On the Throughput Evaluation of Wireless Mesh Network Deployed in Disaster Areas

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Abstract— **After disasters such as earthquakes and tsunamis, the network infrastructures might be extremely damaged or destroyed while Internet connection becomes much more necessary. Therefore, deploying networks in disaster areas has received much attention especially after the great earthquake in Japan on March 11, 2011. Among many kinds of networks, Wireless Mesh Network (WMN) is considered as one of the most suitable solutions because it can easily configure a network without any wired infrastructure. In our national project on disaster recovery network, we attempt to build a WMN connecting remaining routers (i.e., the routers that remain functional after the disaster) by using a Movable and Deployable Resource Unit (MDRU) as a base station, which has processing servers, storage servers, and Internet connectivity. However, in order to have a good network design, many experiments such as simulations need to be done beforehand. In this paper, we provide an adequate throughput evaluation of the deployed network with many configurations, which are close to reality. The results demonstrate that the network can, at the same time, provide basic Internet access to a significantly large population of users.**

I. Introduction

Lying on the Pacific Ring of Fire with thousands of earthquakes every year, Japan has encouraged researches on disasters for many years [1]. Since the great earthquake and tsunami on March 11, 2011, that damaged a wide range of areas in Japan, the government and many organizations have focused more on this research area. After disasters have occurred, network infrastructures might be damaged while emergency communications, such as safety confirmation and management from the government, become much more important. In such situations, it is necessary to quickly recover the network by using the remaining infrastructures such as access points, personal computers, mobile devices, and so forth.

Among many kinds of networks, WMN has been considered as the most suitable network for disaster recovery applications [2], [3]. The reason behind this is that a WMN can be easily deployed without any wired connection between the network-nodes. Moreover, since each user-node in the WMN can also operate as a router to forward packets, we can build wireless networks covering wide areas. In addition to the inherited characteristics from ad hoc networks such as self-organization and flexibility [4], WMNs offer many advantages like robustness, stable topology, and reliable coverage [5].

Therefore, our national project, namely "the R&D on the reconfigurable communication resource unit for disaster recovery", aims to use the WMN paradigm to deploy recovery networks in disaster areas. A recovery network will be configured by using an MDRU as the base station which comprises processing and storage servers. The MDRU connects directly to the Internet, and thus it is able to bring the Internet connection to the devices in the area after the network is constructed. However, in order to come up with the final design of the MDRU, it is necessary to conduct various experiments beforehand.

In recovery networks, throughput is one of the most important factors that need to be evaluated by experiments. By analyzing the relationship between the offered load and throughput, we can create a good design to avoid a huge amount of packet loss. It is also meaningful because the demand of using Internet is likely to increase significantly after disasters.

In fact, there have been some researches on the theoretical values of throughput [6], [7]. However, those values were calculated by using many ideal assumptions while the throughput depends on a number of factors including network topology, channel conditions, MAC layer characteristics, and so forth. Therefore, an adequate experimental evaluation is still required. In this paper, we introduce throughput evaluation using both simple and realistic parameters. In the simple network, all access points in the backbone network act as user-nodes and try to send as many data packets to the gateway as possible. By constructing and conducting a simple yet effective network simulation, we confirm the differences between the throughputs of one-hop and multi-hop networks. A comparison between simulated maximum throughput and the theoretical one is also presented in our work. In the network scenario based on realistic parameters, we configure our model based on Chigasaki city (in Japan) as a case study.

In this paper, we also provide a discussion about network joint design especially in disaster areas. In particular, problems related to using multi-channel and calculating the optimal offered load beforehand is discussed. By using the results of this paper, we can consider many modifications in designing the MDRU to achieve higher performance in terms of network throughput.

The remainder of this paper is organized as follows. Section II surveys some related works on throughput analysis. In Section III, we briefly present the realistic environment of the national project and the theoretical throughput values provided from previous researches. Our throughput evaluation is presented in Section IV. Finally, Section V concludes the paper.

II. Related works

Together with the increasing knowledge of disasters, there have been more researches focusing on information and communication. Among the most related organizations in Japan, Nippon Telegraph and Telephone (NTT) has made much effort for limiting the impact of disasters. In a publication in 1990, Adachi and Obata [1] introduced disaster prevention measures for telecommunications network systems. Their introduced design guidelines are based on three fundamental principles: improving network reliability, preventing isolation, and rapidly restoring services. The three principles are still valuable for current telecommunications networks. Moreover, rapidly restoring services is one of the most important reasons that WMNs are considered to be used in disaster recovery networks. Akyildiz *et al.* [4] also introduced spontaneous (emergency/disaster) networking as an application scenario.

