Characterization of 802.11 Wireless Networks in the Home

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***Abstract*— Anecdotal evidence suggests that home wireless networks may be unpredictable despite their limited size. In this work, we deploy six-node wireless testbeds in three houses in the United States and the United Kingdom. We examine the quality of links in home wireless networks and the effect of (i) transmission rate, (ii) transmission power, (iii) node location, (iv) type of house, (v) external interference, and (vi) 802.11 physical layer technology. We provide empirical evidence suggesting that homes are challenging environments for wireless communication. Wireless links in the home are highly asymmetric and heavily influenced by precise node location, transmission power, and encoding rate, rather than physical distance between nodes or local interference. We discuss our findings and their implications on the design of home 802.11 networks.**

I. INTRODUCTION

Home wireless networks have become increasingly popular due to ease of deployment and low cost compared to wired networks. However, the transmission principles in wireless communications are dramatically different than those of wired networks. A recent study of wireless access points deployed over a metropolitan area demonstrates significant challenges to performance and connectivity [1]. Similarly, deployment of a wireless network in an enterprise environment, while relatively well understood, typically requires a site survey to engineer a network with proper coverage and capacity. Comparatively little is known about the properties of home wireless networks, beyond anecdotal evidence.

In this paper we attempt to measure the characteristics of home wireless networks. A typical home wireless network consists of an access point, several PCs, and increasingly, multimedia and consumer electronic devices. Given the typical transmission range of IEEE 802.11a/b cards one may presume that a home network is highly unlikely to face the same deployment challenges as an enterprise wireless network or wireless hot spot. This is the question we will investigate. While we focus on home wireless networks, we expect these results to be applicable to small-to-medium sized business deployments and other small wireless networks.

Using a small network of devices deployed in three homes, two in the United States and one in the United Kingdom, we study the properties of wireless links in home environments. We examine the impact of transmission rate and transmission power on the quality of wireless links. We show that despite the small size of home wireless networks, connectivity between any two wireless devices is not guaranteed or necessarily predictable, regardless of transmission power or rate. We also show that small changes in antenna orientation and node location can have a dramatic and unpredictable impact on the connectivity of the network. Our results span both 802.11a and 802.11b technologies and do not show strong correlation with the physical distance between nodes. These results suggest that a typical home user cannot depend on common sense alone in deploying a high-performance wireless network. Instead, technologies such as mesh routing and network self-configuration may be required in the home.

TABLE I
DESCRIPTION OF HOMES USED IN EXPERIMENTAL TESTBEDS.

Label	Size (ft^2)	Construction	# Floors	# Nodes
ushome1	2,500	Wood	2	6
ushome2	2,000	Wood	2	6
ukhome1	1,500	Brick / steel	3	6

II. EXPERIMENTAL ENVIRONMENT

Our experiments are intended to assess the quality of wireless links in home environments. We evaluate three homes, two in the United States and one in the United Kingdom. High-level details of the different homes hosting our experiments can be found in Table I. Our experiments are designed to investigate the impact of the following parameters:

- Type of house, e.g. size, construction material.
- Wireless technology used: 802.11a or 802.11b.
- Transmission power, denoted by txpower.
- Transmission rate, denoted by txrate.
- Node location.
- Interference from appliances.

A. Experimental Setup

We deployed six wireless nodes inside each home. Nodes were deployed in different rooms, wherever computing or consumer electronic devices might be located. For 802.11b experiments the nodes were small form-factor PCs with Netgear MA701 compact flash 802.11b wireless cards. The nodes ran Linux kernel version 2.4.19 and the hostap driver [2]. For 802.11a experiments the nodes were laptops with NetGear WAG511 CardBus 802.11a cards running Linux kernel version 2.4.26 and the MIT madwifi-stripped driver [3]. Our measurement methodology was common among all experiments. All nodes join an ad-hoc network operating on a frequency that is at least 5 channels away from the next occupied 802.11 frequency. Each node is instructed in turn to send a series of

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[*] Other names and brands may be claimed as the property of others.

UDP probe packets to every other node. Each probe packet lists the source node, as well as its number in the series. The size of the probe packet and the duration of each sub-experiment are configurable. In all experiments, link-layer retransmissions were disabled, the probe size was 1024 bytes, and the duration of each sub-experiment was 150 seconds, with a frequency of one packet every 500 ms. Lastly, each individual wireless link is assessed independently, and no simultaneous transmissions take place inside the network.

B. *Methodology*

In our testbeds, we examine the impact of node location, antenna orientation, and obstacles. To assess the impact of each factor, we deploy the six nodes described above in selected locations inside a house. In each experiment, all nodes test their connectivity to every other node using a series of 300 probes for a duration of 150 seconds for a given combination of txrate and txpower. Experiments are carried out during the night to avoid interference from moving people.

Each experiment allows us to quantify the loss rate observed by each wireless link, as well as the sequence of successes and failures. We graphically present the obtained matrix in Figure 1 as collected in *ushome1* when *txrate* is 2 Mbps and *txpower* is 30 mW. Every row in Figure 1 corresponds to probes sent from a specific source node. In each subplot, a bar denotes the successful reception of a probe by the destination node. From Figure 1 we can see that in *ushome1* and under the selected transmission power and rate, communication from node-5 to node-2 is extremely limited; most probe packets were lost. In addition, we see that despite the fact that node-3 has a very low delivery success rate to node-4, the quality of the link in the reverse direction is nearly loss-free. Such link asymmetry has been reported in previous performance studies of wireless networks [1], [4] and was found to be quite common in the home environments studied in this paper.

C. *Validation*

To validate whether these results represent actual link characteristics or a transient affect, we run two experiments with the exact same node deployment and at the same time of day. We then compute the loss rates observed for each wireless link under each test. In Figure 2 we present the results obtained across the two experiments with the same setup. Each experiment results in four subplots, where *txrate* is either 2 Mbps or 11 Mbps and *txpower* is either 30 mW or 1 mW. Each subplot contains the performance of individual wireless links in terms of their loss rate in each direction. (Figure 1 contains the source data presented in the lower left plot of Figure 2(a).) While not exactly identical, the performance shown in each subgraph of Figure 2(a) is similar to that of Figure 2(b). Links that are poor or asymmetric in one run, tend to also be poor or asymmetric in the next. Thus, network performance does not change significantly from one run to the next. We ran the same validation test in each home and found this result was easily reproducible.

To determine whether 150 seconds is sufficient to obtain an accurate view of the quality of the wireless link, we also measured links over a longer period of time. Using a transmission rate of 11 Mbps and a transmit power of 30 mW, we performed the same experiment in *ushome1* for a time span of 20 minutes (instead of 2.5 minutes). We then compared the success rates derived using the entire time series with the success rates that would be estimated by the first 300 samples (i.e. 150 seconds). In Figure 3, each point represents the two success rate measurements for each unidirectional link. In each case, the success rate measured in 150 seconds was a reasonable estimate of the success rate over the 20 minute period. Thus, 150 seconds is long enough to assess the medium-term properties of each link under the tested conditions.

We must also consider the effect of time of day on link performance. Recall that experiments were typically performed at night to avoid interference from household activity. To determine if results obtained at other times of day would vary significantly, we performed a 150-second link test for a single node pair in *ushome1* once per hour for 24 hours. As shown in Figure 4, while link quality may fluctuate somewhat with time, a ”good” link tends to remain ”good” (and a ”bad” link remains ”bad”), despite small deviations over time. To avoid any complications from time of day specific behavior, we tried to collect comparable data at the same time of day.

III. RESULTS

We now evaluate the home wireless environment along six dimensions: (i) *txrate*, (ii) *txpower*, (iii) node location, (iv) house type, (v) external interference, and (vi) physical layer.

A. *Overall characteristics of a home network*

Using 802.11b radios, a full set of measurements like those presented in Figure 1 was collected for four combinations of transmission power and rate. In Figure 5 we present our results for all combinations from *ukhome1*, *ushome1*, and *ushome2* respectively. The deployment of nodes in the individual homes is schematically shown in Figure 7. We refer to this initial layout of the nodes in each home as *layout1*.

