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A Performance Evaluation of Multiple MDRUs Based Wireless Mesh Networks

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***Abstract*—Since communications services become much more demanded after disaster strikes, it is necessary to promptly set up a temporary communications infrastructure to provide services to those in need. The Movable and Deployable Resource Unit (MDRU) based Wireless Mesh Network (WMN) is an attractive candidate to achieving this goal. In MDRU based WMN, the MDRU is transported to the disaster affected area by either ground or air transportation like truck or helicopter. After arriving at the disaster area, it configures any remaining wireless Access Points (AP) in the area to provide connectivity services. This work provides an insight on the performance of MDRU based WMN under the situation where multiple MDRUs are deployed within close region to increase the overall coverage and performance of the network. A simulation is conducted to estimate the performance of the network under both scenarios where mesh tier operates under a single channel and where a channel assignment scheme is applied. We show that the performance of MDRU based WMN can be greatly enhanced by deploying multiple MDRUs to the area. However, since the number of available MDRUs is limited, using more MDRUs than necessary is not efficient. We discuss some of the factors that should be taken into account when selecting an appropriate number of MDRUs for a single area.**

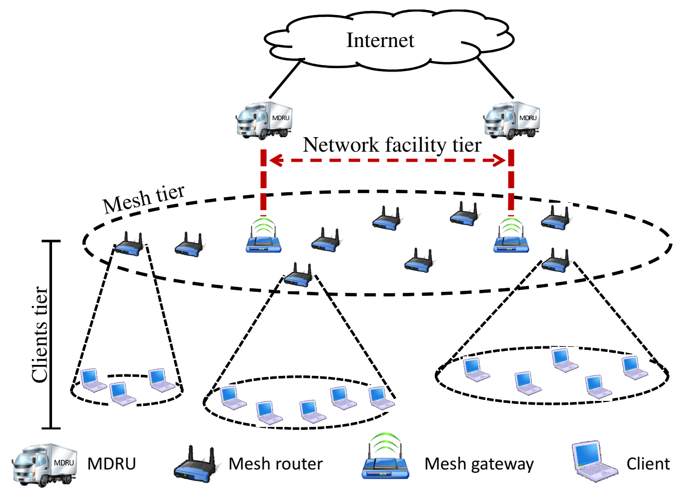

Fig. 1. An overview of MDRU based WMN.

I. Introduction

It is commonly known from history that drastic disaster, such as tsunami, earthquake, or tornado can cause enormous damage to the affected area. Communications services play an important role in disaster recovery. Therefore, a temporary communications infrastructure is necessary to be able to provide the required communications service to the disaster area, such as providing a means of communication for disaster recovery personal, making safely confirmation possible, and providing up to date information to the disaster victims. One of the promising network infrastructures, which aims to promptly restore communications service to the disaster area is the Movable and Deployable Resource Unit (MDRU) based Wireless Mesh Network (WMN) proposed by [1]. As mentioned by the article, MDRU(s), which is composed of communications and other necessary equipment can be deployed to the disaster area by transportation truck or helicopter. After arriving at the affected area, MDRU will attempt to construct WMN from either the remaining wireless Access Points (AP) within range or the access points that are transported along with the MDRU itself. Thus, this makes it possible to provide communications services to those in need. In addition, multiple MDRUs can be deployed to provide more coverage and increase the overall performance of the network.

WMN is a classification of wireless communications network where multiple network nodes known as the Mesh Router (MR) interconnect to form an Ad-hoc like network that relays information in a multi-hop fashion to a node known as the Mesh Gateway (MG), which has connectivity to the outside network. Some of the main characteristics that set WMN apart from wireless Ad-hoc network are that nodes that participate in WMN like MRs and/or MGs are normally considered to be static while nodes in wireless Ad-hoc network are considered to be mobile. In addition, WMN traffic are usually considered to flow only to and from the gateway node or MG while in mobile Ad-hoc network, the communication usually happen between participating nodes. WMN is widely applicable to many areas such as establishing community network [2], and disaster recovery network [1] [3] [4].

