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Indoor deployment of IEEE 802.11s mesh networks: Lessons and guidelines

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ABSTRACT

Emerging wireless mesh networks (WMNs) are known for their fast and low cost deployment. Conventional mesh deployment focuses on the outdoor environment, which regards the WMNs as backbone networks. This study deploys and measures indoor IEEE 802.11s mesh networks to extend WLAN capabilities with extensive experiment configurations. The testbed is constructed in a laboratory and a field crossing three floors of a building. Disagreeing with previous research, the results of this study indicate that RTS/CTS can improve throughput by up to 87.5%. Moreover, compared with the IEEE 802.11b/g, 802.11n achieves better fairness for multi-stream or multi-hop communications. Experimental results also suggest that a longer beacon interval, e.g. 500 ms, can improve channel efficiency for a denser deployment. On the other hand, sparser deployments should use a shorter beacon interval, e.g. 100 ms, to enhance link stability.

1. Introduction

IEEE 802.11s wireless mesh networks (WMNs) [1] have generated extensive research and commercial interest in recent years. Unlike ad hoc networks and sensor networks, which are primarily motivated by military, crisis, or environmental applications, WMNs show potential for commercial applications such as last-mile wireless access or home wireless networking. WMNs can largely reduce the wiring cost and complexity of network deployment by *multi-hop relaying*. As illustrated in Fig. 1, devices in the service range of an 802.11s WMN consists of mesh stations (MSTAs), mesh portals (MPPs), mesh access points (MAPs), and non-mesh wireless stations (STAs). Mesh devices, including MSTAs, MPPs, and MAPs, form a wireless backhaul by connecting with neighboring devices via the wireless medium and relaying traffic for each other. In addition, an MPP bridges the traffic between a WMN and external networks, such as a wired LAN. An MAP provides the functionalities of IEEE 802.11 access point (AP). A conventional IEEE 802.11 STA connecting to a nearby MAP can then communicate with other STAs or access the Internet.

1.1. Lab and field testbeds

Many WMN testbeds have been developed for academic research purposes and commercial trials [2–8]. There are generally two categories of testbeds built by previous work. The first category is implemented in a well-controlled laboratory environment, such as a shielding room. One of the most well-known lab testbeds is the ORBIT project [9]. The benefit of this category is that the strictly-controlled environment reduces the unexpected effect from external error sources, like the wireless signal generated by the widespread wireless devices and noise emitted by microwave ovens [10,11]. However, the disadvantage of this approach is that the scale of experiments, constrained by time and laboratory space, is usually quite small. Therefore, the results from lab testbeds can indeed validate an idea under the clean environment, but are not general enough to be applied to all configurations in real-world deployment.

The second category of WMN testbed is the field trial. Most previous studies on this category build the testbed

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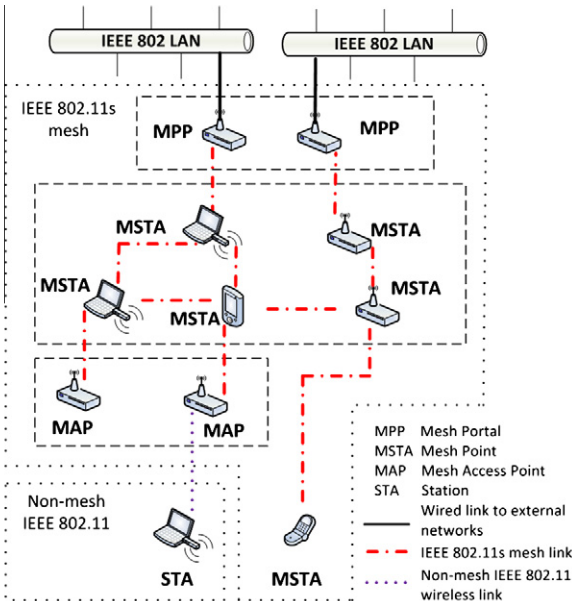

Fig. 1. IEEE 802.11s mesh network architecture.

outdoors, e.g., in an urban or rural area. The devices used in an outdoor environment are usually commercial products [4,5,8] because they must sustain harsh open-air conditions for extended periods of time. The advantage of this approach is that the results collected from a *large-scale* outdoor testbed are undoubtedly a good reference to real-world outdoor deployment. The disadvantage is that the results can vary greatly with highly changeable channel conditions and traffic loading. Meanwhile, the outdoor results might not be applicable to *indoor*, *small-scale* WMNs. Outdoor WMNs typically aim to provide last-mile or community wireless access, and hence need to deploy dozens to hundreds of MSTAs. To guarantee link capacity and signal quality, neighboring MSTAs should be within *line-of-sight* and equipped with *directional* antennas. Unlike outdoor WMNs, however, indoor WMNs provide wireless access coverage to a single building, especially important for old buildings without Internet facilities. The scale of an indoor WMN is much smaller, and its devices are much cheaper, e.g., plastic case without waterproof consideration. In addition, signal decay is more serious in indoor WMNs due to non-line-of-sight deployment. Noise sources are also different from the ones in outdoor environment [11]. As a result, deployment guidelines obtained from outdoor testbeds could not be applied to indoor WMNs.