As expected, in most cases link loss rates were higher when the encoding rate was higher and lower when the power level increased. While each home represents a small space, wireless connectivity was not always omnipresent. Across all rates and power levels, a large number of asymmetric links were present. In most experiments, at least one pair of nodes had greater than 30% loss. And, as seen in Figure 5(b), while the increase in transmission power improved some links, the overall problem was not eliminated. This initial set of experiments demonstrates that lossy links are likely to be found inside every home, and in some cases, loss cannot be eliminated by reducing the transmission rate or increasing the transmission power. On the other hand, such changes do not appear to affect the quality of links with low loss rates.

B. *Small changes in antenna orientation and location*

There are several reasons why particular node pairs may not be able to communicate. The location of the nodes and the orientation of their antennas impact the obstacles in their direct path, and thus multi-path fading and signal attenuation. To evaluate these effects in the home, we modify *layout1* such that the nodes are translated by a few inches and rotated such that their antennas face a different direction. We call this deployment *layout2*. We perform the same series of experiments on *layout2* and present the results in Figure 6.

We observe that a small change in node location and orientation can have a significant impact on link quality. While *ukhome1* and *ushome2* had few links with a loss rate above 50% in *layout1*, there were several such links in *layout2*. Since the distance between nodes did not change significantly, and since the change observed between *layout1* and *layout2* was much greater than normal variation (Section II.C), exact node placement must be a key contributor to performance.

Our findings for *ukhome1* are summarized in Figure 7(a). The leftmost figure denotes the node pairs that experienced the worst connectivity (links with greater than 95% loss) in *layout1*. In the middle we identify links with the worst connectivity in *layout2*. Under the new configuration, the set of nodes that cannot communicate has dramatically changed. Similar findings were obtained for *ushome1* and *ushome2* as shown in Figure 6(b) and (c) and Figure 7(b) and (c).

C. Large changes in node placement

The previous section considered the impact of small changes in node location. We now move a subset of nodes in *ukhome1* (nodes 2 and 7) from their position in *layout1* to a different location within the same room (rightmost plot of Figure 7 (a)). The other nodes were moved slightly. We call this configuration *layout3*. Loss rates measured for *layout3* are shown in Figure 8. From Figure 5(a) and Figure 8 we observe that *layout3* has more significant loss (both in number of links and quality of links) than *layout1*.

The above results clearly demonstrate the challenges of home environments on wireless networks. Node positioning has a dramatic impact on the connectivity of the network, and ”randomly” selecting the location of a node will not ensure its connectivity. Moreover, ”randomly” selecting the location for an access point does not necessarily ensure a fully connected network. For example, in layout3 node locations 2, 4, and 6 would not be good choices for an AP, as they would not have good connectivity to all other nodes.

D. The relationship between link quality and distance

In Section III.A we demonstrated that home wireless links tend to be highly asymmetric. The presence of asymmetry suggests a loose relationship between distance and link quality. In this section we look into this question in more detail.

Figure 9 presents the loss rate between node pairs for *layout2* in each home versus the distance between the nodes. Clearly there is no correlation between physical distance and wireless link quality in these home networks. This result holds across homes and across *txrate* and *txpower* settings.

Our results thus far demonstrate that physical obstacles that fall between nodes as a result of their placement tend to determine the performance of home wireless links, rather than physical distance and transmission power.

E. External interference: microwave oven

Homes have a variety of sources of radio interference. Microwave ovens are one source of broad-spectrum interference that can cause packet loss in wireless networks. In Figure 10 we show the effect of a 600W microwave oven on the loss rate of an 802.11 radio. A receiver was placed at varying distance to the microwave. A sending node was placed a constant 15 feet from the receiver and transmitted packets at 30 mW and 11 Mbps for a period of 30 seconds. Measurements were taken with the microwave active and idle. Our results suggest that a microwave oven creates localized interference, which falls off within 1 foot. The lower loss rate at 0 feet was likely due to shielding from the microwave oven door.

F. Comparison between home networks

Across homes, results differ substantially. In *layout1*, the largest home, *ushome1*, had the worst performance, and the smallest home, *ukhome1* had the best performance, particularly at low transmit power. While this result suggests that distance may play a significant role in performance, the results presented in Section III.D demonstrate that loss rate is not correlated with distance. Further, under *layout2*, *ukhome1* performed significantly worse, with the most links over 95% loss. Thus, the key parameter is precise node location and orientation, rather than home size or distance between nodes.

G. The 802.11a physical layer

While the preceding data was collected using the IEEE 802.11b physical layer, other physical layers may possess different characteristics. In this section, we consider the performance of the IEEE 802.11a physical layer in the home. As in II, we deploy laptops with 802.11a wireless cards in the same locations as the 802.11b nodes and perform the same series of connectivity experiments. Each experiment is completed with the same transmission power: 30mW. We considered four different link encoding rates: 6 Mbps, 18 Mbps, 36 Mbps, and 54 Mbps. Two node deployments were used, where *layout1* is the initial deployment, and in *layout2* node orientations and locations are changed slightly. The loss rates in *ushome1* for *layout1* and *layout2* are reported in Figure 11; results for *ushome2* are shown in Figure 12.

As might be expected, the characteristics of 802.11a wireless links in the home are not entirely unlike 802.11b wireless links. As the link encoding rate increases, the packet loss rates generally increase as well. Many links are lossy, and some links are highly asymmetric. In some cases it is possible to create a nearly loss-free network at low data rates, but only at specific node locations and orientations. As with the 802.11b results, the networks in both homes were sensitive to small changes in node position and orientation, resulting in significantly different link quality between *layout1* and *layout2*. Finally, as shown in Figure 13, link loss rates do not correlate with the distance between node pairs.

While the 802.11a results were similar to the 802.11b results, one difference is quite clear. In the home, 802.11a links appear to have a rather ”binary” behavior, despite the lack of link-layer retransmissions. Link loss rates in the 802.11b experiments took on a much wider variety of values.

Figure 14 provides a summary comparison between 802.11a and 802.11b. In both homes the 6 Mbps 802.11a links were much more reliable than either the 2 Mbps or 11 Mbps 802.11b links. Thus, one would expect 802.11a to provide better throughput in the home. However, the 54 Mbps link encoding performed very poorly between almost all node pairs. Thus, unless nodes are very optimally placed in the home, it is unlikely that 54 Mbps will be attained. While one might expect the 802.11a MAC to perform better in equal environments, lower levels of interference from non-802.11 devices in the 5 GHz band may also contribute to the superior performance of 802.11a in the home environment.

IV. RELATED WORK

Several recent studies have evaluated large wireless networks deployed across university campuses. Kotz and Essien [5] studied a 476 access point wireless network deployed across a large campus, focusing primarily on user traffic characteristics rather than link performance measurements. Aguayo, et al. [1] studied the link characteristics of a 38-node 802.11b mesh network deployed across a large university campus. Their results suggest that wide variation in link quality is common in real-world wireless deployments and indicates a low correlation between loss rate and distance. Other studies have investigated the characteristics of wire-less links in sensor networks. Zhao and Govindan [4] measured the link characteristics of 60 sensor nodes deployed in an office building, an outdoor park, and a parking lot. The study finds that many links operate in a ”gray area” with difficult-to-predict intermediate loss rates and performance.

While it is not unexpected that wireless link performance will vary when deployed across large geographic areas, our study focuses specifically on the characteristics of home networks and demonstrates that variations in link quality are very common even when wireless networks are deployed within the relatively small area of a home.

V. CONCLUSIONS

Using six-node testbeds deployed in three different houses in the United States and the United Kingdom we studied the properties of home wireless networks. We showed that despite a home’s relatively small size, omnipresent connectivity is not guaranteed. Homes tend to feature wireless paths with a variety of obstacles which may render wireless communication impossible between node pairs.

