to the MG). In this case, the arrival intensity λ is derived from the probability that a data frame will arrive at the MR at a given time interval, which is the ANL successful transmission probability, s_{s_c}, defined in the previous subsection. However, as the real time spent in one successful transmission is not the same as the real time spent in one idle time interval, the rate of the number of data frames arriving per time period still has to be determined. With t_{success}, t_{idle}, and t_{collide} being the time taken to successfully transmit useful data, time per one idle interval, and time wasted per collision, respectively, the rate of data frames arriving per time period can be determined as

$$\lambda = \frac{s_{s_c}}{s_{s_c} t_{\text{success}} + s_{i_c} t_{\text{idle}} + s_{c_c} t_{\text{collide}}}. \tag{20}$$

The average service time at the BNL can be obtained in an analogous way. Since the data frame only really leaves the queue when it arrives at the MG, we can utilize the arrival intensity at the gateway as a measure of how many frames successfully leave the BNL. The opposite of the arrival rate (i.e., how many frames arrive per second) will give us how long it takes for any frame to arrive at the MG on average. Additionally, note that this value corresponds to data frames coming from all MRs. Because we are interested in the value for a single MR, we multiply it by n_m. Finally, as mentioned in its definition, μ is the inverse of this last value, which leads us to

$$\mu = \left(n_m \frac{s_{s_m} t_{\text{success}} + s_{i_m} t_{\text{idle}} + s_{c_m} t_{\text{collide}}}{s_{s_m}} \right)^{-1}. \tag{21}$$

After P_{empty} is determined, we calculate the probability that an MR will transmit within this given time interval by using the MR transmission Markov chain shown in Fig. 5. The MR transmission Markov chain is composed of many states where state "0" represents that the MR transmits. Furthermore, state "1" to state "$W - 1$" represent the random backoff window from one to the maximum backoff window, W. The idle state is the state where there is no data frame to be sent. Since MR will select a backoff window with equal probability, the probability

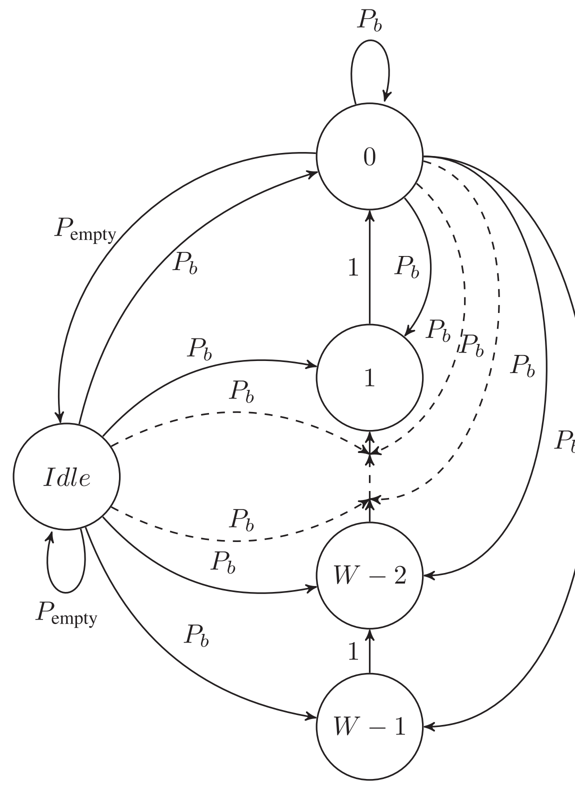

Fig. 5. The MR transmission Markov chain. State 1 to W − 1 represent the backoff time while state 0 is where the node transmits the data frame. Idle state is where there is no data frame to be sent.