1.2. Indoor field deployment benchmarked by lab tests

Indoor and outdoor WMNs possess distinguishable attributes and limitations. To the best of our knowledge, only a little previous work focuses on indoor WMNs [3,4]. Therefore, this study combines the deployment methodologies of laboratory and field testbeds to make observations and provide guidelines for indoor IEEE 802.11s WMN deployment. Specifically, 802.11s mesh entities of this study are implemented on a chipset complying with IEEE 802.11n [12]. First, we constructed a *laboratory* testbed. The experimental results of this testbed provide a basic benchmark for field deployment. Then, we deployed a testbed in a three-floor *field* environment, and conducted numerous experiments to investigate the effect of different configurations on complex channel conditions.

The rest of this article is organized as follows. Section 2 reviews previous studies and summarizes the differences of key findings among those literals. Section 3 describes the IEEE 802.11s testbed and experiment methodology. Section 4 presents experiment results. Then, Section 5 summarizes the lessons and guidelines learned. Finally, Section 6 concludes the work.

2. Related work: Effect of RTS/CTS and rate adaptation

Researchers have recently built a number of WMN testbeds to evaluate the performance characteristics of WMNs in real environments. Koutsonikolas et al. [3] reported on the configurations of the TCP maximum window size and other two important MAC parameters, i.e., Request-to-Send/Clear-to-Send (RTS/CTS) and data rates, in the indoor WMN (named MAP) deployed at Purdue University. According to their observation, RTS/CTS and auto-rate adaptation (operating at 2 and 5.5 Mbps) should be enabled for 4-hop flows, and disabled for 1-hop and 2-hop flows. Sun et al. [4] also studied the impact of different MAC configurations of RTS/CTS and auto-rate adaptation (for 802.11b/g) on an indoor WMN testbed called UCSB MeshNet. Their study focuses on performance evaluation in terms of latency and loss rate for video and voice traffic. They recommended that RTS/CTS should *not* be used for multimedia traffic, and that the auto-rate adaptation does *not* always lead to capacity improvement in bursty traffic.

In addition to studies on indoor WMN testbeds, several researchers have examined outdoor WMN testbeds. DGP [5] and FRACTEL [6] are 802.11b outdoor WMNs deployed to determine the performance of wireless networks in rural and semi-urban areas, respectively. Both of these studies indicate that external interference, generated by non-WiFi sources or from WiFi sources in adjacent channels, significantly increases the packet error rate of 802.11b long-distance links. As a result, [5,6] believed that RTS/CTS may *not* really help in such situations. Camp et al. [7] investigated a measurement study of an 802.11b outdoor WMN testbed (named TFA) and highlighted the importance of measurements in accurately planning mesh networks. They also demonstrated that the RTS/CTS scheme has an overall *negative* effect on per-node throughput with minimal gains in fairness, while a *static* rate limiting scheme yields a fair multi-hop throughput distribution even with heavily loaded traffic. In addition, Arjona et al. [8] evaluated the feasibility of singe-radio mesh technology and its competitiveness with cellular networks on an 802.11g outdoor WMN (called Google WiFi) for urban deployment built by Google. Like [7], they concluded that rate limitations for each user could improve the fairness of multi-hop transmissions. Their study also shows that *disabling* the RTS/CTS scheme might improve overall performance at the

Table 1
Summary and comparison on the previous work.

	HW/SW Tech.		Configuration recommendation		
	Platform	802.11 PHY	Beacon interval	RTS/ CTS	Auto rate
Our work (indoor)	Realtek AP + Linux	802.11b/ g/n	○	◎	◎
MAP [3] (indoor)	PC + Linux	802.11b	–	○	○
UCSB [4] (indoor)	Linksys AP + OpenWrt	802.11b/g	–	×	○
DGP [5] (rural)	Soekris + Linux	802.11b	–	△	–
FRACTEL [6] (semi-urban)	Laptop + Linux	802.11b	–	△	–
TFA [7] (urban)	PC + Linux	802.11b	–	○	×
Google WiFi [8] (urban)	Tropos device	802.11 g	–	○	×

◎: Suggested, ○: Case dependent, △: Not necessary (helpless), ×: Not suggested, –: No study.

expense of causing throughput fluctuation on nodes experiencing the hidden terminal problem [13].

Table 1 summarizes and compares the current measurement results with prior studies on WMN deployments. Our testbed is one of the few 802.11n indoor WMNs [14] based on 802.11s. This study offers three major findings: (a) a performance comparison between 802.11n and 802.11g under multi-flow and multi-hop transmissions; (b) an analysis of the impact of beacon interval on the connectivity and throughput of the WMN testbed; and (c) the finding that RTS/CTS can increase the throughput and that the auto-rate adaptation is good for indoor deployment. The last finding does not completely agree with the observations of previous studies, which may come from different test environments and configurations. In [3], the operating data rates, i.e., 2 and 5.5 Mbps, are robust when comparing to other data rates of 802.11b/g/n. In this case, the RTS/CTS mechanism might be less helpful in transmission protection. Also, their suggestions for the using of auto-rate adaptation scheme are not representative of 802.11b/g/n systems, because the rates they used are only a small subset of 802.11b/g/n rates. Another study [4] focused on the latency and loss rate for multimedia transmissions, while the current study examines throughput. Other studies [5–8] deal with outdoor testbeds where the deployment density is sparse, so the benefit of using RTS/CTS to reduce collision is less than its overhead. Moreover, due to line-of-sight deployment, the operating data rates of outdoor WMNs could be predictable according to long-term channel conditions.