Our results demonstrate that wireless links inside homes tend to be stable over time, highly asymmetric, and highly variable from one link to the next. In home environments, precise node location is perhaps the single most important factor determining the quality of wireless communication. Indeed our results clearly confirm that distance has no impact on the quality of the wireless links, while small changes in antenna orientation and node location can dramatically change the performance of individual links.

IEEE 802.11a and 802.11b networks have similar overall characteristics with respect to loss rate, even though the performance of 802.11a appears to be slightly better in the home. Nonetheless, in both 802.11a and 802.11b, operation at the highest allowable rate may not be possible due to high loss.

The wide variety of link performance in home networks suggests that new topologies may be appropriate. The precise location of the AP will have a significant impact on overall performance. In many cases, a given AP deployment will not yield a connected network. Since AP deployment is typically determined by the point of entry of the Internet service and aesthetic concerns, these results suggest that mesh networking and other self-configuring network topologies may be necessary in home networks.

In general, our results demonstrate that home networks are not benign and face problems similar to those found in larger scale networks. In future work, we intend to further assess the performance of home wireless networks and to evaluate the effectiveness of self-configuration technologies in the home.

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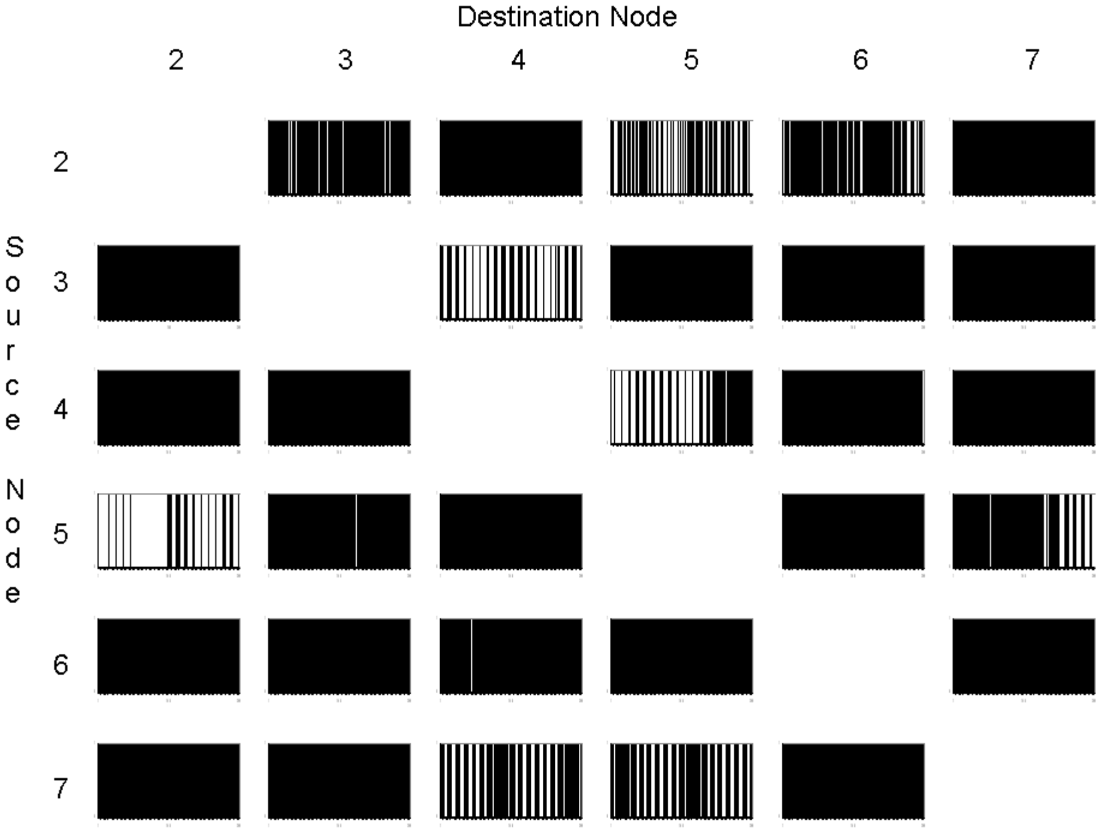
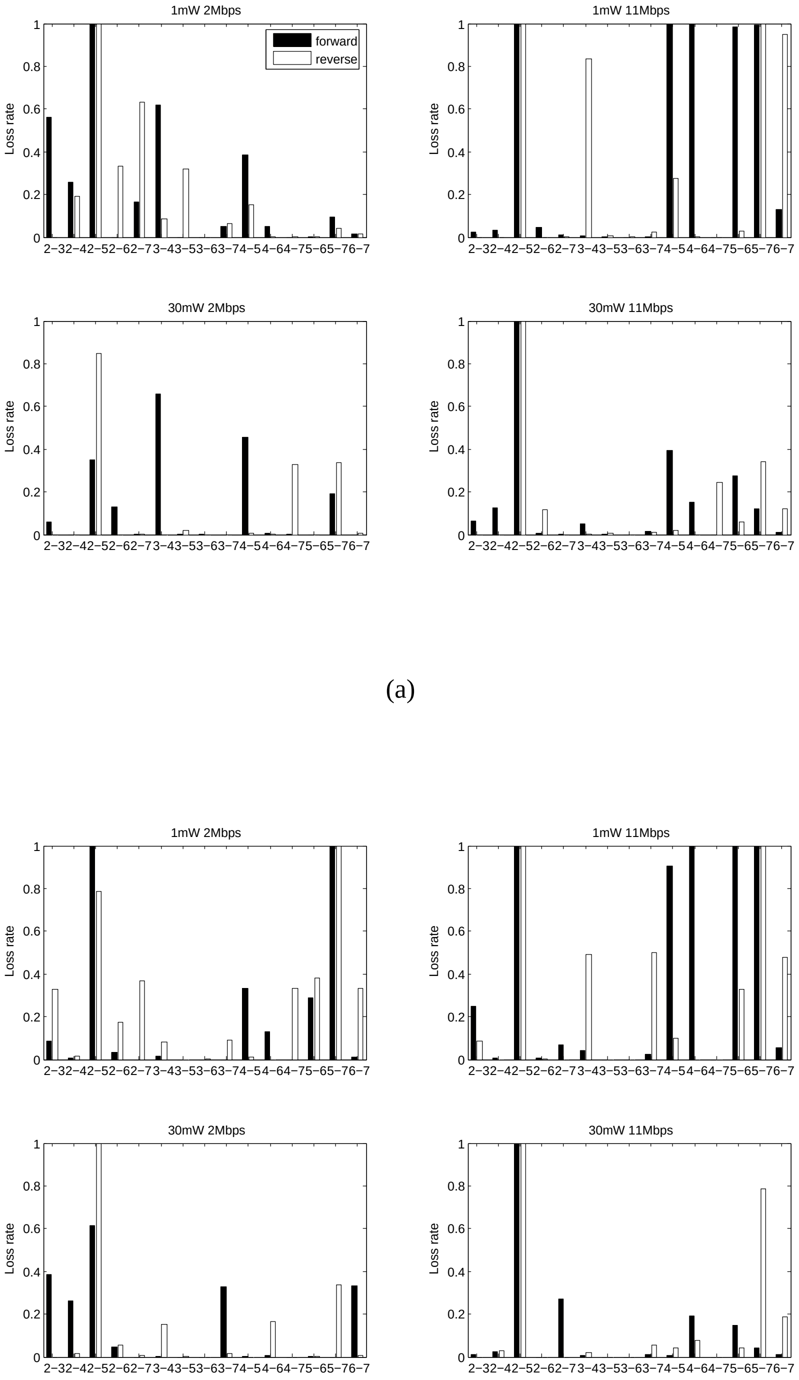


Fig. 1. Matrix of probe packets successfully delivered between each pair of nodes in *ushome1* at 30mW and 2Mbps.



