

QOMB Wireless Network Emulation Testbed: Evaluation and Case Study

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ABSTRACT

This paper presents several evaluation tests, as well as a case study of large-scale wireless network emulation experiments performed using QOMB, the wireless network emulation testbed at the National Institute of Information and Communications Technology, Hokuriku Research Center in Ishikawa, Japan. The evaluation tests demonstrate the accuracy of wireless network emulation using QOMB in single and multi-hop settings, as well as in scenarios involving node mobility. The large-scale experiments illustrate the most important features of QOMB and its versatility by an OLSR protocol study in a MANET scenario including 50 emulated mobile nodes.

Categories and Subject Descriptors

I.6.6 [Simulation and Modeling]: Simulation Output Analysis

General Terms

Experimentation, Measurement, Verification

Keywords

Wireless network emulation, wireless network testbed, OLSR, MANET, large-scale experiments

1. INTRODUCTION

Wireless network technologies such as WLAN are now widely deployed in corporations, universities, homes and even public spaces. They are used from terminals with a wide range of specifications and processing power, in both static and mobile settings. Other wireless network technologies, such as ZigBee or WiMAX, have appeared in recent years to address new user needs, as well as the limitations of existing technologies.

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The realistic evaluation of network applications and protocols running over such wireless technologies plays a significant role in understanding their performance characteristics. It also contributes to their improvement, by allowing to conduct the necessary R&D testing.

The two key requirements for making it possible to perform realistic assessments of network applications and protocols are:

- Carry out repeatable controlled experiments with the applications or protocols under test;
- Use scenarios that are sufficiently close to reality in terms of experiment conditions and scale.

Testbeds may be the ideal solution in this context, both from the point of view of repeatability and experiment size. In this paper we focus on the wireless network emulation testbed QOMB, designed and implemented by the National Institute of Information and Communications Technology, Hokuriku Research Center in Ishikawa, Japan.

We first present several validation experiments done with QOMB that prove the accuracy of its wireless network emulation mechanisms. Then we use the OLSR protocol as a case study to demonstrate that QOMB addresses the two aforementioned requirements. The case study uses a MANET scenario that includes 50 mobile nodes, and experimentally quantifies the influence of the transmission power on the network topology that is being built in real time by a widely-deployed OLSR implementation.

The paper is organized as follows. In Section 2 we discuss the main design elements, as well as the most important features of QOMB. Then we proceed in Section 3 to show several of the validation tests that we have carried out on QOMB to evaluate its accuracy. Following that, in Section 4, we present several large-scale OLSR experiments that we have performed using QOMB. Section 5 discusses related work in the field of wireless network testbeds, and the differences with respect to QOMB. We end the paper with conclusions and references.

2. QOMB DESIGN

The QOMB testbed was created by integrating the wireless network emulator QOMET [1] with the large-scale network experiment environment StarBED [6]. QOMB has been presented in [2], and we summarize here its most important design aspects and features.

2.1 QOMET

QOMET is a wireless network emulator using a two-stage approach for converting a user-defined scenario representation into network degradation parameters that are then used to configure a link-level emulator such as Dummynet [11], thus reproducing in a wired network the communication conditions of the emulated wireless network.

The process of using QOMET for emulation experiments involves the following three steps:

1. Create the scenario description;
2. Process the scenario description to compute the equivalent network parameters;
3. Apply the computed network parameters in the wired network.

Only step 1 above requires direct user actions, as he/she needs to describe in an XML-based language all the characteristics of the wireless network scenario that is to be emulated. These include the initial position and movement of the wireless nodes, the properties of the wireless adapters, the characteristics and topology of the environment (such as RF propagation-related constants, street and building topology), and so on.

Models for the following wireless networks are available: IEEE 802.11a/b/g, active RFID tags, and IEEE 802.15.4 (in development). Wireless adapters are characterized through two main parameters: (i) receive sensitivity, that indicates the minimum received power level for which an adapter can operate at a certain transmission rate; (ii) transmit power, i.e., the power of the signals transmitted by the adapter. To account for RF propagation effects, such as attenuation and shadowing, QOMET uses the log-distance path loss model, defined by attenuation coefficient, shadowing factor, and wall attenuation [9]. Node mobility can be specified by using simple models such as linear motion, “classical” models such as random waypoint, and also a specific model called behavioral motion, that automatically computes the trajectory of a node in a certain topology of streets and buildings given its starting position and destination. QOMET can use real map data provided in GIS format for defining the street and building topology of the virtual environment.