3. IEEE 802.11s testbed

3.1. Testbed devices

The testbed used in this study implements a WLAN mesh system on the Realtek RTL8192SE + RTL8196B devices for all MSTAs, MAPs, and MPPs. The device is an 802.11b/g/n 2 × 2 (2 transmitters, 2 receivers) Multi-Input Multi-Output (MIMO) WLAN IC (RTL8192SE) integrated with an Ethernet interface and a 330 MHz 32-bit MIPS processor (RTL8196B). The Realtek platforms can automatically lower the TX power and adjust the RX initial gain to avoid interference. The device runs an embedded Linux (version 2.4.18), upon which the mesh system architecture is built. Fig. 2 illustrates this architecture. Only MPPs enable the IEEE 802.3 interface, and only MPPs and MAPs activate the bridge module.

An IEEE 802.11 network interface controller (NIC) includes a hardware beacon generator that periodically broadcasts beacons. The WLAN manager in the driver can adjust the beacon interval from 20 ms to 1024 ms. To support IEEE 802.11s, the WLAN driver is extended with two components, the *mesh manager* and the *mesh data forwarder* (the dotted boxes in Fig. 2), for the mesh control plane and data plane, respectively. The mesh manager is responsible for establishing and maintaining links with neighboring MSTAs. It records the associated MSTAs in the mesh neighbor table and removes an entry from the table if it does not receive a beacon from that MSTA for a certain period, i.e., 15 s in this implementation.

In the mesh data plane, the receiving handler (RX handler) dispatches a mesh data frame to the mesh data forwarder. The mesh data forwarder validates the connection status of the transmitter in the mesh neighbor table. Then, it sends the frame to the transmission handler (TX handler) if the frame still needs to be relayed in the mesh. If the node is the destination or the node (i.e., MAP or MPP) that bridges the frame to the destination on the external network, a data frame is posted to the upper layer of the protocol stack. Finally, an open-source link-layer bridge module, called an Ethernet Bridge, processes the remaining task of bridging traffic between different interfaces.

3.2. Experiment configuration

This subsection describes the environment and topology of the experiment. A two-phase deployment plan is used to establish the benchmark of the 802.11s testbed. In the first phase, the testbed was deployed in a laboratory

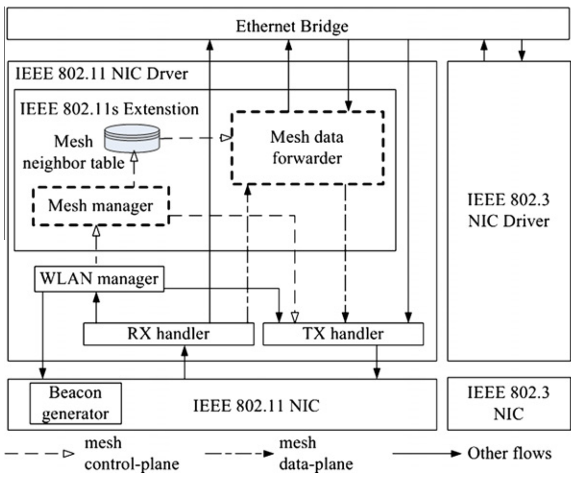

Fig. 2. System architecture of the mesh devices.

to evaluate its basic capacity and performance for a *dense* deployment. Fig. 3a shows the *chain* topology with five nodes in the laboratory environment, in which MAPs are placed 50 cm apart. Next, Fig. 3c shows 9 MAPs used to construct a 3-by-3 *grid* topology, where each grid edge is also 50 cm. Although the placement the MAPs is, the laboratory experiments could not only provide results under a controllable environment comparing with the large-scale experiments. But the results could also suggest the possible lessons for indoor WMNs. This configuration can be taken as the sample topology of the field deployment. These experiment results provide benchmarks and configuration suggestions for the field experiment.

In the second phase, a 9-node, 3-by-3 grid WMN was deployed in the sixth to eighth floors of the Microelectronics and Information Systems Research Center (MIRC) at National Chiao Tung University. Three MAPs were deployed on each floor, as Fig. 3b shows. The distance between MAPs was approximately 25 m. The resulting mesh network covered three floors of the MIRC building. Besides the experimental deployment, four access points standing by on the same channel were detected on the three floors during trials. Figs. 3c and 3d show pictures taken from the laboratory and field, respectively.

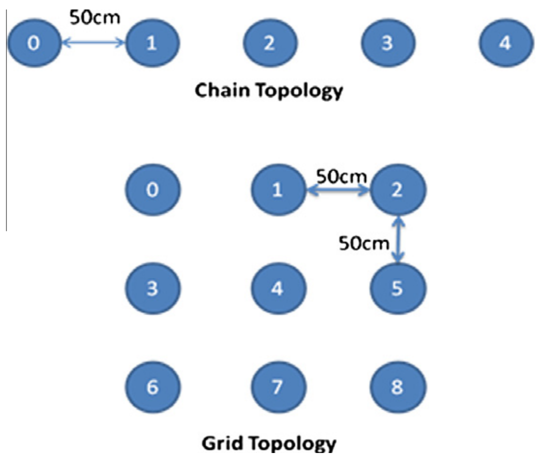

Fig. 3a. Topologies and pictures of the testbed in laboratory and field. Laboratory test topology.