(a)

(b)

Fig. 2. Loss rates for each pair of nodes in two runs at *ushome1*.

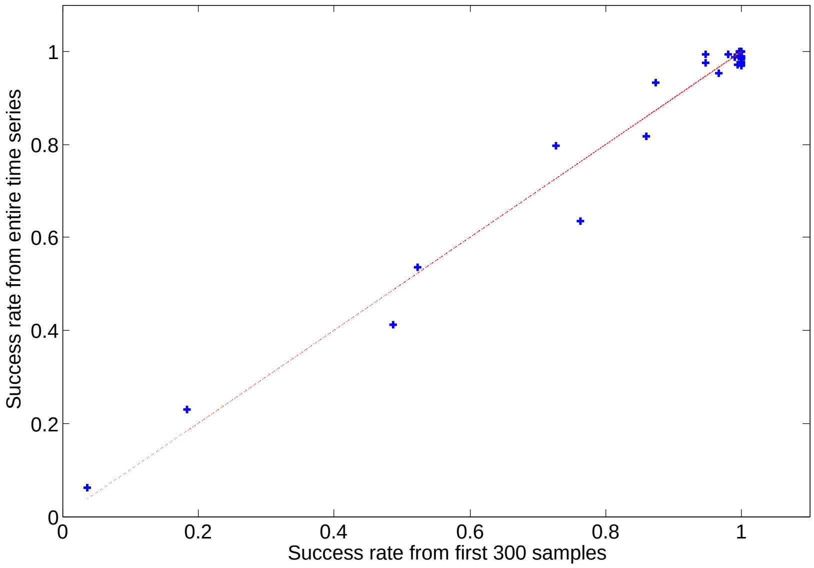


Fig. 3. Comparison of success rate results for 300 and 2400 sample lengths. Straight line is used as reference of equality (y=x).

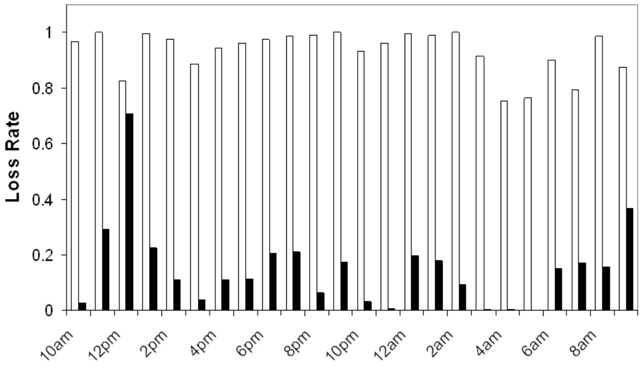
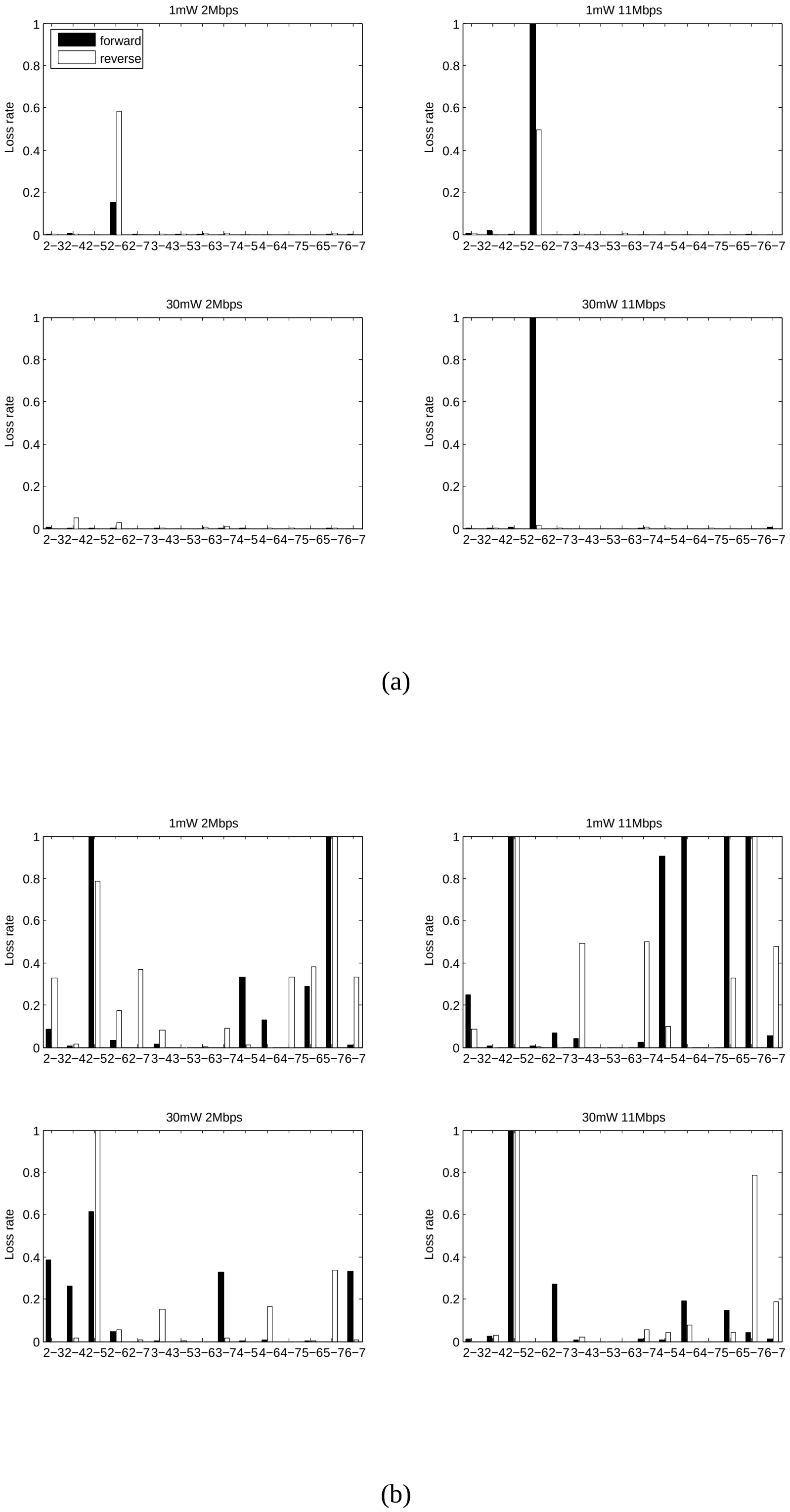


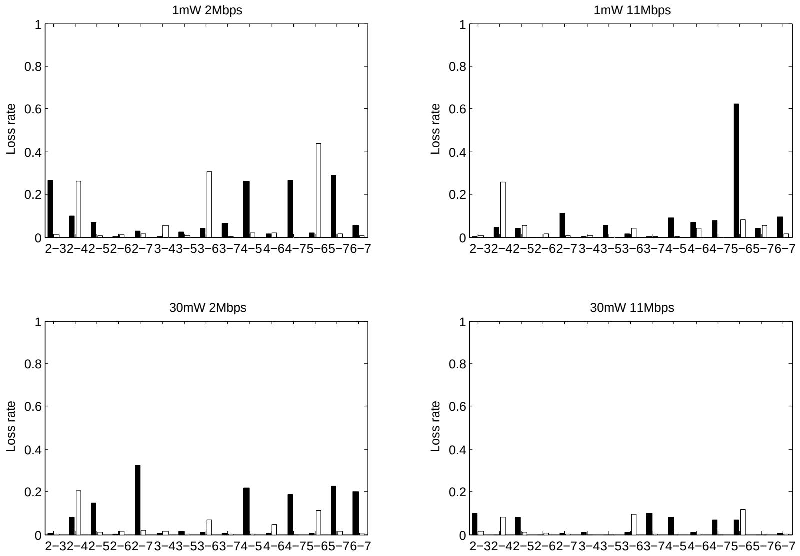
Fig. 4. Loss rate as a function of time of day for *ushome1* (txpower=30mW, txrate=11M). First bar is node-4 to node-6, second bar is node-6 to node-4.