Step 2 above is accomplished by a QOMET library called *deltaQ*, that integrates all of the models mentioned above. First it generates the mobility-related evolution of the scenario. The communication conditions between nodes are then calculated by *deltaQ* based on the positions of the nodes and the environment through which they communicate. These conditions will be adjusted during experiment execution, in real time, depending on the traffic sent by nodes, so as to account for the congestion of the wireless channel. This is necessary because of the contention that occurs when multiple nodes use concurrently a wireless network. The corresponding model included in *deltaQ* uses traffic statistics gathered in real time, and communicated between instances of the *deltaQ* library that are responsible for the emulation of the wireless node communication on each testbed host. These statistics are used to compute the effective channel utilization at each moment of time, which is then used to derive realistic wireless communication conditions. This framework is described in more detail in [7].

Step 3 is carried out on an experimental testbed such as StarBED by employing another library of QOMET, namely

wireconf, which is effectively a wrapper around the link emulator Dummynet that makes it possible to change in real time the network degradation introduced by the latter according to the parameters computed by *deltaQ* for the dynamic network scenario. The result of this process is that, from the point of view of network applications and protocols, the wired-network testbed behaves similarly to a wireless network, in which conditions vary due to the movement of the nodes, radio propagation effects, as well as channel congestion.

2.2 StarBED Integration

The use of StarBED, which has more than 1000 PCs available for experiments, allows making large-scale experiments with QOMET, and their integration resulted in QOMB. The QOMB testbed makes use of the experiment-support tools provided on StarBED to simplify the task of making experiments, and adds several specific files that enable the wireless network emulation features. Next we discuss the QOMET integration with StarBED through the support tool named SpringOS.

SpringOS is used to manage experiment execution on the StarBED testbed. SpringOS facilitates the usage of the testbed by multiple users simultaneously, both for experiment hosts and switches. This is done through access restrictions and mediation mechanisms for sharing such resources.

For using StarBED by means of SpringOS, users have to write a configuration file that describes the experiment. Based on the this configuration file, SpringOS automatically performs the following tasks:

1. Assign experiment hosts;
2. Upload the appropriate operating system to the assigned hosts;
3. Configure experiment switches to build the required target topology;
4. Drive the execution of the experiment according to the configuration file.

Note that using SpringOS for steps 1 to 3 above is essential for ensuring a correct execution of the experiment in a multi-user environment. For the experiments described in his paper, at step 2 we used a FreeBSD operating system image onto which all the necessary software (such as the OLSR daemon and the traffic generator) was installed, and distributed it to all the experiment hosts.

The most important step from a user perspective is step 4. For this purpose we use on QOMB specific SpringOS configuration files and scripts that are in charge of starting the real-time component of QOMET, which employs the *wireconf* library to control the communication conditions between hosts. In addition to this, one has to write the commands to start and stop the specific applications that are used in a particular experiment, such as routing protocols, traffic generators, etc. Predefined QOMB configuration files and scripts can be used as templates for this task.

3. QOMB EVALUATION

We have performed several series of experiments in order to verify that the results of wireless network emulation experiments done on QOMB are in accordance with those of

real-world trials, as well as with those of simulation experiments. Even though real-world experiments may appear as the first choice for comparison, the well-known repeatability issues and the uncontrolled interferences that occur for such experiments prevent a thorough validation. As a consequence, we also turned our attention to network simulators. While the accuracy of the simulation results is sometime contested, this approach is still the most-used methodology for network-related research, allowing controlled and repeatable experiments.

For the real-world trials we used laptops running Windows XP. The wireless adapters were Buffalo AirStation, and in some cases LAN Express AS, both of them IEEE 802.11b compliant. For simulation experiments we used QualNet Developer [12] and NS-2 [14]. Both in emulation experiments and real-world tests, traffic was generated using Iperf [13], for UDP as well as for TCP. Equivalent traffic sources were used in simulation experiments. In all the scenarios that will be presented next, each type of experiment was repeated 3 times using the same conditions.

3.1 Single-hop Experiments

The single-hop experiments that we carried out were aimed at verifying that the emulation results obtained in simple scenarios with one or multiple senders transmitting traffic to one destination are comparable with those of equivalent real-world trials and simulations.

3.1.1 One Sender

In this experiment the sender produces either UDP or TCP traffic. For UDP tests, we set the datagram size to one of the values in the set {64, 128, 256, 512, 1024, 1472} bytes, and the offered rate is 7 Mbps. For TCP tests, the TCP payload is set to 1460 bytes, and the TCP window size is 8 kB. In both cases, the largest Ethernet frame size produced will have the maximum allowed size, 1514 bytes.