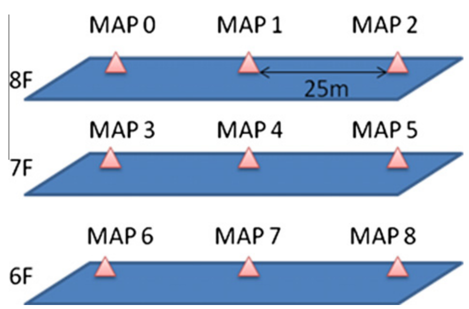

Fig. 3b. Topologies and pictures of the testbed in laboratory and field. Field test topology. MAP4, 5, 7 and 8 were shut down when studying the chain topology in the field.

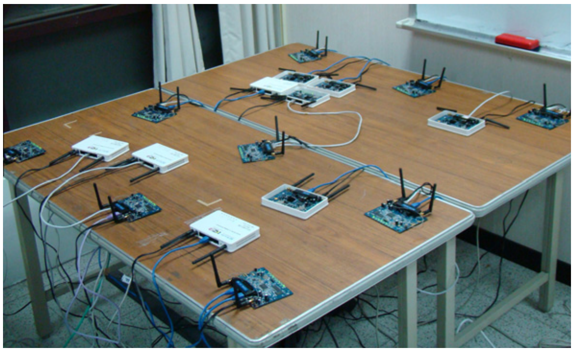

Fig. 3c. Topologies and pictures of the testbed in laboratory and field. Picture of laboratory testbed.

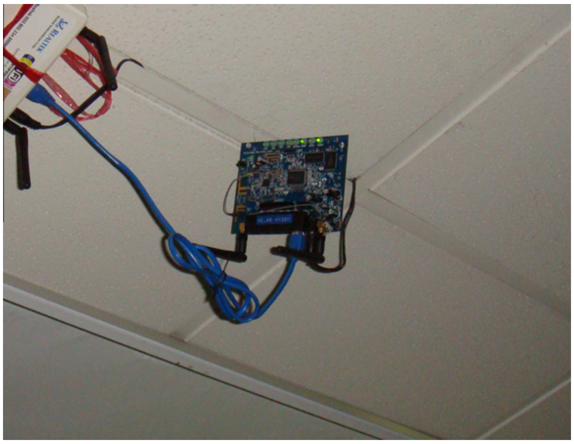

Fig. 3d. Topologies and pictures of the testbed in laboratory and field. Picture of field deployment.

We adopted the *access control list* (ACL) to disable undesired mesh links in the experiments. For example, mesh links are disallowed in the grid topology if two MAPs are neither horizontally nor vertically adjacent. Note that an allowable mesh link does not imply a connected link. Section 4 examines the issue of link stability. We did not use an attenuator in our experiments because the 802.11n MIMO is too sensitive to be precisely controlled with attenuators in a small laboratory space. It is also impractical to attach an attenuator to a MAP in real-world deployment.

3.3. Experiment methodology

For convenience, each MAP was equipped with the Simple Network Management Protocol daemon (SNMPd). This makes it possible to remotely control the embedded Linux on the MSTAs through the SNMP. Fig. 3d shows that a data collecting node connects the MAP via the wire-line. Therefore, statistics can be collected directly by a wired connection without interfering with the test traffic.

We used Netperf [15] to measure the TCP stream performance for the MAPs. Each experiment was repeated more than five times to obtain the average results. Because the duration of each run dominates the convergence of the results, most of the experiments run for more than 1 h to collect enough data and satisfy the convergence. This study defines the traffic stream transmitted from the MPP to the MAPs as the *downlink* traffic. On the other hand, the traffic stream from MAPs to the MPP is the *uplink* traffic. In a *single-stream* experiment, only one TCP stream is transmitted at a time. In a *multi-stream* experiment, which demonstrates a multi-user environment, four MAPs transmit simultaneously. Because of channel quality and data rate generated by Netperf, our field experiments can barely support more than four simultaneous Netperf streams.

4. Experimental results

This section presents the most representative results for both laboratory and field deployments with respect to the configurations of *RTS/CTS*, *802.11 PHY*, and *beacon interval.* Unlike previous deployment studies, this study examines network configuration guidelines for indoor mesh networks. Table 2 describes the default configurations of the testbed. Unless otherwise specified, the experiments in the following subsections follow these default configurations.

4.1. RTS/CTS

The RTS/CTS scheme is known for solving the hidden terminal problem in IEEE 802.11 WLAN. However, exchanging the RTS/CTS frames causes additional channel access overhead, including time spent on transmitting RTS/CTS with the basic data rate, i.e. 1 Mbps, regulated by the IEEE 802.11 standard, and certain inter-frame spaces (IFSs). This subsection discusses how RTS/CTS affect TCP performance in the laboratory and the field.

Table 2
Default testbed configurations.

Parameter	Setting
PHY	IEEE 802.11n
Data rate	Auto
RTS/CTS	Off
Beacon interval	Lab: 500 ms; field: 200 ms
Basic rate	1 Mbps
Link expire timer	15 s
Access control	Allow adjacent nodes only

Fig. 4a illustrates the single-stream performance of both laboratory and field experiments. This figure can be viewed as the throughput benchmark for our testbed. The one-hop throughput of an 802.11n-based WMN without RTS/CTS is 22.95 Mbps. The TCP performance decreases as the hop count increases. The field results of all cases in Fig. 4a are approximately 40% of the laboratory throughput values when the RTS/CTS scheme is not activated. If the scheme is activated, the field results are approximately 60% of the laboratory results.