(a)

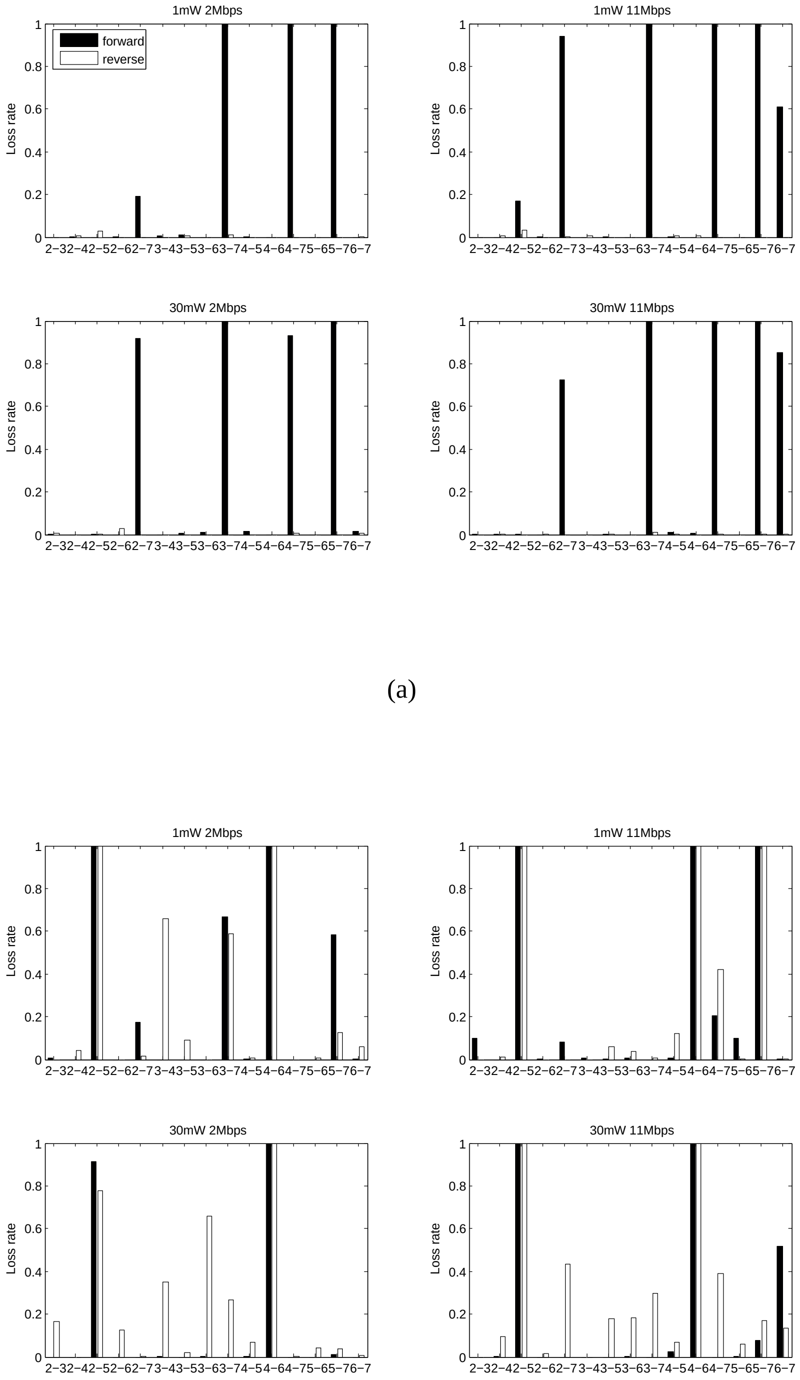
(b)

Fig. 5. Loss rate for node pairs for *layout1* in (a) *ukhome1*, (b) *ushome1*.



(c)

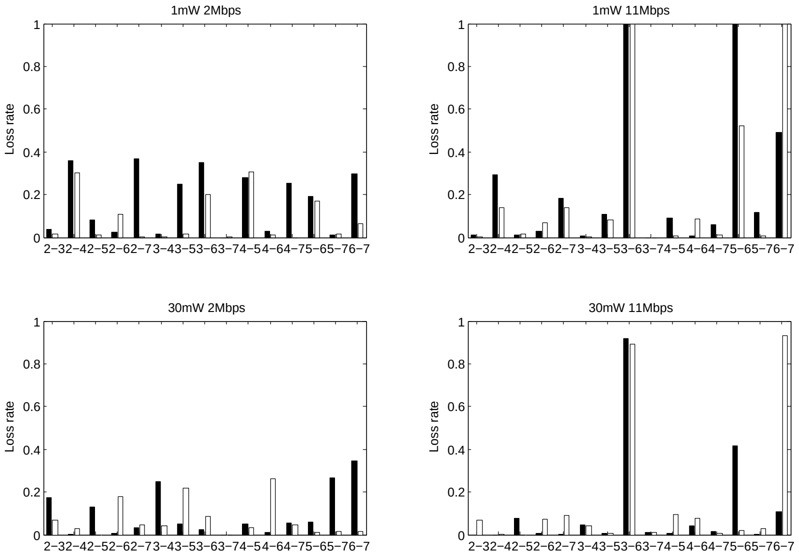
Fig. 5. Loss rate for node pairs for *layout1* in (c) *ushome2*.



(a)

(b)

Fig. 6. Loss rate for each pair of nodes for *layout2* in (a) *ukhome1*, (b) *ushome1*.



(c)

Fig. 6. Loss rate for each pair of nodes for *layout2* in (c) *ushome2*.