We performed the experiments at each operating rate of the IEEE 802.11b standard, i.e., 1 Mbps, 2 Mbps, 5.5 Mbps, and 11 Mbps. The measurements were done over a period of 100 s, and we report the average throughput value over that interval as computed by Iperf.

Let us look first at UDP performance. We only discuss in this paper the results obtained at 11 Mbps, however those for other operating rates are similar. Figure 1 shows that there is a general good agreement of the results amongst all experiment techniques. One thing to note is that the rate at which WLAN MAC protocol acknowledgments are sent differs between the LAN Express adapters, which use 11 Mbps, and the Buffalo ones, which use 2 Mbps. QOMET follows the same convention with LAN Express, whereas QualNet and NS-2 follow the same convention with Buffalo. This difference explains the slight mismatch of the results between the systems following each of these conventions. For reasons that we have not identified yet, LAN Express performance decreases with packet size, and we noticed an unexpectedly low throughput for 1472-byte packets, inferior to the results of all the other systems. Still, the difference between the results obtained for all packet sizes on QOMB, and those obtained with the card that uses the same MAC acknowledgment convention, namely LAN Express, is around 8% on the average.

Next we present the results obtained for TCP at all four operating rates of IEEE 802.11b. Note that, since the LAN

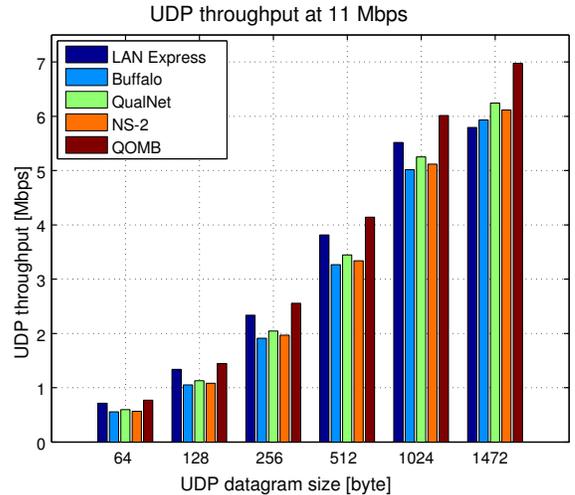


Figure 1: UDP performance at 11 Mbps for single-hop experiments with one sender.

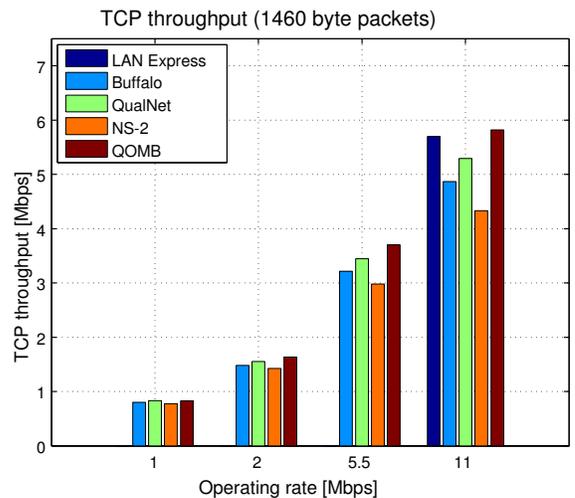


Figure 2: TCP performance at all operating rates for single-hop experiments with one sender.

Express adapter operating rate could not be configured, results are only available for 11 Mbps in that case. Figure 2 shows that there is in general a good agreement of the results. Comparing QOMB to LAN Express gives a good fit, with a difference of only 2% in average throughput values.

Note that both in UDP and TCP tests, the throughput obtained with QOMB is superior to that obtained in the equivalent real-world scenario (LAN Express). This is because in emulation we assumed error-free communication conditions, whereas the real-world adapter is subjected to the potential electromagnetic interferences present in all real environments.