When the RTS/CTS scheme is turned on in the laboratory experiments, Fig. 4a shows a decrease in TCP performance, comparing with the results of no RTS/CTS scheme. In the field experiments, however, activating RTS/CTS slightly improved the throughput. This is because all the MAPs in the laboratory experiment are located in the *same* collision domain. Since there is *no* hidden terminal problem, the RTS and CTS messages become additional overhead that frequently occupies the channel. However, when the testbed is deployed in the field, the transmission distance is not only longer, but the channel condition is also more complicated. Therefore, RTS/CTS help protect the transmissions from the hidden terminals in field trials, achieving a higher throughput.

Figs. 4c and 4d depict the TCP performance of downlink multi-stream experiments in the field testing. In Fig. 4c, the MAP2 of Fig. 3b is configured as a MPP that simultaneously transmits four TCP streams. Two of these streams are one-hop streams, while the other two traverse three hops. Note that different routing paths of the three-hop streams would result in different performance; however, to examine the real-world WMN properties, we did not put any constraint on the routing decision. Thus, the actual paths were decided in the run-time. In the experiments for Fig. 4d, MAP4 is configured as a MPP, and therefore, all four TCP streams only traverse one-hop. The results in Figs. 4c and 4d match the observation from Fig. 4a that RTS/CTS alleviate the hidden terminal problem and increase the

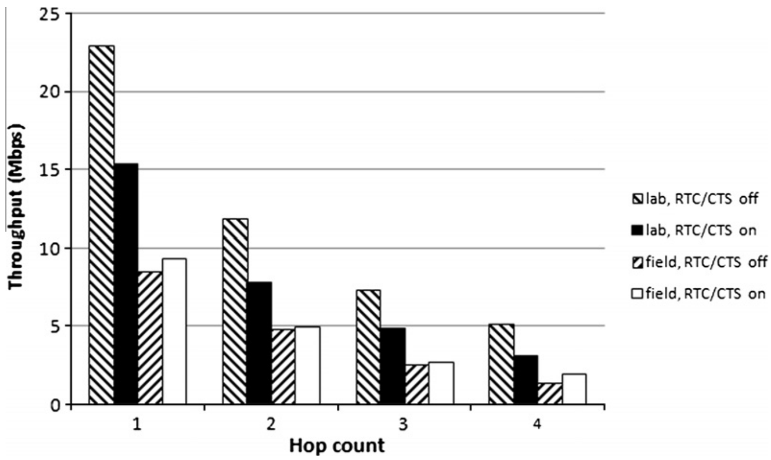

Fig. 4a. Comparison of TCP throughputs between laboratory and field experiments. Effects of enabling RTS/CTS (single-stream, chain topology).

TCP throughput. Moreover, the improvement in Fig. 4d becomes more obvious, i.e., about 33.5% for 802.11n and 87.5% for 802.11b/g, when comparing the results in Figs. 4a and 4c. This improvement may arise from the broader RTS/CTS effective area, as the RTS/CTS initiator (the traffic source) is at the center of our deployed floors. Fig. 4d shows that the throughput of the cross-floor link seems better than the links at the same floor. This is because the distance between the cross-floor MAPs is shorter than the neighboring MAPs at the same floor.

To summarize, the RTS/CTS scheme is recommended for indoor deployment and higher throughput can be achieved when the RTS/CTS signal covers more interference sources. If a WMN is deployed in the same collision domain, however, RTS/CTS are not necessary.

4.2. IEEE 802.11n vs. 802.11b/g

As mentioned in Section 2, most related studies examine 802.11b/g WMNs. The 802.11n standard, however, adopts different technologies that utilize a MIMO design to support higher data rates. This subsection examines the characteristics of an 802.11n-based WMN.

Fig. 4b compares the single-stream TCP throughput of 802.11n and 802.11b/g from 1-hop to 4-hop in both laboratory and field environments. Laboratory results show that the 802.11n outperforms 802.11b/g by 25% at all hop counts. This is reasonable because 802.11n can transmit data at higher rates than 802.11b/g. However, the results in the field experiments are not consistent at the first-hop. In Figs. 4b and 4c, the performance of 802.11b/g surpasses the 802.11n for the one-hop transmissions, while these results are reversed in Fig. 4d. We verified this inconsistency by conducting the same experiments several times, finally concluding that this fluctuation comes from the 802.11n PHY sensitivity to channel conditions and antenna position. Although 802.11n frames can be transmitted at a higher data rate, these high-data-rate frames are more likely to be dropped due to the need for better received signal quality for successful demodulation. There-

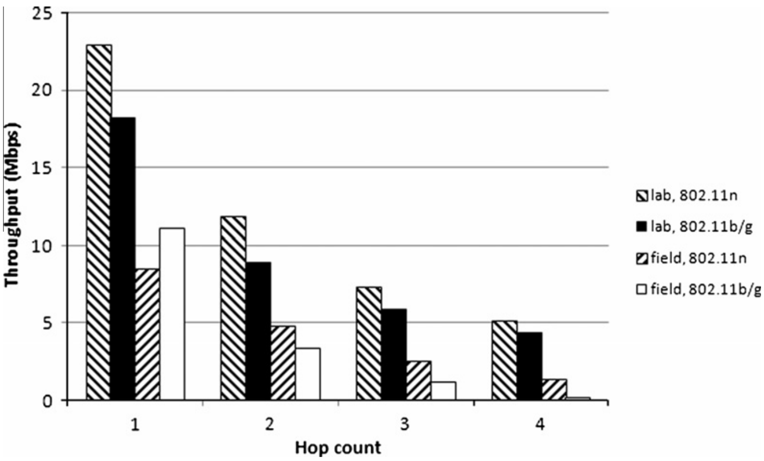

Fig. 4b. Comparison of TCP throughputs between laboratory and field experiments. Comparison of IEEE 802.11b/g/n rates (single-stream, chain topology).