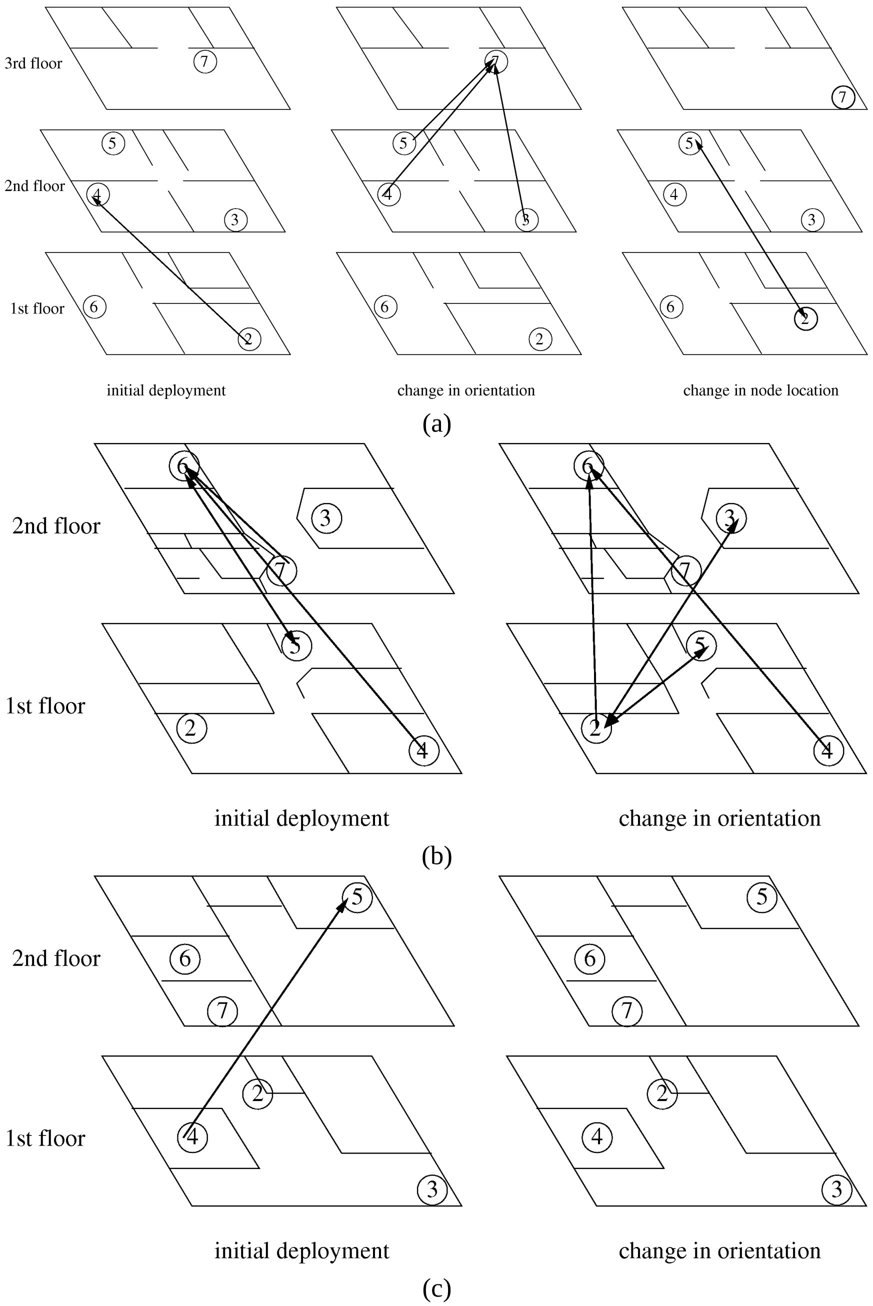


Fig. 7. Abstract home floorplans and location of links with greater than 95% loss rate at 1 mW and 11 Mbps under different configurations: (a) *ukhome1* for *layout1*, *layout2*, and *layout3*, (b) *ushome1*, and (c) *ushome2* for *layout1* and *layout2*. Dashed lines indicate asymmetric links.

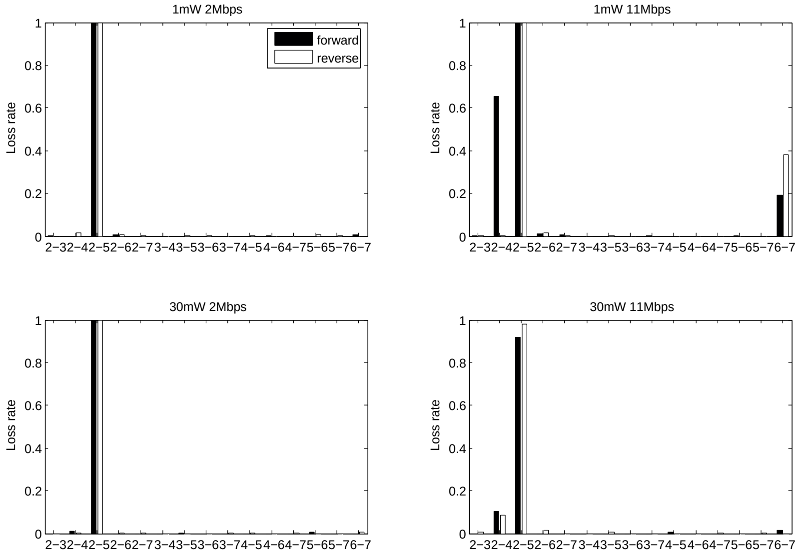
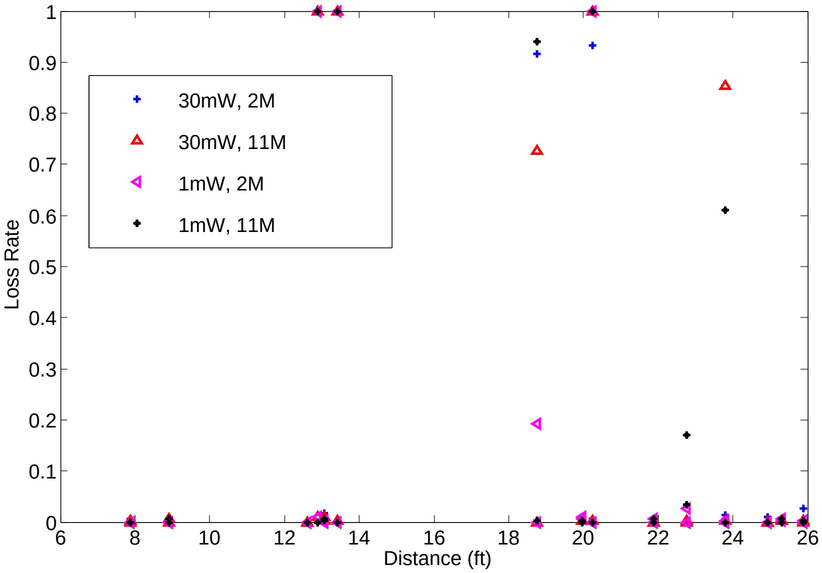
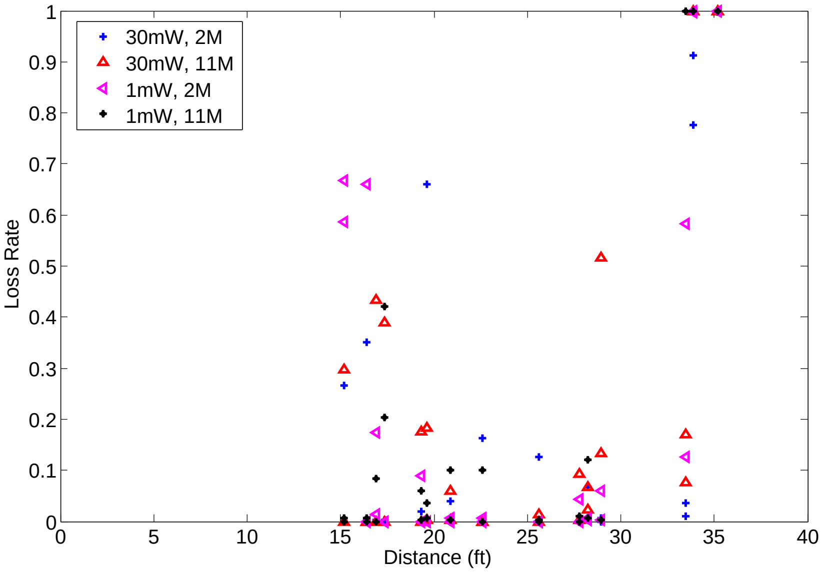


Fig. 8. Loss rate for each pair of nodes in *ukhome1*, *layout3*.

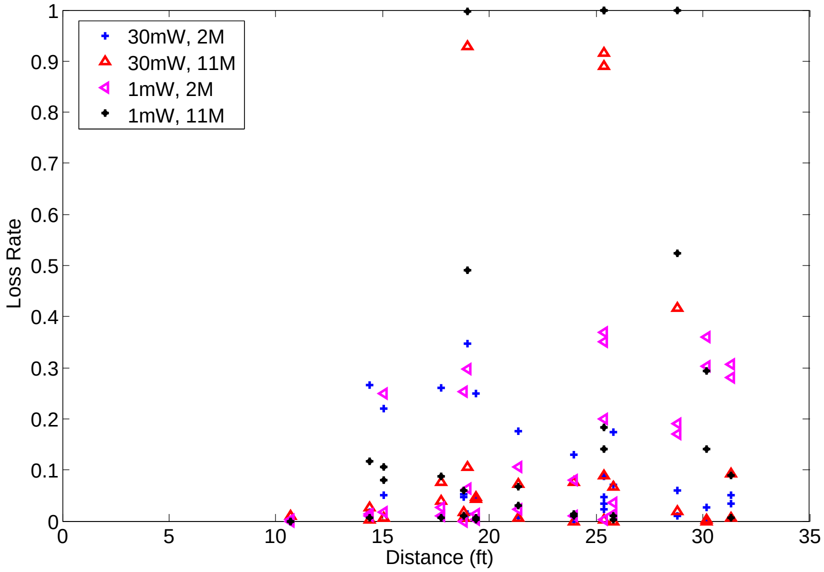


(a)



(b)

Fig. 9. Loss rate for each pair of nodes against their distance for (a) *ukhome1* and(b) *ushome1* under *layout2*.