Due to the higher demand in communication during disasters, throughput is considered to be one of the most important factors. It has received increasing attention recently especially on analyzing its limits. Jun *et al.* [6] proposed a method to calculate the theoretical maximum throughput of 802.11 networks for various technologies and data rates. However, this method does not support multi-radio and multi-channel networks. The research concentrated on analyzing the contention window sizes and qualitative performance of the IEEE 802.11 standard. By using the theoretical maximum throughput, we can control procedures of quality of service schemes to determine the upper bounds on available bandwidth.

Gupta and Kurmar [8] provided a method to estimate lower and upper bounds of network capacity. The theoretical values are calculated under both protocol and physical models of non-interference. It is implied that the network capacity bounds will sharply decrease if the node density increases. The authors also proved that splitting the channel into several sub-channels does not change those results. Therefore, their suggestion is that network designers should focus on designing networks with a smaller number of nodes. Related to number of nodes, Jun and Sichitiu [9] also proved that the throughput of each node in a WMN decreases as $O(1/n)$, where n is the total number of nodes in the network.

Ng and Liew [7] set up a real 6-node multi-hop network to show that uncontrolled sources can cause high packet-loss rate, re-routing instability, and unfairness problems. The results proved that by controlling offered load at the sources, we are able to eliminate the problems without modifying the 802.11 multi-access protocol. The authors also considered the optimal offered load that was pointed out by Li *et al.* [10].

Akhtar and Moessner [11] introduced a study on the impact of various network design parameters on the capacity of WMNs. An analytical grid-based framework was proposed to estimate the capacity of multi-radio multi-channel WMNs while taking into account grid size, number of aggregator nodes, number of radio channels, and so forth. The results presented an inverse relationship between number of aggregator nodes and capacity.

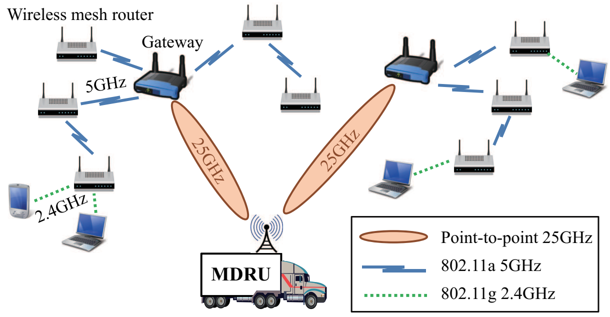

Fig. 1. An example of infrastructure considered in the national project.

III. Motivation

The MDRU based architecture contains three layers: network facility layer, network layer, and platform layer. The three layers cover all parts of the whole system from logistic tasks like MDRU transportation to applications demanded in disaster areas. However, in the scope of this paper, we focus on the network layer to measure the throughput at the gateways of the network in a realistic environment. In order to have a good evaluation, we compare the experimental results with some theoretical values introduced by some previous works.

A. The realistic environment of the national project

Fig. 1 demonstrates an example of infrastructure considered in the national project. The MDRU is considered as a base station which constructs the network for the whole area. It chooses some wireless mesh routers as gateways and uses 25GHz band to connect to them. To create the network backbone, gateways connect to other routers by using 5GHz band. Mesh routers and gateways can connect directly to the users by using 2.4GHz band. The standard used in gateway-router, router-router and router-user connections is 802.11a/g. Since all gateways and routers use a popular standard, they can be normal access points which are widely used.

We can consider that the connections between gateways and the MDRU have no bottle-neck because these connections use 25GHz band. Therefore, this paper attempts to measure the throughput only at the gateways. Moreover, since the connections between gateways, routers, and users use IEEE 802.11 standard, theoretical values such as throughput limits of IEEE 802.11 can be used to make a relevant comparison.