MDRU based WMN is an attractive network architecture for disaster recovery because it is extremely robust, can be quickly deployed after disaster strikes, can cover a great distance, and can provide reliable connectivity services as demonstrated in [1] and [5]. In addition, as it relies on existing devices such as the remaining wireless APs, it can be quickly set up without having to physically establishing any infrastructure. In addition, the process of configuring remaining wireless APs into MRs also has another advantage in that it completely removes the probability that those remaining wireless APs will cause interference with the system as pointed out by [6].

II. Background

A. MDRU based Network Architecture

MDRU based WMN network is a type of network architecture, which aims to promptly setup communications infrastructure within the disaster area, where the fixed infrastructure may be damaged or destroyed by the disaster. It is composed of several components, namely the MDRUs themselves, MRs, MGs, and clients. MDRUs are large communications device composing of many communications equipment that have connectivity to the outside network like Internet via fiber optics or other means. MRs are either the remaining wireless APs such as those commonly found in residential and commercial areas or those APs, which are deployed in conjunction with the MDRUs. MGs are those MRs, which are equipped with special Fixed Wireless Access (FWA) receiver described by [7]. FWA receiver allows MGs to communicate with the MDRUs using a Quasi-Millimeter wave band, which operates at 26 GHz. Finally, clients are WiFi equipped devices like personal computer, tablet, smartphone, etc.

After arriving at the disaster area, MDRU will initiate an initialization signal that can propagate a large distance. Any compatible AP that receives the initialization signal will switch its operation mode from normal WiFi AP to an MR. MRs will then form a wireless mesh backbone with any MGs within the area and finally form the MDRU based WMN network. It is possible for multiple MDRUs to coexist within a single area to increase coverage or overall performance. An illustration of MDRU based WMN is shown in Fig. 1 where it is also possible to see that the network can be separated into three different tiers, namely the network facility tier, mesh tier, and clients tier. The network facility tier includes the communication between MGs and MDRUs through the equipped FWA receiver. The mesh tier is where MRs and MGs act as wireless mesh backbone network that carry information from the clients tier to MGs, which in turn forward the information to network facility tier. The connectivity in mesh tier is carried out by IEEE 802.11a in the 5GHz frequency band that operates at data rate of 54 Mbps. Finally, the clients tier is where the MRs and MGs act as WiFi APs to provide connectivity services to the WiFi equipped clients within their vicinity. Each MR acts as an IEEE 802.11g AP in the 2.4GHz frequency band that operates at data rate of 54 Mbps.

B. Related Works

In addition to MDRU based WMN, there are also other WMN deployment, which are evaluated in literature. One of these deployments includes the Roofnet WMN describes by [2], which is a single tier WMN built on 802.11b. The deployment of each MR is not planned as it is hosted by a volunteer user. It can achieve an average throughput of 627 kbits/second. Braunstein describes Extreme Networking System (ENS) in [3], which is a WMN architecture for emergency respond. ENS is a tier based WMN, which is similar to MDRU based WMN. However, while the clients tier and mesh tier exist for both architecture, MDRU based WMN has the added complexity of the network facility tier, which is missing in the ENS. Additionally, one of the unique characteristic of the MDRU based architecture is that it relies on the existing infrastructure such as remaining wireless APs.

Sakano decribes the MDRU based WMN in [1] along with providing initial performance evaluation of the network. In addition, [5] also provides detailed performance evaluation for both simple network environment and realistic network environment. The authors offer calculation of optimal offered load. The performance evaluations from the mentioned works provide an insight on the performance of the MDRU based WMN. However, both of these works only consider a network that only has a single operating MDRU. We take a different approach in focusing on multiple MDRUs scenario.