(c)

Fig. 9. Loss rate for each pair of nodes against their distance for (c) *ushome2* under *layout2*.

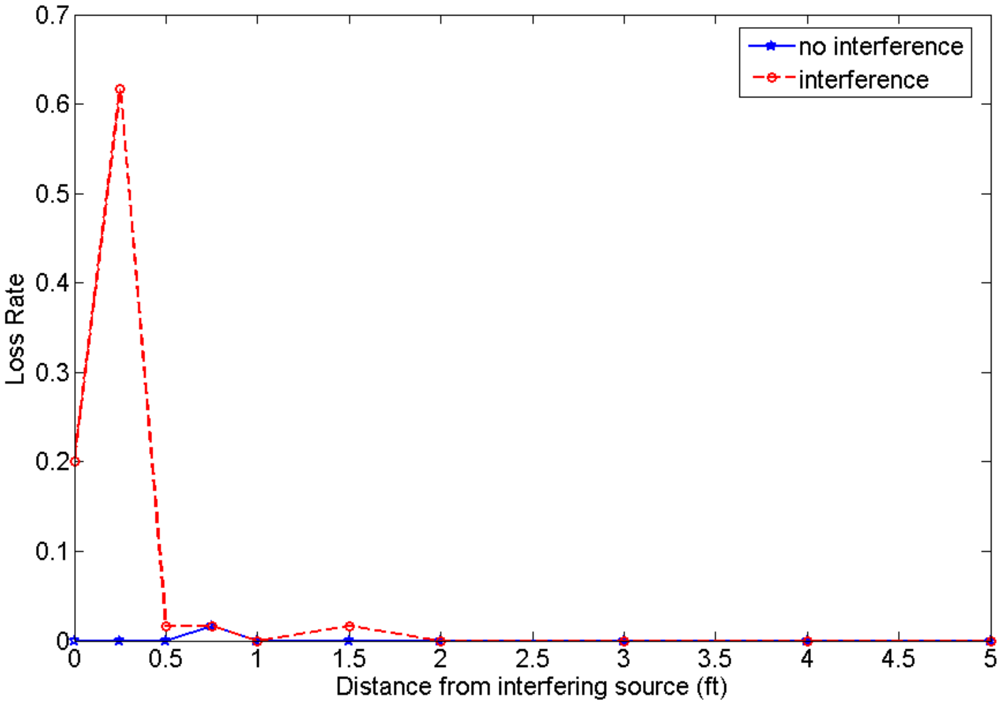


Fig. 10. The impact of a 600W microwave on a receiver at varying distance from the interference source and a distance of 15 feet from the sending node.

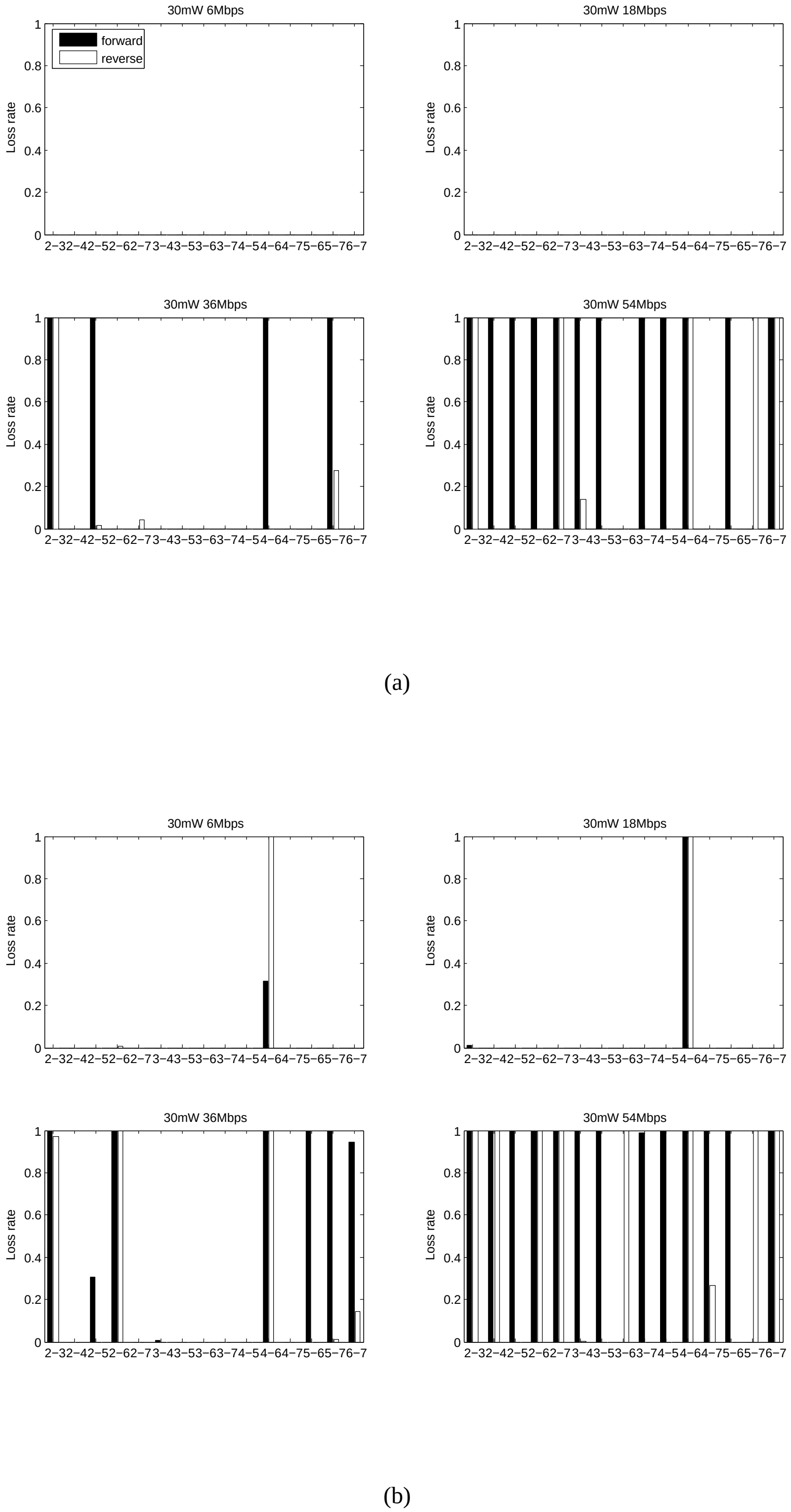
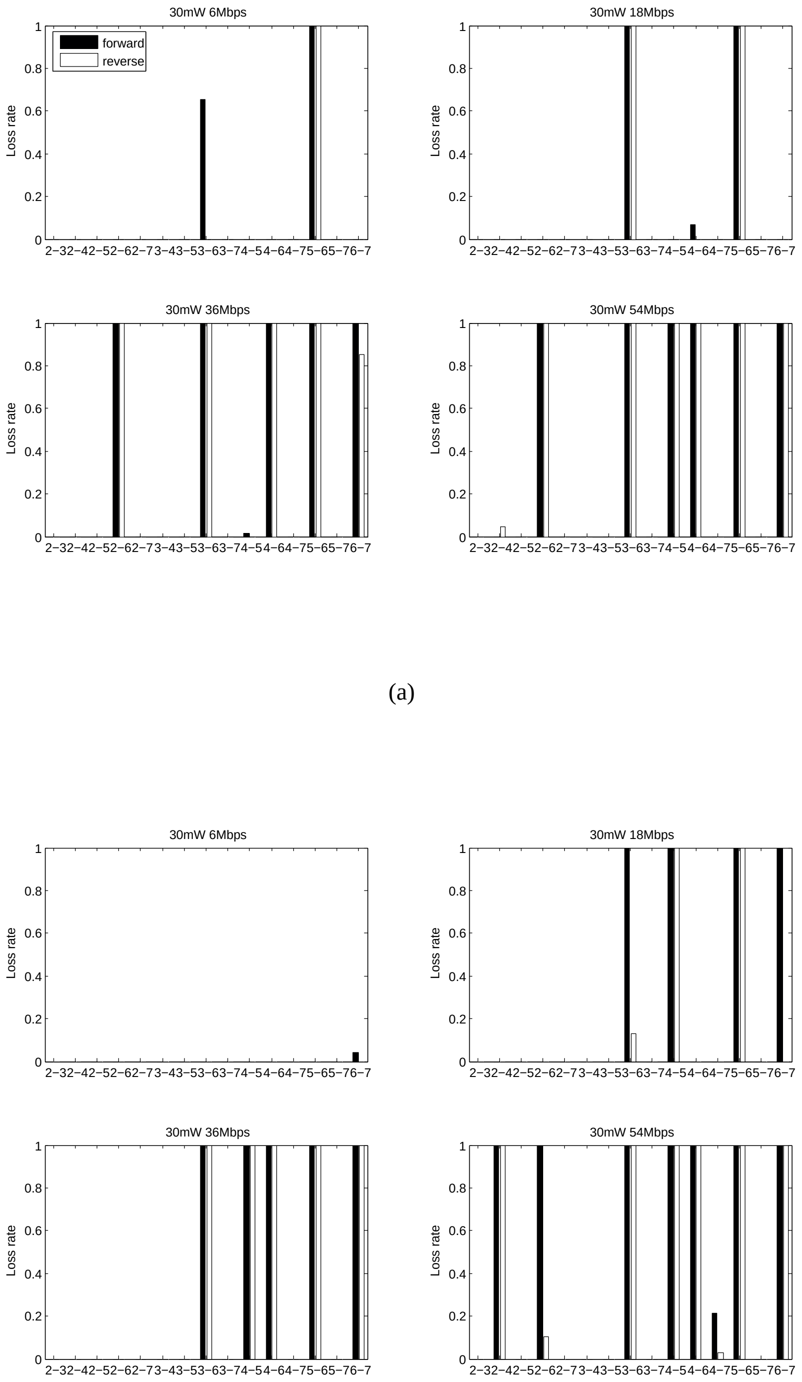