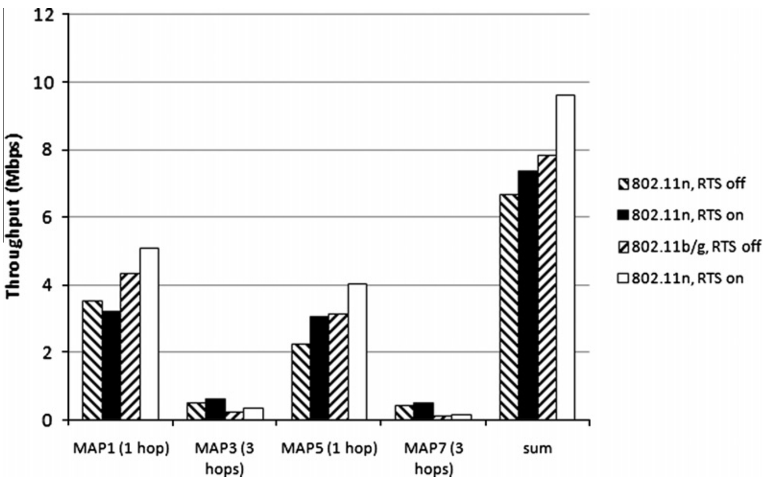

Fig. 4c. Comparison of TCP throughputs between laboratory and field experiments. Effects of setting MPP's location at corner in the field (downlink multi-stream, grid topology).

fore, channel quality fluctuations in the field leads to variations in 802.11n performance.

The phenomenon in which a channel is constantly occupied by some users is called the *channel capture effect* [4]. Fig. 4e presents the multi-stream TCP performance in a chain topology to demonstrate the channel capture effect. In this figure, the amount of data originating from the first-hop MAP in 802.11b/g is similar to that in 802.11n, i.e., the throughput ratio of 802.11b/g to 802.11n is 0.98. However, the throughput difference between 802.11b/g and 802.11n does not increase linearly as the hop count increases, i.e., the ratios for 2, 3 and 4 hops are 0.32, 0.48 and 0.65, respectively. The reason should be the channel resource used by 802.11b/g to deliver the same amount of data is higher than that in 802.11n because 802.11b/g has slower data rates. Thus, in 802.11b/g, most channel resources are spent on one-hop transmissions, and there are few remaining resources for the other hops, as Fig. 4e shows. In other words, the channel capture effect is more serious in 802.11b/g, and produces more unfairness in the TCP throughput.

To summarize, 802.11n does not necessarily outperform 802.11b/g because of the critical requirement of received signal quality for high data rates. However, multihop transmissions can take advantage of the higher data rates of 802.11n. 802.11b/g suffers from the channel capture effect, which causes significant unfairness in the WMN. Therefore, 802.11n is still the preferred standard for an indoor WMN.

4.3. Beacon interval

As mentioned in Subsection 3.1, the MSTAs in the proposed testbed relied on received beacons to maintain links with their neighbors. In this setup, a link is deleted if no beacon is received from the neighbor for 15 s. Therefore, the periodical beacon announcement is still necessary. However, just like other IEEE 802.11 control frames, a bea-

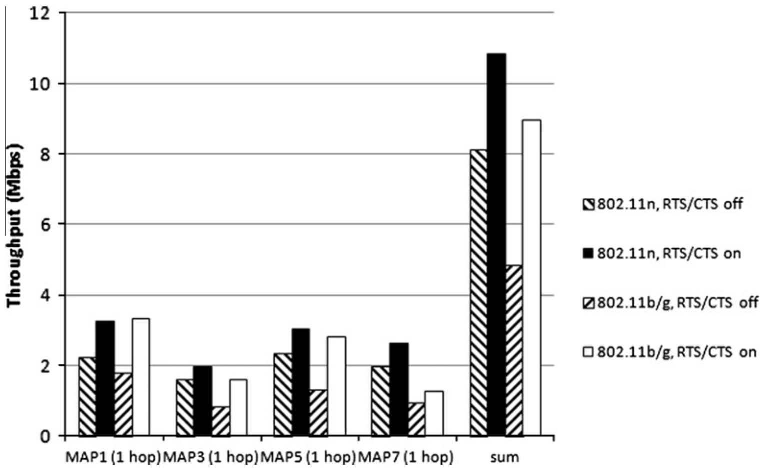

Fig. 4d. Comparison of TCP throughputs between laboratory and field experiments. Effects of setting MPP's location at center in the field (downlink multistream, grid topology).