3.1.2 Four Senders

The experiments with four senders are intended to verify how QOMB is able to reproduce congestion conditions in the emulated wireless network. For this purpose we configured the transmission starting time of the four senders so that it

Table 1: Transmission time shift of the four senders in single-hop experiments

Sender id	1	2	3	4
Time shift [s]	0	10	20	30

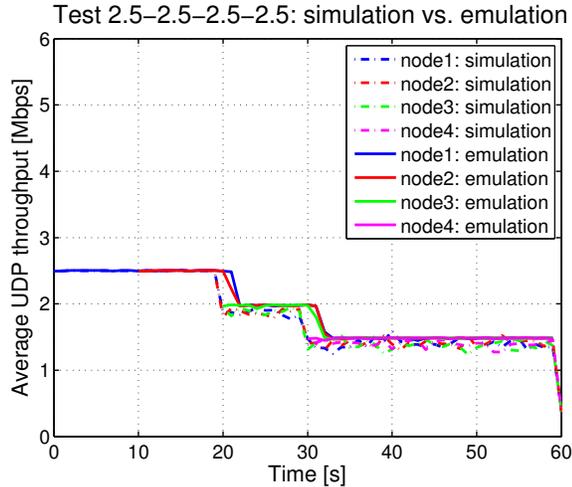


Figure 3: UDP throughput for single-hop experiments with four senders: simulation versus emulation.

is shifted with respect to the others. This leads to a gradual congestion of the wireless channel, and allows evaluating its effect. The time shift in seconds with respect to the experiment start for each of the senders, numbered from 1 to 4, is given in Table 1. Total experiment duration was 60 s.

We did several series of experiments with this type of scenario. For real-world tests we used the Buffalo wireless adapters, and for simulation we used QualNet. WLAN operating rate is fixed to 11 Mbps in all cases. The four senders transmit UDP traffic with a constant rate; the UDP datagrams have 1024 bytes. The results we present below are obtained in the case when each sender transmits 2.5 Mbps. We did other experiments with 6 Mbps per sender, and also with mixed settings, in which one sender transmits 6 Mbps and the others 1 Mbps. In all cases the results were conforming to expectations.

In Figure 3 we present the comparison between simulation and emulation. Initially, the senders 1 and then 2 manage to output the entire amount of offered traffic. However, when the third sender begins transmitting at time 20 s, the channel becomes saturated, and the total throughput per sender decreases. A similar effect takes place at time 30 s, when the fourth sender begins transmitting. The results are almost identical between simulation and emulation, and in all cases the nodes share the channel equally. In quantitative terms, the average of the difference between emulation and simulation throughput values during the entire experiment duration is of about 6%.

In Figure 4 we show the comparison between the real-world trial and emulation. Although the trend of the results is similar in both cases, it is obvious that the real-world results have more variability. Moreover, there is a slight unfairness for node 3, which consistently has a lower through-

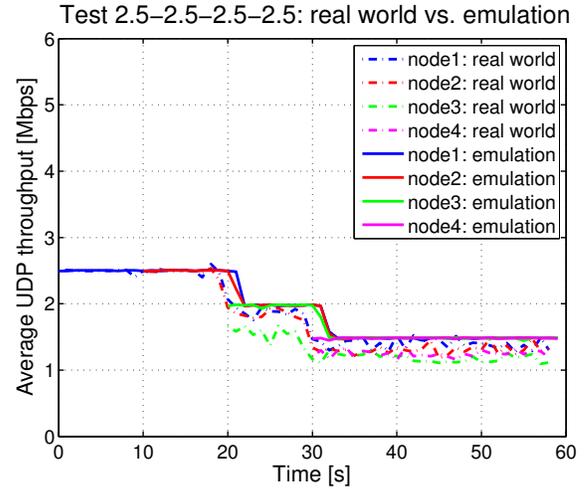


Figure 4: UDP throughput for single-hop experiments with four senders: real world versus emulation.

put than the other senders. This can be explained by the fact that, although the wireless adapters of the participating nodes are identical, small differences in antenna orientations with respect to each other, as well as the spatial positioning of the nodes leads to a certain asymmetry of the setup. This leads to results that differ from the theoretical prediction, even though the difference is not significant. Such effects emphasize the difficulties and issues related to real-world trials, and a possible advantage of emulation and simulation from repeatability point of view. As a result, in our experiments, the average of the difference between emulation and simulation throughput values during the entire experiment duration is of about 13%, a larger value than for simulation mainly due to the particular behavior of node 3.

We conclude that QOMB is able to emulate with sufficient accuracy the contention that is created when more nodes located in the same interference area compete for the utilization of the wireless media. The results match closer those of simulation than those of real-world tests. This is because it was easier to create similar emulation and simulation scenarios, whereas the real-world experiment could only be modeled in an approximate manner.