of transitioning to any backoff state is P_b, which is determined as

$$P_b = \frac{1 - P_{\text{empty}}}{W}, \tag{22}$$

where P_{empty} is the probability of the buffer being empty as defined in Eq. (18) and W is the maximum backoff window of the MR. The MR transmission Markov chain in Fig. 5 can be represented by the following transition matrix

$$\boldsymbol{P_m} = \begin{pmatrix} P_{\text{empty}} & P_{\text{empty}} & 0 & 0 & \cdots & 0 & 0 \\ P_b & P_b & 1 & 0 & \cdots & 0 & 0 \\ P_b & P_b & 0 & 1 & \cdots & 0 & 0 \\ P_b & P_b & 0 & 0 & \ddots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \ddots & 1 & 0 \\ P_b & P_b & 0 & 0 & \ddots & 0 & 1 \\ P_b & P_b & 0 & 0 & \ddots & 0 & 0 \end{pmatrix}. \tag{23}$$

We have to solve this Markov chain for the steady-state probability of state "0" to determine the probability that the MR will transmit. Since the matrix is large, it cannot be solved by the direct technique used in the previous subsection. However, it is important to note that the matrix is a form of lower Hessenberg matrix. Thus, we can use the backward substitution technique. First, the equilibrium equation is

$$\boldsymbol{P_m s_m} = \boldsymbol{s_m}, \tag{24}$$

where P_m and s_m are the transition matrix and a distribution vector similar to that of Eq. (6). s_m is defined as

$$\boldsymbol{s_m} = \begin{pmatrix} s_{\text{idle}} & s_0 & s_1 & \cdots & s_{W-1} \end{pmatrix}^T. \tag{25}$$

From Eq. (24), it is possible to see that

$$s_{\text{idle}} = P_{\text{empty}} s_{\text{idle}} + P_{\text{empty}} s_0 \; ; \tag{26}$$

$$s_k = P_b s_{\text{idle}} + P_b s_0 + s_{k+1} \; , \; \forall k / 0 \leq k \leq W-2; \tag{27}$$

$$s_{W-1} = P_b s_{\text{idle}} + P_b s_0 \; . \tag{28}$$

By considering Eq. (27), Eq. (28) and a recursive sum from s_k to s_{W-1}, we can redefine s_k as

$$s_k = (W-k)(P_b s_{\text{idle}} + P_b s_0). \tag{29}$$

Additionally, by manipulating Eq. (26), we can alternatively define s_{idle} as

$$s_{\text{idle}} = \frac{P_{\text{empty}}}{1 - P_{\text{empty}}} s_0. \tag{30}$$

Since all elements in s_m are probabilities within the same sample space, the sum of all elements will have to add up to one; hence,

$$\sum_{k=0}^{W-1} s_k + s_{\text{idle}} = 1. \tag{31}$$

However, by using Eq. (29), we arrive at the conclusion that

$$\sum_{k=1}^{W-1} s_k = P_b(s_{\text{idle}} + s_0)\frac{W(W-1)}{2}. \tag{32}$$

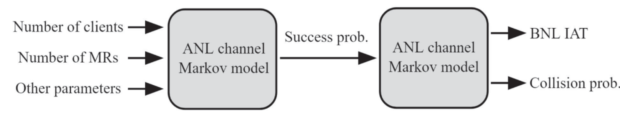

Fig. 6. Diagram for the order on which the values are calculated in our model.

Thus, by substituting Eq. (32) into Eq. (31), we end up with

$$(s_{\text{idle}} + s_0)\left(1 + \frac{P_b W(W-1)}{2}\right) = 1. \tag{33}$$

Finally, by combining Eq. (30) and Eq. (33) we are able to appropriately find s_0.

$$s_0 = (1 - P_{\text{empty}})\left(1 + \frac{P_b W(W-1)}{2}\right)^{-1}. \tag{34}$$