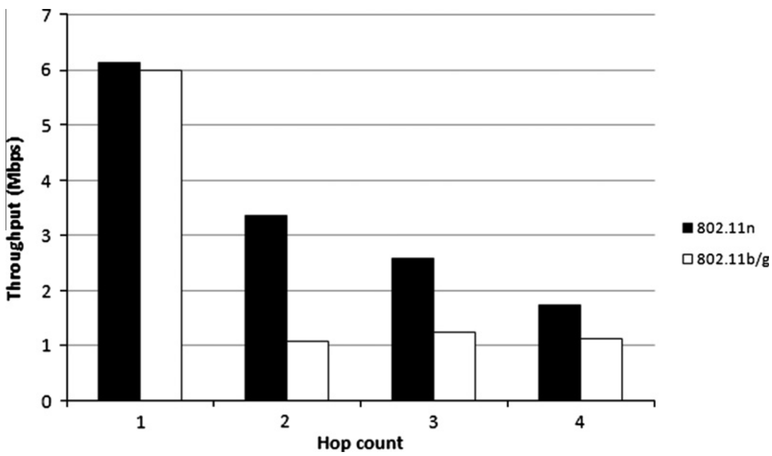

Fig. 4e. Comparison of TCP throughputs between laboratory and field experiments. Channel capture effect of IEEE 802.11b/g rates in the field (uplink multistream, chain topology).

con frame is transmitted at the basic data rate, i.e. 1 Mbps, and therefore consumes a lot of channel resources. We use an extreme example to demonstrate how beacons can impact channel utilization in a WMN. Assuming that the beacon size is 250 bytes, broadcasting a beacon will occupy approximately 250×8 (bits)/10^6 (1 Mbps) = 2 ms of the channel. If the beacon interval is 100 ms and there are more than 50 MSTAs within the same collision domain, the channel could be fully occupied by beacons, i.e., 2 ms $\times$ 10 (beacons/s) $\times$ 50 (MSTAs) = 1 s. At the same time, many beacons would be lost with additional traffic competing for the channel.

This study set MAP4, which is located at the center of the WMN, as the MPP, and performed *multi-stream* experiments in both laboratory and field environments. All of the four streams are one-hop. Fig. 4f shows the aggregated TCP throughput under different beacon interval settings. When the beacon interval increased to 500 ms in the laboratory experiment, there was significant improvement of 43% in uplink TCP throughput. In the field experiment, the same beacon interval increase caused 22% and 25% improvement in downlink and uplink throughput, respectively. This is because a beacon is transmitted at 1 Mbps, occupying a lot of channel access time. Prolonging the beacon interval allows more data traffic to access the channel, enhancing channel utilization. However, the downlink throughput in the laboratory experiment only improved slightly when the beacon was set to 500 ms. We think this may come from the computation limitations of the test platform to simultaneously generate TCP data and route packets in both IP and data-link layers to four destinations.

Although Fig. 4f shows that increasing the beacon interval can significantly improve the throughput in laboratory and field environments, this change also affects link stability. As mentioned before, a mesh link is deleted when the MSTA does not receive a beacon from a specific neighbor for a predefined period of time, e.g. 15 s in our testbed. To illustrate how the beacon interval impacts link stability in a WMN, we counted the number of link state changes at each link. The rate of link state change can then be derived by dividing the number of link state changes by the experiment time. We recorded the link state of the WMN every 10 s for 1 h in the field experiment. Results show that the link state change rates are 0.059, 0.083, and 0.13 for beacon intervals of 100 ms, 500 ms, and 1000 ms, respectively. The link state change rates of 500 ms and 1000 ms are significantly increased. When the beacon interval was 1000 ms, we could not proceed with the field experiments because the link failed frequently. This is also the reason why we only present the TCP results of 100 ms and 500 ms.

To summarize, a longer beacon interval keeps mesh links stable in a small and dense deployment, while the link state becomes changeable in a large and sparse deployment, especially when the channel is not clean. Therefore, in a dense deployment, the beacon interval could be set to a longer value, e.g. 500 ms, to consume less channel resource for mesh control plane and reserve the resource for mesh data plane. However, to maintain the link stability, a shorter beacon interval, e.g., 100 ms, is recommended in a large and sparse deployment.

5. Lessons and guidelines

This section summarizes the lessons learned from the experiments, including those that are not described in Section 4, and provides guidelines for indoor mesh deployment. The suggestions are itemized as follows:

5.1. Activate RTS/CTS in the indoor deployment

Unlike the conclusion of [4–6], this study shows that RTS/CTS should be activated in indoor field deployment, especially when there are many interference sources and the MSTAs are not in the same collision domain. Nevertheless, if the WMN is deployed in the same collision domain, the RTS/CTS scheme is still not recommended as suggested in [4]. Based on our observation, RTS/CTS can effectively resolve the *hidden node problem*. Studies in [5,6] focus on long-ranged outdoor WMNs, the signal is highly interfered