3.2 Multi-hop Experiments

The multi-hop experiments were intended to demonstrate that QOMB can emulate correctly not only local congestion conditions, but also the more complex situation of multi-hop setups. Such scenarios are particularly relevant for ad hoc, MANET and mesh network topologies, for which multi-hop communication is an intrinsic characteristic.

The real-world trial setup, which was also the basis for the emulation and simulation scenarios, is shown in Figure 5. A total of four laptop PCs were deployed in our research center, each of them using Buffalo adapters configured to the fixed WLAN operating rate of 11 Mbps (no rate adaptation allowed). The distance between PCs is between 7 and 8 m, ensuring that the first and last node cannot communicate with each other. In addition to the experiment nodes, in the real-world setup we used a WLAN analyzer located in

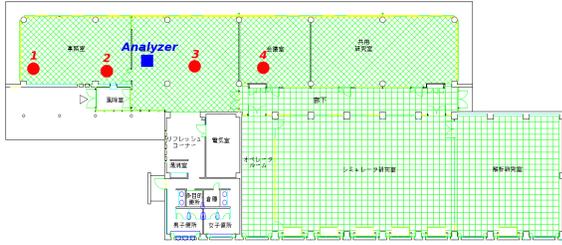


Figure 5: Setup for multi-hop experiments.

the middle of the configuration to capture the wireless traffic of the laptops.

The traffic in the multi-hop experiments was a UDP stream with an offered rate of 6 Mbps and 1024-byte datagrams. Traffic generation lasted for 100 s. In these experiments multi-hop routing was achieved by statically configuring the routing tables of the PCs. Nevertheless, in a typical ad hoc network, multi-hop routes would be created by a routing protocol such as OLSR or AODV.

For the setup in Figure 5 we carried out several series of experiments. In all of them the traffic destination was node 1, and the sender was one of the nodes 2 (effectively leading to single-hop communication, and used for validation purposes), 3 or 4, respectively. We show below the results obtained when the sender is node 4, which is the most interesting case from multi-hop communication point of view.

We compare first emulation against simulation (see Figure 6). The UDP throughput per hop shows a similar behavior in the two cases: the throughput on the link 4→3 is highest, creating congestion, and the remaining capacity is shared equally by the remaining links, 3→2 and 2→1. The absolute throughput values differ by a certain amount because we could not reproduce exactly the same scenario both in emulation and simulation (QualNet doesn't support the log-distance path loss model). The average difference between throughput values for the entire experiment duration is around 15%. Although the difference is certainly significant, we claim that it is acceptable given the experimental conditions, and proves that the behavior of QOMB and QualNet are in general lines the same.

When comparing emulation against real-world tests (see Figure 7), the throughput on the link 4→3 is almost the same in both cases, with more variability in the real-world trial, as expected. The links 3→2 and 2→1 have a lower throughput, because of the difficulty to reproduce by emulation exactly the same conditions with the real-world trial. Another effect, which only appeared in the real-world trials, is noticeable at time 110 s, when node 4 ceases transmission. Node 3 seems to buffer a significant amount of traffic, and it outputs it at a high rate once the traffic source, node 4, stops sending, thus freeing the wireless media. We assume that this behavior is specific to Windows XP, and we do not consider this effect significant from a wireless network emulation validation perspective. Nevertheless, if we quantify the average difference between average throughput values, we obtain a difference between emulation and real-world experiments of about 16%. Note that this difference refers to the average throughput for the period over which each wireless node is active.

To summarize, the experiments we have presented for the

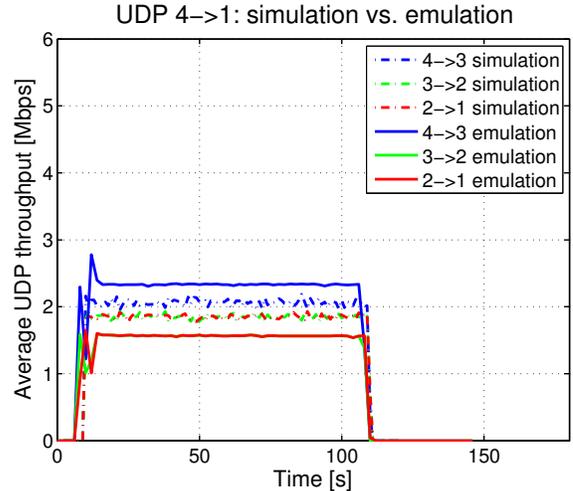


Figure 6: Per-hop UDP throughput for indoor multi-hop experiments: simulation versus emulation.

case of multiple nodes, both in single hop and multi hop scenarios, show that it is possible to reproduce in a wired network, with reasonable accuracy, the contention present in wireless networks. In our experiments with multiple nodes, the average differences between simulation and emulation throughput results range between 6 and 15%, while the average differences between the real-world and emulation throughput values range between 13 and 16%.