III. Multiple MDRUs based architecture

It was mentioned that some works has already been done on evaluating performance of MDRU based WMN, we instead focus on the multiple MDRUs architecture aspect of the MDRU based WMN. Even when a single MDRU is able to provide acceptable service to a very large area, there are some advantages in deploying multiple MDRUs to the disaster area to enhance the overall performance of the network. Two of the main advantage of deploying multiple MDRUs are as follows:

1) Coverage improvement: Since in the MDRU based WMN, MRs have to forward their traffic to the closest MG so that the traffic can then be forwarded to the MDRU and the outside network. Therefore, the number of MDRUs available plays a key role in determining the performance in the mesh tier. Normally, when there are more MDRUs, the coverage area also become larger assuming that they are not deployed to an exact same location. Therefore, more MGs can actually establish network facility tier connection to a MDRU and overall reduce the average number of MRs to closest MG hops. There are already many works in the literature, which show that larger number of hops to the destination (MG) can lead to lower performance. The authors of [8] shows that the end-to-end throughput capacity is greatly reduced when the number of hops increases. This is because of the interference between neighbouring nodes since only a single node can transmit within an interference range.

2) Capacity improvement: It was mentioned in [7] that the channel can be allocated optimally so that there are no interference between each MDRU cell. Therefore, the capacity of the network facility tier can be easily estimated by using the link capacity estimation of FWA link introduced by [7]. The capacity of link i, C_i can be approximated by

$$C_i = \frac{l_i}{\sum\limits_{j \in I(i)} l_j} \times C_{channel}, \tag{1}$$

where l_i is the expected load of link i and $I(i)$ is a set of all link that are interfering with links i. $C_{channel}$ is the capacity of the channel. If we assume that each MDRU will serve equal number of MGs then we can easily see from equation 1 that the overall capacity of network facility is just

$$C_{nft} = C_{channel} \times num(\text{MDRUs}), \tag{2}$$

where $num(\text{MDRU})$ is the total number of MDRUs. By just looking at equation 2, it is possible to see that the capacity in network facility tier greatly improves with the number of MDRUs deploys.

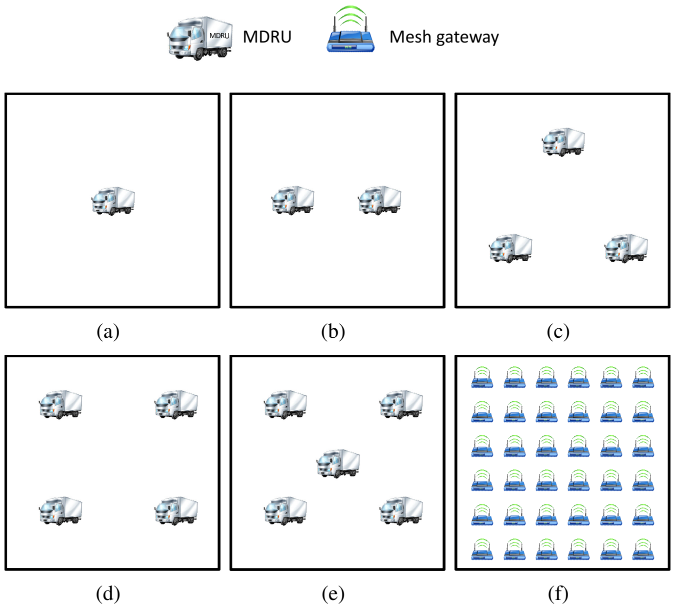

Fig. 2. Subfigures (a) to (e) provide the MDRUs deployment layout for the cases of one to five MDRUs deployment and (f) provides the layout for MGs deployment

IV. Performance Evaluation

A. Bottleneck Analysis

One of the unique characteristic of the tier based architecture is that since the traffic is carried from one tier to another, thus the overall performance of the network is dependent upon the tier that has the lowest performance. In another word, the tier that has the worst performance will become a bottleneck and will affect the overall performance of the network. In this work, we will be focusing on the network facility and mesh tier. The reason for omitting the clients tier is that the capacity of clients tier is much larger when comparing to two other tiers. Since the clients tier is composed of MRs operating as wireless APs through IEEE 802.11 network. The capacity can be estimated using the Theoretical Maximum Throughput (TMT) introduced by [9]. TMT is defined by the authors of [9] to be the upper limit of the throughput that IEEE 802.11 network can achieves. Some important assumptions that were used are no dropping packet from collision and no buffer overflow. Therefore, the actual throughput achievable in a more realistic scenario may be even lower than TMT. Nerveless, TMT is still a very useful tool in estimating the upper bound capacity of the clients tier and any other 802.11 based network. From [9], TMT can be calculate by following equation:

$$\text{TMT} = \frac{8x}{ax+b} \times 10^6\text{bps}, \tag{3}$$

where x is the size of MSDU in bytes, and a and b are constants unique to different MAC scheme and spread spectrum technologies, which can be found in [9]. Since our clients tier operate through 802.11a with data rate of 54 Mbps and using RTS/CTS the value of a and b are 0.14815 and 225.94, respectively. Assuming that each wireless AP operates in channel that will not interfere with its neighbours' cell, the capacity of the clients tier, $C_{clients}$ can be seen as

$$C_{clients} = \text{TMT}_{clients} \times num(\text{MRs}), \tag{4}$$

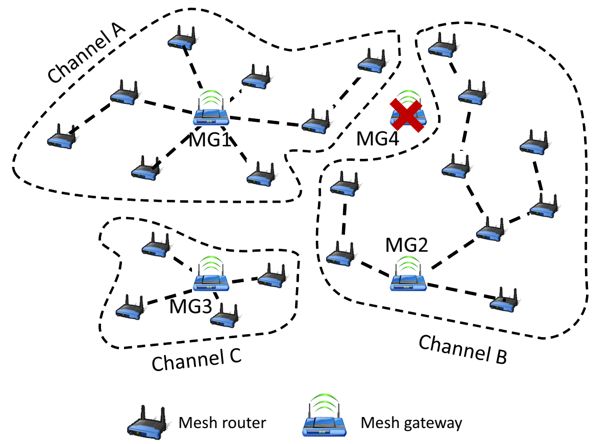

Fig. 3. An overview of the implemented channel assignment scheme where MG4 is outside MDRU transmission range.

TABLE I. Simulation Parameters

Parameter	Value
Simulation area	1315(m)×1315(m)
Number of MDRUs	1 to 5
Number of MGs	36
Number of MRs	1260
Transmission range of MDRU	400(m)
Transmission range of MR	80(m)

where num(MRs) is the total number of MRs and $\text{TMT}_{clients}$ represents the TMT of clients tier. When comparing $C_{clients}$ to the mesh tier capacity, which could only be

$$C_{mesh} = \text{TMT}_{mesh} \times num(\text{MGs}), \tag{5}$$

in the best case where num(MGs) and TMT_{mesh} represent the number of MGs and TMT of mesh tier, respectively. This is because a single gateway could only send or receive TMT_{mesh} of traffic, and by the best case we assume that all MRs are distributed equally within one hop of each MG. In addition, each MG does not interfere with each other. Both of these assumptions are not realistic; however, only the best case is required to determine the bottleneck tier of the network. Since mesh tier operates with 802.11a, $\text{TMT}_{clients}$ and TMT_{mesh} has the same value. However, since MGs are the type of node that requires special equipment, number of MGs will be less than number of MRs. Therefore, $C_{clients}$ is more than that of C_{mesh}. In addition, $C_{clients}$ is also much higher than C_{nft} since from [7], $C_{channel}$ is only a little larger than $\text{TMT}_{clients}$, but there are clearly many more MRs than MDRUs. With this, it is possible to see that the bottleneck will either be the mesh or the network facility tier.

B. Scenario

In order to evaluate the performance of the MDRU based WMN network, we conduct extensive simulations using Qualnet network simulator. Fig. 2 illustrates the deployment pattern of MDRUs and MGs, where multiple MDRUs are deployed within an area of 1315 meters by 1315 meters. A total of 1260 MRs are deployed randomly while 36 MGs are deployed in a 6×6 grid with equal separation as shown in Fig. 2(f). This represents the facts that MRs are remaining wireless APs