With the value of s_0, it is possible to use the steady-state probabilities of the channel transmission Markov chain with the parent node being the MG and the child node being the MRs to find the actual interarrival time of data frames at the MG. Firstly, the real steady-state probabilities of the Idle, Success, and Collide states are determined using Eqs. (12), (13), and (14), but instead with the BNL parameters as follows

$$s^*_{i_m} = \frac{1}{2 - (1 - s_0)^{n_m}} \tag{35}$$

$$s^*_{s_m} = \frac{s_0(1 - s_0)^{n_m - 1}}{2 - (1 - s_0)^{n_m}} \tag{36}$$

$$s^*_{c_m} = \frac{1 - (1 - s_0)^{n_m}}{2 - (1 - s_0)^{n_m}}. \tag{37}$$

Finally, we determine the interarrival time at the MG, IAT, using the BNL channel steady-state probabilities derived above as

$$IAT = \frac{s^*_{s_m} t_{\text{success}} + s^*_{i_m} t_{\text{idle}} + s^*_{c_m} t_{\text{collide}}}{s^*_{s_m}}. \tag{38}$$

IAT is a useful metric for showing the performance of the MDRU based WMN since it gives how long it takes for packets from the clients to reach the final destination. Lower values mean a higher network throughput while higher numbers mean not many data frames are arriving at the MG.

D. *Summary of Assumptions*

Our mathematical assumptions are as follows. We assume that the 802.11 channel access behaves following a Markov chain model [21], [26]. We also assume that user nodes transmit following Eq. (2), as explained in [21]. Finally, we also assume that the buffer of the MRs behaves as an M/M/1/B queue due to its operation as a simple First-in First-out queue with limited capacity [27].

V. Results and Discussion

In this section, we present the results through Figs. 7, 8, 9 and 10. In order to derive the results, we utilized the model from the previous section following the diagram in Fig. 6. For the other parameters, we considered that a single time slot takes 9 microseconds, "request to send" and "clear to send" procedures take 4 and 3 microseconds, respectively, and data transmission takes 113 microseconds. The idle state only takes the time slot

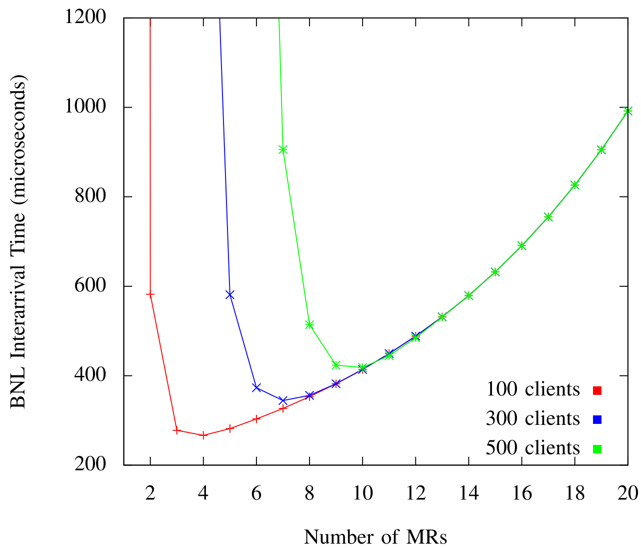

Fig. 7. The estimated interarrival time at the MG versus the number of MRs.

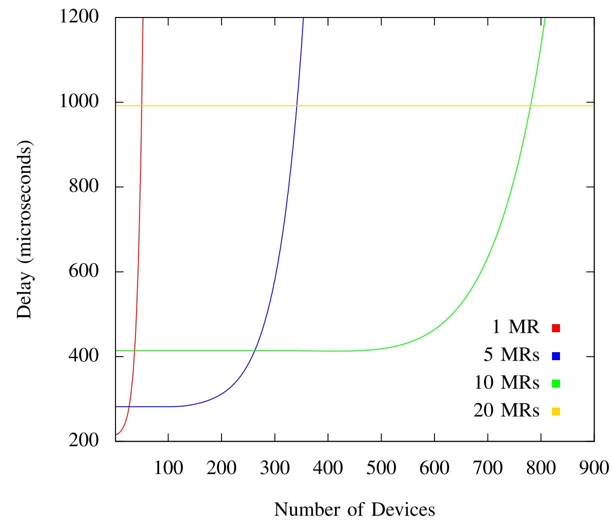

Fig. 9. Calculated IAT versus the number of clients for different numbers of MRs, showing network stability from different number of MRs.