3.3 Mobility Experiments

A third class of experiments was dedicated to investigating the mobility-related aspects of QOMB. For this purpose we used real-world setups with a fixed node and a mobile node (a person carrying a laptop) that follows a predefined trajectory. These experiments were performed both in outdoor and indoor environments, and then reproduced through emulation on QOMB, and through simulation by using NS-2.

In Figure 8 we show the scenario for the indoor experiment carried out within our research center. The total experiment duration is of about 110 s, and the walking distance between the start and final positions is of about 35 m. The trajectory of the mobile node (the sender) includes periods of motion, of variable length, separated by pauses at several milestones, each pause lasting for approximately 10 s. The arrows in the figure indicate the position of the mobile node at regular time intervals. The parameters used in emulation for the indoor log-distance path loss model are: attenuation coefficient, $\alpha = 4.02$, and shadowing factor, $\sigma = 7.36$ dB, according to the values proposed in [3]. The traffic is a 64 kbps UDP flow that mimics a VoIP stream.

To demonstrate the accuracy of the log-distance path loss model implemented by QOMET, and that of the parameters used, we show first (see Figure 9) the variation of the received power, P_r , with respect to time, as the mobile node follows the trajectory in Figure 8. Except for the difference at the beginning of motion, which is not significant since the value is in the range of very high received power, there is a remarkable consistence between the measured and computed values.

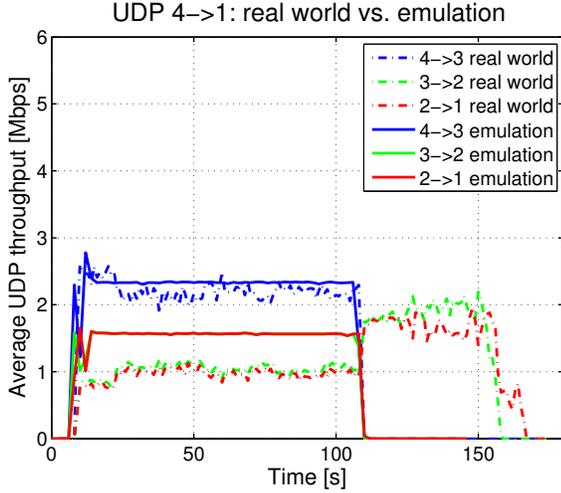


Figure 7: Per-hop UDP throughput for indoor multi-hop experiments: real world versus emulation.

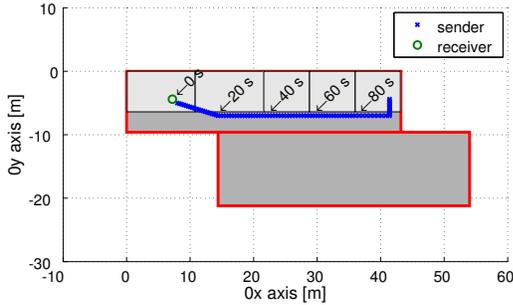


Figure 8: Motion trajectory for the indoor mobility experiment.

Figure 10 shows the UDP throughput variation with respect to time for this experiment. Emulation results follow reasonably closely the real-world measurements. It is important to note especially the fit that exists between the moments when performance degrades in the real-world trials and in emulation. In both cases, at around 80 s, node motion leads to an important decrease in received power, as shown in Figure 9; as a consequence, communications conditions degrade. QOMB is able to reproduce this behavior by using only simple parameters, such as receive sensitivity, transmit power, and the log-distance path loss model constants.

4. OLSR EXPERIMENTS

In this section we use the OLSR protocol as a case study to demonstrate how the features of QOMB can be used in practice to perform large-scale repeatable realistic experiments in controlled settings.