B. Theoretical maximum throughput

Jun *et al.* [6] introduced a method to calculate the theoretical maximum throughput at the MAC layer, namely T_{MAC}, which divides the MAC Service Data Unit (MSDU) by the time for transmitting each MSDU packet,

$$T_{MAC} = \frac{(MSDU\ size)}{(Delay\ per\ MSDU)}. \quad (1)$$

MSDU is defined as a packet pushed from the higher layer down to the MAC layer. The value *Delay per MSDU* is calculated by sum of all delay components including Distributed Inter Frame Spacing (DIFS), Short Inter Frame Spacing (SIFS), BackOff (BO), Request To Send (RTS), Clear To

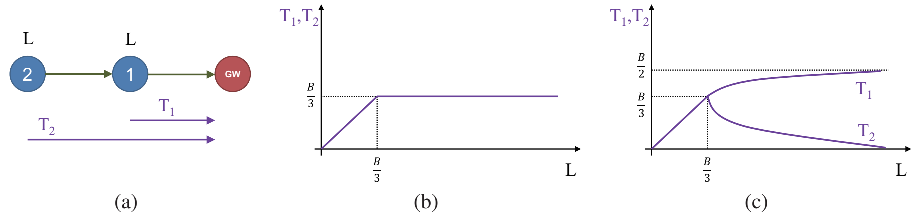

Fig. 2. (a) Two nodes have the same offered load L. The ideal (b) and real (c) throughputs of node 1 and node 2.

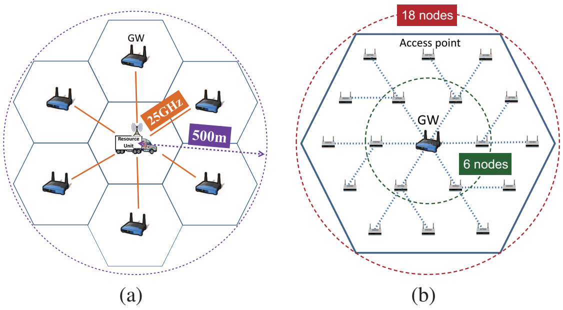

Fig. 3. (a) Network overview. (b) Topology inside one cell

TABLE I

SIMULATION SETTINGS FOR EXPERIMENT 1.

Simulation area	416 [m]×416 [m]
Number of user-nodes	6, 18
Radio type	802.11a
Channel	5 [GHz]
Physical data rate	18 [Mbps]
MSDU size	120, 240, 480, 960, 1200 [bytes]

Send (CTS), Acknowledgment (ACK), and payload size. We can achieve the values of these delay components from IEEE 802.11 specifications [12].

They also introduced a method to calculate the maximum throughput at the application layer, which is:

$$T_{APP} = \frac{\beta}{\alpha + \beta} \times T_{MAC}, \quad (2)$$

where α is the total overhead above the MAC layer, and β is the application datagram size. T_{APP} is calculated by Eq. (2) with an assumption that there is no fragmentation in the lower layers.

C. *Throughput in multi-hop networks*

Jun and Sichitiu [9] introduced a valuable study on relayed traffic and fairness. Consider a simple scenario as shown in Fig. 2 where the two nodes have the same offered load L. B denotes the nominal MAC layer capacity. In the ideal case, when the offered load value L increases, every node in the considered network achieves the same throughput as shown in Fig. 2(b). However, in the real results demonstrated in Fig. 2(c), the received throughputs of two nodes are different. The research concluded that the capacity of the network will depend on offered load if the absolute fairness is not enforced.

In this paper, we attempt to measure the throughput at the gateway, and based on the results we can estimate the fairness in the experiments.

IV. PERFORMANCE EVALUATION

In order to evaluate the performance of the recovery network, we consider a network topology as shown in Fig. 3. An MDRU takes charge of the area within the radius of 500 meters and the area is divided into seven cells as shown in Fig. 3(a). As a result, each cell covers a 416m×416m area. Each cell has a gateway at its center. We assume that within each cell, the routing path is fixed and access points are placed as shown in Fig. 3(b). In experiments, users will be uniformly distributed within the whole area.

Since the MDRU uses 25GHz band to connect with the gateways, we can consider that there is no bottle-neck at those connections. Therefore, in this performance evaluation, we focus on the throughput at the gateways. In other words, the experiments will be carried out with only the network in Fig. 3(b). QualNet 5.1 [13] is used to run all simulations in this work.

A. *Experiment 1: a simple network*

In the first experiment, we consider a simple network as in Fig. 3(b) with access points acting as traffic sources, i.e., user-nodes. All user-nodes send data to the gateway at the same time and with the same offered load. The offered load of each user-node is set with a wide range of values. We also attempt to send packets from only the six closest user-nodes to the gateway in order to evaluate the differences between one-hop and multi-hop networks. The simulation settings for the first experiment is summarized in Table I.