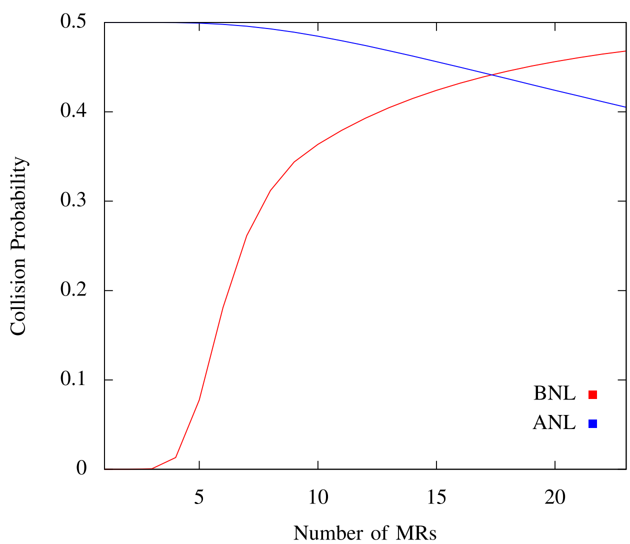

Fig. 8. The probability of collision in the BNL and ANL channels.

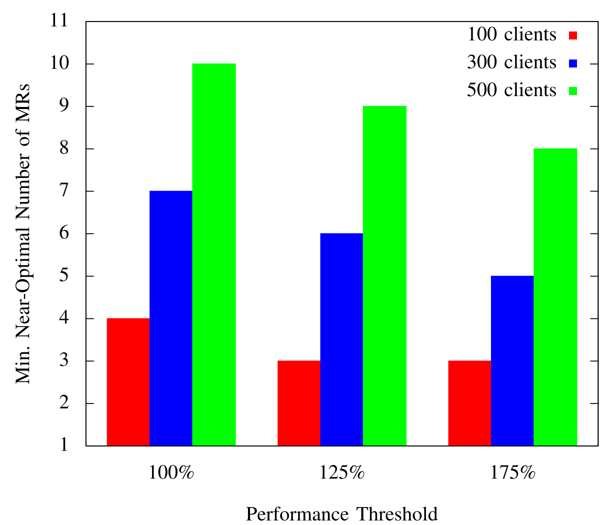

Fig. 10. The MNO for the evacuation center with various capacities.

time, while the collision state utilizes one "request to send" and the transmission state utilizes both "request to send" and "clear to send" as well as the data transmission time. We considered a backoff window of 20 for both BNL and ANL [28]. Because of limitations in the number of orthogonal channels, there can be 23 MRs at most.

Fig. 7 shows the IAT through 3 curves corresponding to 100, 300 and 500 clients, respectively. The expected number of clients is the number of clients that are expected within a specific evacuation center. In an actual situation, this number represents the maximum capacity that an evacuation center can support, which can be easily identified in the evacuation center specifications. The x-axis represents the number of MRs that is used in constructing 2RN and the y-axis represents the IAT. It is possible to see from the figure that the IAT decreases until the optimal number of MRs is reached. After the optimal number of MRs is reached, introducing more MRs would result in worse performance as shown in Fig. 7. The behavior is caused by the interlevel tradeoff properties of the MDRU based WMN. With a low number of MRs, collision in the ANL will be high, and thus, fewer data frames will be transmitted to the MRs. However, as shown in Fig. 8, more MRs is not always better. Fig. 8 shows two curves, which represent the collision probability for the BNL and the ANL. As it can be seen, more MRs lower collision in the ANL, since the MRs share the users and consequently have less workload, but also mean more collision in the BNL, as more senders compete in that environment. This also explains why the curves all converge ultimately: with high numbers of MRs, the bottleneck moves to the backbone and the number of clients becomes irrelevant as the performance worsens. This, indeed, suggests that the interlevel tradeoff property does exist and should be strongly considered in designing the network.