For this purpose we consider a search-and-rescue scenario in an urban environment, for example after an earthquake. The scenario includes a total of 50 wireless nodes. One of them plays the role of the gateway, providing external connectivity to all the other nodes. The remaining nodes are

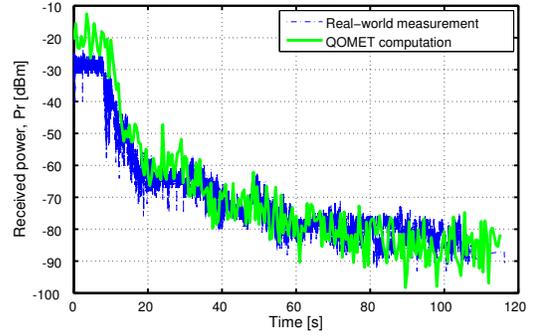


Figure 9: Received power variation in the indoor mobility experiment.

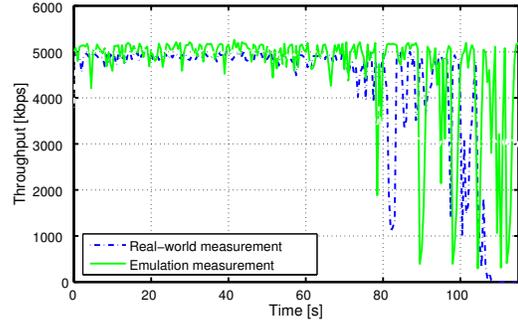


Figure 10: UDP throughput variation in the indoor mobility experiment.

mobile, and they move to predefined locations in the urban environment. Trajectories are generated using the behavioral model in QOMET. The street topology of the urban environment is created using real GIS map data for an area in Kawasaki, Japan. The parameters used for the outdoor log-distance path loss model are: attenuation coefficient, $\alpha = 3.32$, and shadowing factor, $\sigma = 3.1$ dB, according to the values in [3]. The network is of MANET type, and we used an unmodified OLSR implementation for routing purposes, namely olsrd-0.5.5 [8].

There are numerous studies that can be done with this kind of scenario, such as, for instance, analyze application performance when using the different routing metrics available in OLSR. However, for illustration purposes, in this paper we shall modify a parameter of the wireless network, namely the transmit power of the emulated WLAN adapters, P_t . This setting is important in wireless networks because it is directly related to power consumption.

The values we assigned to P_t range from a very low value (1 mW) to the largest value allowed by the IEEE 802.11b standard (100 mW). For each run of the experiment, a fixed P_t value was set for all the adapters. Total experiment duration was 500 s.

As the experiment proceeded, we logged in real time the network topology created by OLSR by using a customized visualization plugin for olsrd. There are two main reasons why we only focus on topology analysis in this paper: (i) the evaluation done in Section 3 helped build reasonable confidence regarding the way in which wireless communi-

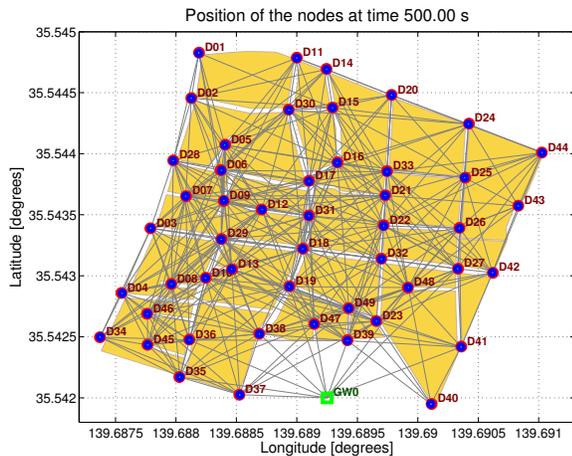


Figure 11: OLSR topology at the end of the search-and-rescue scenario (transmit power $P_t = 10$ mW).

Table 2: OLSR topology statistics for the routes from all the mobile nodes to gateway for several power settings

Transmission power P_t [mW]	1	2	10	50	100
Average route length [hops]	4.37	2.83	2.02	1.37	1.24
Maximum route length [hops]	8	5	3	2	2
Disconnected node count	3	2	0	0	0

ication conditions are reproduced on QOMB; (ii) we did not yet conduct similar experiments using alternative platforms. Note that we are in the process of organizing similar experiments on the wireless network testbed ORBIT [10], and we plan to report the comparison of the experimental results in a future paper.

Figure 11 shows an instance of the OLSR topology at the end of the experiment done for $P_t = 10$ mW. GW0 marks the location of the fixed gateway, and D01 to D49 mark the destinations reached by the mobile nodes. We observe that the connectivity is quite good for this scenario, even though the power setting is relatively low.