TABLE II. AVERAGE HOP COUNT FROM THE CLOSEST MG

Number of MDRUs	1	2	3	4	5
Average hops	3.78	2.51	2.19	1.90	1.90

within the area, and MGs are the FWA equipped device that are transported along with the MDRU. Each MR attempts to send a fixed amount of traffic to one of the deploys MDRUs in a multi-hop fashion through either the MG or other MRs. Multi-hop transmission are necessary because as shown in Table I, we can see the transmission rage of FWA links are only approximately 400 meters according to [7]. Therefore, MDRU(s) may not be able to cover every MGs in some scenario such as when there are only a single MDRU in the simulation area. In addition, some MRs may fall outside the transmission range of the MG, resulting in having to relay traffic through other MRs. In the network facility tier, MGs communicate with MDRUs via FWA link, where each MDRU operates in different orthogonal channel. Two scenarios are considered, the first is when the mesh tier communication are performed using only one single channel and the other is when a simple channel assignment scheme is implemented.

1) Single Channel: Many channel assignment algorithms have been proposed to enhance the performance of WMN such as [10] and [11]. However, all those methods required MRs to have multiple radio interfaces, which is not applicable in MDRU based WMN. Since each MR is only equipped with a single radio interface, an optimal channel assignment can be a complex problem. Thus, operating in a single channel is sometimes employed in WMN like as seen in the roofnet WMN evaluated in [2]. In this scenario, all operations in mesh tier operate in a single channel.

2) Multiple Channels: In this scenario, we consider a simple channel assignment scheme where each gateway are assigned an orthogonal channel. Since in 802.11a there are many orthogonal channels, it is possible to assign the channel in a way that the MGs, which are assigned the same channel will be outside the interfering range of each other. Each MRs first scan each channel for any operating MGs. Once it finds an operating MG that has available connectivity to a MDRU, it will be assigned the same channel as its target MG. In the case that a MR is not within transmission coverage of any MG, it will check its surrounding neighbours and assigns itself to the channel that has at least a MR that has a path to MDRU. Fig. 3 illustrates the implemented channel assignment scheme. In this case, all MGs are within the transmission range of the MDRU with an exception of MG4. MG1, MG2, and MG3 are assigned channel A, B, C, respectively. Therefore, the MRs that are within the transmission range of each MG are assigned the corresponding channel. In addition, nodes that have to do multi-hop transmission are assigned the channel of their parent MR.

C. Results

Fig. 4 and Fig. 5 presents the simulation results for the performance of MDRU based WMN using multiple MDRUs for both the single channel and channel assignment scenario, respectively. The performance is measured using the percent-

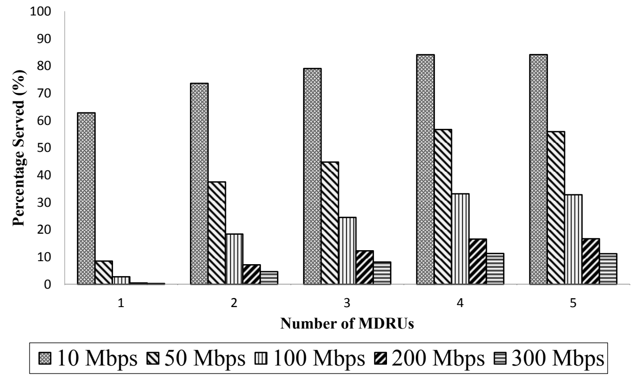

Fig. 4. Performance of MDRU based WMN in single channel scenario

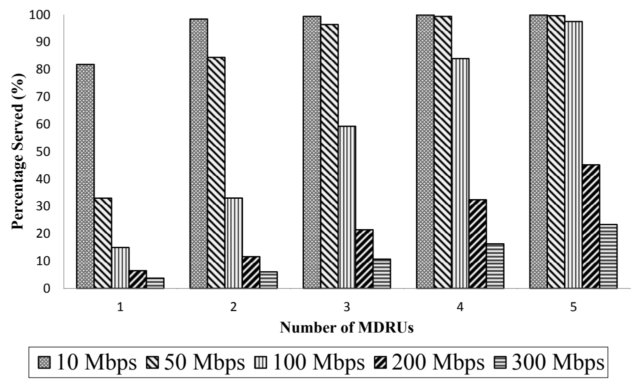

Fig. 5. Performance of MDRU based WMN in channel assignment scenario.