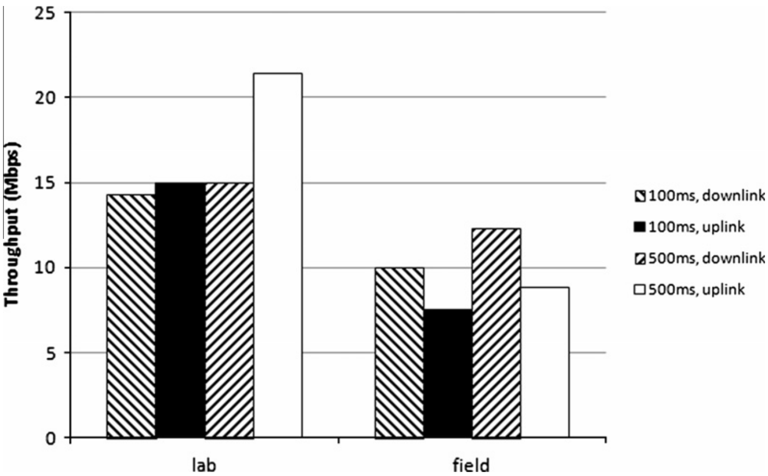

Fig. 4f. Comparison of TCP throughputs between laboratory and field experiments. Comparison of the total throughput when setting MPP at center in field (multi-stream, grid topology).

by the non-WiFi interference sources. Therefore, RTS/CTS cannot alleviate the interference.

5.2. 802.11n is suggested for multi-flow, multi-hop

Although 802.11b/g performs no worse than 802.11n in one-hop transmissions in the field, the low-rate 802.11b/g frames occupy more channel resources for each hop. The first-hop node in an 802.11b/g chain topology generates almost 70% of the total throughput, producing a serious channel capture effect. Therefore, *starvation* may occur at MSTAs with a large hop count in an 802.11b/g WMN. Thus, 802.11n is still preferred for WMN deployment.

5.3. Beacon interval matters

The beacon interval can affect the frequency of updating the link state. However, transmitting beacons with 1 Mbps consumes much of the channel. It is a tradeoff between the link stability and the maximum throughput. We recommend setting the beacon interval at a longer value, e.g. 500 ms, in a small and dense deployment. A smaller beacon interval of 100 ms is preferred for a large and sparse deployment, especially when the channel condition is not good. This is because the link stability is also critical for the WMNs. If the link is unstable, it is possible that the MAP cannot link to any other MAPs or packets drop frequently due to link loss.

5.4. Fixed rate does not help

The results from two studies on outdoor testbeds [7,8] imply that a fixed rate should be used to achieve better throughput. However, the channel quality in our indoor field experiments is much more variable than their outdoor, line-of-sight communication. An aggressive fixed rate might destabilize the transmissions, while a conservative fixed rate produces a poor throughput. An auto data rate mechanism allows the transmission rate to be adjusted dynamically according to the channel quality, but this adjustment mechanism must be sensitive enough to adapt to the fluctuant channel conditions in the field.

5.5. Bottleneck is the channel condition

Results show that the total throughput of a multi-stream experiment is close to the single-stream, one-hop throughput. The throughput bottleneck seems to be the MSTA, and especially the MPP, where traffic streams aggregate. This result matches the findings of previous research [16]. Therefore, the MPP should be located in a position with a clear channel condition, leading to better link quality between the MPP and its neighboring MSTAs.

5.6. Hop-count should not exceed four hops

Considering the performance and the stability for the end-to-end traffic, we recommend that the hop-count should not exceed four hops.

5.7. Mesh size is determined by MPP's capacity and maximum hop count

Based on the item 5 and 6, the throughput performance of a WMN is highly related to the channel quality of the MPP and the hop count of the traffic flow. Therefore, the size of a WMN is determined by the MPP's capacity and maximum hop count.

5.8. Cross-floor links are frangible

Results show that the signal of a cross-floor link is quite unstable. Thus, the cross-floor links should be avoided.

5.9. Angle and direction of antenna pairs are critical

IEEE 802.11n adopts the MIMO technique to achieve higher data rates. Similar to previous findings [17], angle and direction of the antennas of the MAPs in our experiments directly affected the measured received signal strength (RSS). Because RSS is one of the criteria of data rate adjustment, antennas placement is a critical factor in networking performance.

5.10. Avoid links with asymmetric RSS values

By changing the antenna placement, the RSS values seen by the peers in a link may have huge difference. RSS could be a factor in WMN routing metrics. If the RSS measured by the peers is asymmetric, the routing path may not be symmetric, e.g., there is another MSTA with a better RSS value measured by only one end of the peers. Previous research [18] indicates that asymmetric routing could lead to serious problems for Ad hoc On-Demand Distance Vector Routing (AODV) [19], from which the 802.11s routing protocol is derived. Therefore, the links with asymmetric RSS values may cause asymmetric routing problems.

6. Conclusion

This study develops and evaluates an IEEE 802.11s wireless mesh network testbed for indoor environments. Based on observations, this study provides guidelines for tuning various parameters in indoor WMNs. Extensive experiments are conducted in both laboratory and field environments. Unlike previous studies, the experiment results of this study recommend activating RTS/CTS if the mesh nodes do not coexist in the same collision domain. Results also show that the 802.11b/g PHY performs no worse than 802.11n with respect to one-hop transmissions. However, 802.11b/g can cause serious unfairness because one-hop nodes constantly occupy the channel. Besides, the beacon interval should be set to a longer value, e.g., 500 ms, in a dense deployment, and set to a smaller value, e.g. 100 ms, to enhance link stability in a sparse deployment. Finally, the observations summarized in this article can provide guidance for small or medium scale indoor 802.11 WMNs.

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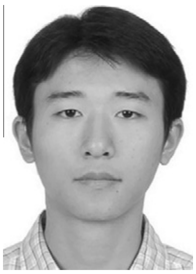

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