If considering a situation in which the optimal transmit power needs to be selected, it is necessary to objectively evaluate the properties of the topology, so that the choice can be done algorithmically. We present several metrics in Table 2 that can be used to compare the network topologies created by OLSR for different power settings. Since our MANET includes a gateway, we propose to quantify the following graph properties for each network topology: (i) the average route length in hops between the mobile nodes and the gateway; (ii) the maximum route length in hops between the mobile nodes and the gateway; (iii) the number of disconnected nodes (in the sense that their traffic cannot reach the gateway).

By analyzing the values reported in Table 2 we conclude that, for the investigated power settings, the value $P_t = 10$ mW is optimal, since the average route length is approx-

imately 2 hops, the maximum route length is 3 hops, and no node is disconnected from the gateway. Note that this is achieved while using a transmit power that is ten times lower than the maximum allowed transmit power of WLANs. Thus, wireless interfaces could dynamically adapt the value of the transmit power, so as to achieve the best trade-off between connectivity and battery life.

5. RELATED WORK

One approach for wireless network experiments is to make use of real wireless testbeds. This approach is employed, for instance, by Emulab [15] and ORBIT [10]. Emulab provides a total of 54 WLAN nodes, out of which 36 are located in one room, and the other 18 are distributed on different floors of an office building. ORBIT provides 400 WLAN nodes in the main experiment area, arranged as a 20 x 20 m grid. This type of approach suffers of two main drawbacks: (i) the WLAN nodes are fixed, therefore no experiments involving mobility are possible; (ii) there can be no time sharing of the testbed, because of the resulting interference between experiments. The latter means that, for example, all the 400 nodes of ORBIT are blocked in a certain time interval, even if only a few of them are effectively used. By comparison, QOMB allows mobility experiments, through the features built into QOMET, and also time sharing, through the mechanisms of StarBED. Certainly, this flexibility is achieved in QOMB by sacrificing some of the realism, given the use of wireless network models instead of real devices.

Mobile Emulab [5] is a solution for bringing mobility to an Emulab-like testbed. Mobile Emulab uses robots that move according to predefined trajectories. However, the physical constraints of the robots make that the range of experiments that can be performed is limited in terms of movement speed, number of nodes, etc. QOMB has no such limits from the point of view of scenario characteristics, and the total experiment size is in principle bounded only by the physical resources of StarBED, currently exceeding 1000 PCs.

There are several large-scale testbeds that use emulation in a similar manner with QOMB to reproduce wireless network conditions on a wired network testbed. In this category enter EMPOWER [16], TWINE [17], and SWOON [4]. Nevertheless, these emulation-based testbeds fail to offer the possibility of creating realistic mobile wireless network scenarios in the way QOMB does. This is because they rely on user-defined network parameters for specifying the communication conditions between nodes; it is hard to expect that these conditions will represent in a realistic manner a complex scenario in which mobile nodes change location and interact with each other in real time. QOMB supports wireless communication and mobility models, making realistic experiments possible; moreover, by changing the wireless network model, different technologies can be experimented with at a minimum cost.

6. CONCLUSION

QOMB is a wireless network emulation testbed that combines some of the advantages of real-world testbeds, such as the use of real network applications and protocols, with those of simulation environments, such as good condition control, and mobility features.

In this paper we presented a series of experiments aimed

at evaluating the wireless network emulation testbed QOMB in single and multi-hop settings, as well as in scenarios involving mobility. The experimental results show that there is in general a reasonable agreement between the results obtained through emulation on QOMB, and the results obtained through real-world trials and simulation experiments in similar scenarios. Throughput differences ranged between 2 and 16% in our experiments, depending on conditions. The largest differences were observed compared to the multi-hop real-world trial with chains of 4 nodes. This issue emphasizes the difficulty in accurately reproducing real-world scenarios by emulation or simulation.

As a secondary conclusion, we discovered that, in most cases, the differences between simulation and real-world results are not so important, which leads us to believe that if one can describe sufficiently accurately a real-world experiment as a simulation or emulation scenario, then the results will be equivalent. Discrepancies only appear when experiment complexity increases, but this is because the scenario doesn't capture accurately all the conditions in the real-world experiment.

We also discussed as a case study the results of several experiments with the OLSR protocol that demonstrate the most important features of QOMB, and its advantages compared to related approaches. While in this paper we only focused on discussing the topology being built by OLSR, one of the directions of future work is to evaluate QOMB more thoroughly in such scenarios, both against testbeds such as ORBIT, and against simulation.

Another future work direction refers to extending the support of QOMB to other wireless network technologies. In this context, we are currently working on including in QOMB a model for WiMAX-based wireless communication.

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