age served defined as

$$\text{Percentage Served} = \frac{\text{Total throughput}}{\text{Total traffic demand}} \times 100.$$

The number of MDRUs used in the experiments is varied from one to five. For the single channel scenario, this scenario indicates that there are congestion in the mesh tier since it only operates within a single channel. Therefore, all MRs or MGs within the same interference range will interfere with each other. Firstly, we can see that the percentage served in Fig. 4 is lower than that of Fig. 5 in all cases even when the network facility tier capacity, which can be calculated from equation 2 remains the same for both scenarios for each corresponding number of MDRUs. This shows that since in the mesh tier throughput of the single channel scenario is much lower than the capacity that can be provided by the network facility tier. Regardless, more MDRUs can still contribute to improving the performance of the network. This improvement come in the form of hop count reduction. Table II shows the average hop count from MRs to the closest MG. As you can see that since more MDRUs can cover more MGs, the average hop count decreases with the number of MDRUs until reaching 4 MDRUs where the coverage cannot increase any further. With the results shown in Fig. 4, we can see that in this scenario, it is only possible to provide up to around 84% of the demanded traffic even when the total demanded traffic is only 10 Mbps.

Fig. 5 shows the performance of the scenario with channel assignment. As shown in the figure, channel assignment greatly increases the performance in mesh tier by reducing interference between MRs. As a result, it is possible to achieve around 82% percentage served when the total traffic demanded is 10 Mbps even with just one MDRU deployed and almost up to 98% to 99% when two or more MDRUs are deployed. This indicates that only one or two MDRUs are required to provide acceptable service to the area when the total traffic demand is 10 Mbps. However, as traffic demand become higher, more MDRUs are required to provide better percentage served. As shown in Fig. 5, when total traffic demand becomes 50 Mbps, two and three MDRUs are required to provide around 84% and 96% percentage served, respectively. Moreover, when total traffic demand become increasingly high like 200 Mbps or 300 Mbps, the percentage served can only reach around 45% or 23%, respectively even with five MDRUs deployed.

D. Discussion

From the simulation results, we can see that by deploying multiple MDRUs, it is possible to greatly increase the performance of the MDRU based WMN. However, since there are limited number of MDRUs available, deploying too many MDRUs to a single area may be a waste of resources since the performance increase may be minimum while these MDRUs can be deployed to other area where they are needed. One of the main factors in determining an appropriate number of MDRUs within an area is the expected traffic demand. As we can see with the case of 10 Mbps, traffic requirement can be fulfilled by just one or two MDRUs. Thus the additional capacity introduced by more MDRUs is wasted. One possible way of estimating the expected traffic load may come from population density. Since a denser area is likely to have more people with communications devices like smartphones and tablets. Another important parameter in determining appropriate number of MDRUs is the performance in the mesh tier. Since MDRU based WMN is a multiple tier architecture, the performance of the whole network is the performance of the bottleneck tier. For example, in Fig. 4 the percentage served cannot be any higher even when the capacity of the network facility tier is still much larger, because the mesh tier cannot send enough traffic to the network facility tier. Therefore, there is no point in increasing the capacity in the network facility tier by deploying more MDRUs when the mesh tier cannot send enough traffic to meet the capacity. Estimating the performance of the mesh tier may not be a straightforward task. However, technique like the bottleneck collision domain demonstrated in [12] may be able to give the insight on the capacity achievable by WMN, which will help in deciding the appropriate number of MDRUs that should be deployed.

V. Conclusion

Communications services are extremely critical for the process of disaster recovery. MDRU based WMN aims to set up temporary communications infrastructure by configuring remaining wireless APs into MRs and continue to provide connectivity services to the disaster affected area. In this work, we briefly described the MDRU based WMN and evaluated the performance of the network. We concluded that the performance of the MDRU based WMN can be greatly enhanced by deploying multiple MDRUs into the area. This improvement comes in the form of increasing capacity in the network facility area and coverage improvement. However, depending on factors such as the expected load and the performance in mesh tier an appropriate number of MDRUs should be considered so that the increased capacity will not be wasted.

VI. Acknowledgement

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