1) Throughput versus offered load: Fig. 4 demonstrates the throughput at the gateway when we send data only from the six closest user-nodes. In this case, all the considered connections are one-hop, and thus, the unfairness issue does not arise. We can see that the shape of curves in Fig. 4 are the same as the one in Fig. 2(b). On the contrary, the results in Fig. 5 show that the throughput decreases to a stable value after reaching the maximum one. The results are considered to be reasonable according to the discussion about multi-hop networks in Section III.

By using the results shown in Figs. 4 and 5, we can estimate the appropriate offered load based on network topology to prevent high packet-loss rate. For example, when 18 nodes concurrently send 1200-byte packets to the gateway, the total offered load should be controlled to be lower than 7Mbps.

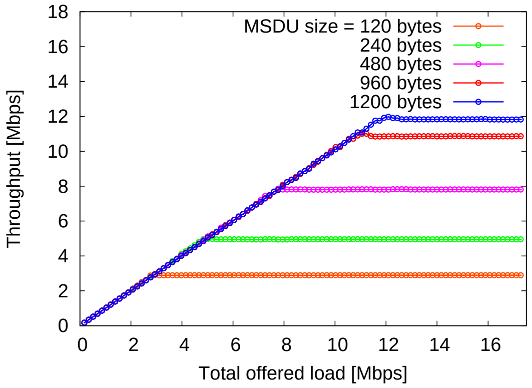

Fig. 4. Throughput at the gateway when only the 6 closest nodes send data.

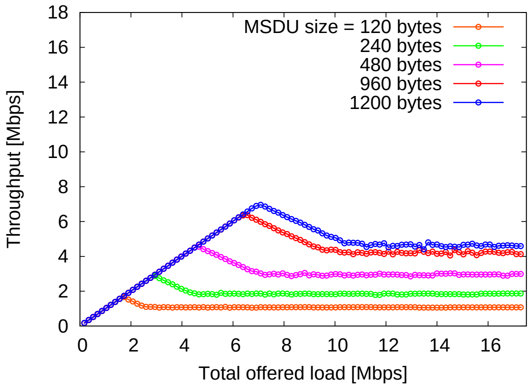

Fig. 5. Throughput at the gateway when all 18 nodes send data.

2) Maximum throughput versus MSDU size: Although it can be understood from Figs. 4 and 5 that the higher MSDU size is the better throughput will be. We provide a more adequate evaluation between the maximum throughput and the MSDU size as shown in Fig. 6. The results show that when we use 6-node topology, the simulated result approximates the theoretical value. Although 18-node topology cannot give us such good throughput, the results as shown in Fig. 6 are important for network design. For example, based on the characteristics of applications in the area, we can find the corresponding maximum throughput and use the value to control the offered load.

B. Experiment 2: a network with realistic system parameters

We conduct an experiment adopting realistic system parameters. The experiment uses the case study in Chigasaki city, which has an estimated population of 235,081, a total area of 35.71 km^2, and a density of 6,583 persons per km^2. There are 45 MDRUs planned to be set up in this city, and thus, each MDRU should provide Internet connection to about 5,000 users. Assuming that the users are distributed uniformly, each small network as in Fig. 3(b) should support about 720 users. In the simulation, we use 5GHz band for the backbone network as shown in Fig. 3(b) and 2.4GHz band for the connections between user-nodes and access points. With the assumption

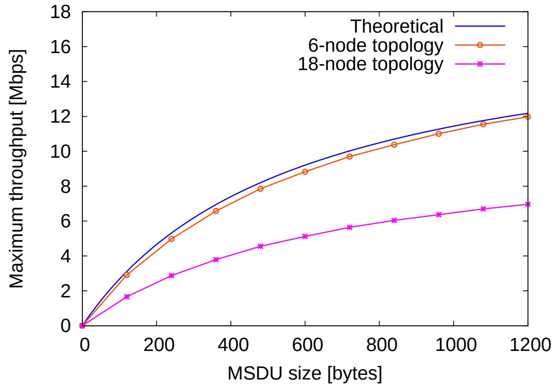

Fig. 6. Maximum throughput in the two considered topologies in contrast with the theoretical value.

that the offered load of each user is 9.6kbps, we attempt to evaluate the throughput at the gateway when the number of users increases. The detailed settings of this experiment are listed in Table II.