Fig. 9 shows the stability of the 2RN networks. As opposed to the traditional definition of stability, which is usually referred to as the connectivity of the network, our definition of stability is that of the resilience to the change in the number of clients. Fig. 9 shows IAT against the number of clients for different numbers of MRs. With respect to the minimum achievable IAT, the figure shows that a smaller number of MRs, such as 1 and 5, are able to achieve lower IAT than that of 10 and 20 MRs. However, it is also shown in the figure that the IAT in the cases of 1 and 5 MRs increases steeply as the number of clients grows while 10 and 20 MRs are much more resilient to the change in the number of clients. Hence, in order to efficiently and optimally deploy 2RN of MDRU based WMN, the number of n_m used to provide network service within the evacuation center should be considered based on the maximum capacity of the evacuation center. Using our derived analysis, it is possible to estimate the number of MRs that should be used to construct the network. This is because using more than the optimal number of MRs may result in degraded throughput for the entire network as shown in Fig. 7. However, it is important to keep in mind that during a disaster situation, the number of devices available is likely to be limited. Therefore, it is more beneficial to keep the number of deployed devices within a facility as low as possible while keeping the performance of the network at an acceptable level.

As seen from the previous results, using the optimal number of MRs does, indeed, result in the optimal performance. However, a near-optimal number of MRs is sufficient as the optimal number only provides a minor increase in performance. Therefore, we define a Minimum Near-Optimal number of MRs (MNO) as the minimum number of MRs that are required to achieve a performance within t percent of the optimal,

$$MNO = \min_{n_m}(IAT(n_m) \leq t \times IAT_{\min})$$

In this case, t can be seen as a quality of experience parameter because a smaller number of MRs is usually more desirable for the network deployment, but the users are also expected to have lower performance in return. Fig. 10 shows MNO required to provide specific t percent of the optimal performance in the 2RN network. The x-axis represents t in percentage where 100% is the optimal performance and 125% and 175% are 125% and 175% of the optimal performance, respectively. The y-axis shows the MNO, which represents the minimum required number of MRs to provide the performance corresponding to the t percentage requirement. It is possible to see from the figure that the MNO requirement for 120% and 160% is lower than that of the optimal point, 100%, and naturally fewer clients also require less MNO. With this information, it is possible to determine the necessary MRs required to provide performance within a given requirement threshold, t. Inversely, it is also possible to determine the performance level that should be expected when there are only a specific number of MRs available. As an example from Fig. 10, if 8 MRs are given, it is possible to provide optimal performance when there are 100 and 300 expected clients. However, the network will deliver 175% of the optimal performance when there are 500 expected clients. Therefore, due to the limited availability of equipment during emergency situations, MNO that matches the expected performance should be used to construct the 2RN.

VI. Conclusion

Natural or man-made disasters are widely known to cause drastic damage on communication infrastructures, paralyzing important means of communication in/out of the disaster areas. Owing to the importance of communications during disaster recovery, disaster relief networks, such as MDRU based WMN, aim to temporarily restore communications within the disaster area after a major disaster strikes. While being able to accommodate a large number of users, the density of disaster victims and rescue personnel at the evacuation center is likely to be extremely high during the 2RN deployment phase. Hence, multiple MRs should be used to provide improved communication services to the evacuation center. However, since the MDRU based WMN is a multi-level network architecture, the interlevel tradeoff characteristic is apparent. Therefore, in order to provide quality communication services, the number of MRs should be predetermined beforehand. This work provides an analytical framework and study for estimating the throughput of MDRU based WMN in order to select the most appropriate number of MRs based on the number of clients that an evacuation center would be able to accommodate. For future expansion of this research, we plan to tackle the issue of network scale that renders most current architectures and protocols unfeasible [29] through the use of Machine Learning-based solution [30], [31].

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