Fig. 7 demonstrates the throughput at the gateway when the number of users varies from 1 to 800. Since the maximum number of users is set to 800 and each user offers 9.6kbps load, the maximum of the total offered load is 7.68Mbps. The simulation results demonstrate that when the number of users is lower than 500, there is almost no packet loss. On the other hand, when the number of users exceeds 500, the throughput at the gateway gradually increases to 6Mbps. Therefore, this network can be considered acceptable for this realistic environment.

C. Discussion

From the simulation results, we can see that although we can calculate the theoretical maximum throughput, the actual throughput of the network is significantly related to network configurations. As shown in Fig. 6, if there are only one-hop nodes transmitting packets to the gateway, the throughput at the gateway will be very close to the theoretical one. However, when we add some two-hop connections, the throughput dramatically decreases. In the conducted simulation, we are using only one channel for all one-hop and two-hop connections in the simple network. This is considered to be the main reason for the low throughput in Fig. 5 since the unfairness issue arises in this case. Therefore, using multi-channel should be considered in designing WMNs to improve network throughput. In order to use multi-channel, applying multi-interface also needs to be concerned.

An example of using multi-channel can be seen from the simulation of the network based on realistic parameters. In this simulation, user-nodes connect to access points by using 2.4GHz band and the connections between access points in the backbone network use 5GHz. As a result, although there are many three-hop connections between user-nodes and the gateway, the calculated throughput in Fig. 7 is almost the same as that in Fig. 5 with the same MSDU size (1200 bytes). In other words, by using multi-channels, the overall network can

TABLE II

SIMULATION SETTINGS FOR EXPERIMENT 2.

Simulation area	416 [m]×416 [m]
Number of user-nodes	1 ∼ 800
Radio type	802.11a/g
Channel 1	5 [GHz]
Physical data rate for channel 1	18 [Mbps]
Channel 2	2.4 [GHz]
Physical data rate for channel 2	48 [Mbps]
Offered load of each user-node	9.6 [kbps]
MSDU size	1200 [bytes]
Simulation trials with different scenarios	20

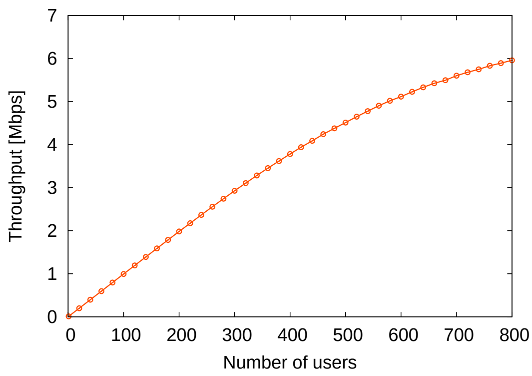

Fig. 7. Throughput versus number of users in Experiment 2.

have a throughput which is quite close to that in the backbone network.

Another issue addressed in this paper is calculating the optimal offered load. With a given MSDU size, we can calculate the maximum throughput at the backbone network. Using the maximum throughput value to limit the total offered load should prevent the high packet-loss rate problem. For example, in the network based on realistic parameters considered in this paper, we can use the maximum throughput achieved in the backbone network (i.e., 6.96Mbps when MSDU size is 1200 bytes) and the offered load of each user-node (i.e., 9.6kbps) to calculate the upper bound of the number of users. This method should be helpful for research, in particular for realistic network design.

V. CONCLUSION

In this paper, we introduced an adequate throughput evaluation in a disaster recovery network which is considered in the national project. The evaluation was conducted with various configurations using both simple and realistic parameters. In the simple network experiment, we compared the differences between one-hop and two-hop networks in terms of network throughput. The results demonstrated that the throughput of one-hop networks is significantly higher than that of multi-hop networks. We also provided a comparison between the theoretical maximum throughput value and the simulated one. We believe that the evaluated results of the maximum throughput versus the MSDU size should be very helpful to estimate the optimal offered load of the network. Moreover, the maximum total offered load should be considered to determine the scope of the actual network.

In the network based on realistic parameters, we evaluated the throughput at the gateway with various numbers of nodes. The results show that when the offered load of each user is 9.6kbps, we can provide up to 500 concurrent network accesses without any packet loss. When the number of concurrent accesses is greater than 500, the throughput gradually increases to 6Mbps. Therefore, the simple design introduced in this paper can be considered acceptable for some case studies like that in Chigasaki city.

By using the simulation results, we noticed that using multi-channel backbone connections in the network should improve the network throughput. This configuration will be addressed in our future work.

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