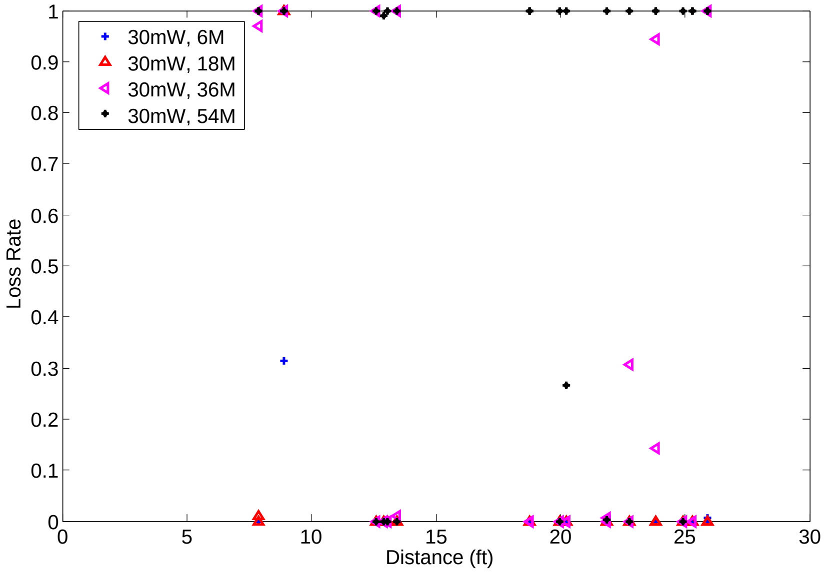
Fig. 11. Loss rate for each pair of nodes for *ushome1* under IEEE 802.11a, with two different node orientations, (a) *layout1* and (b) *layout2*.



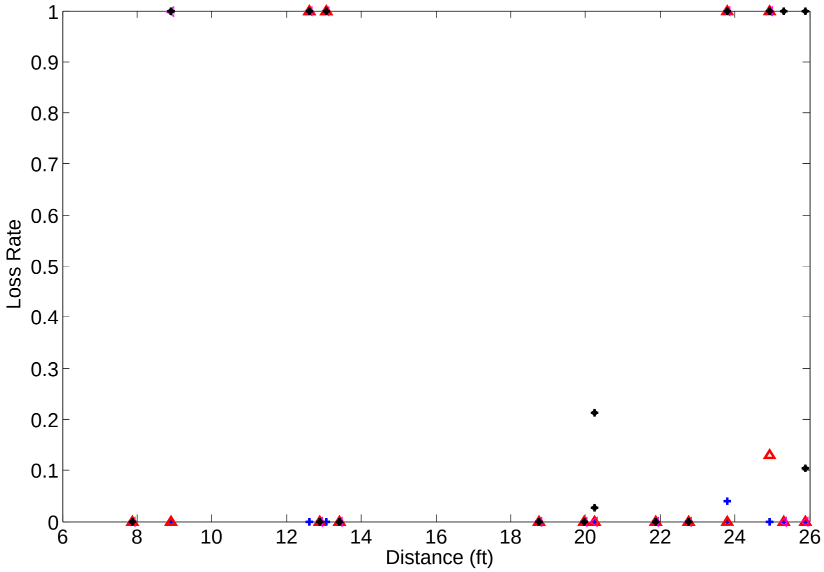
(a)

(b)

Fig. 12. Loss rate for each pair of nodes for *ushome2* using IEEE 802.11a, for two different node orientations, (a) *layout1* and (b) *layout2*.

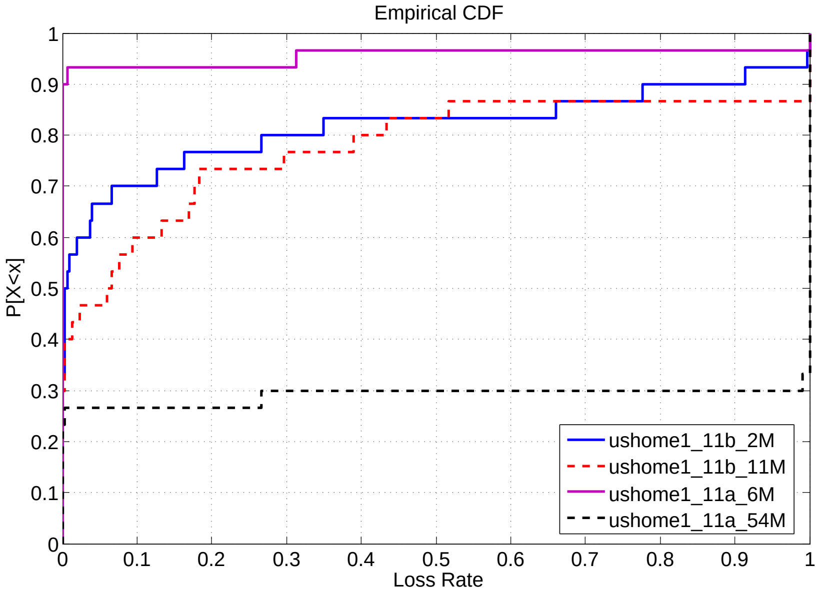


(a)



(b)

Fig. 13. Loss rate for each pair of nodes versus their physical distance under IEEE 802.11a (*layout2*) for (a) *ushome1* and (b) *ushome2*.



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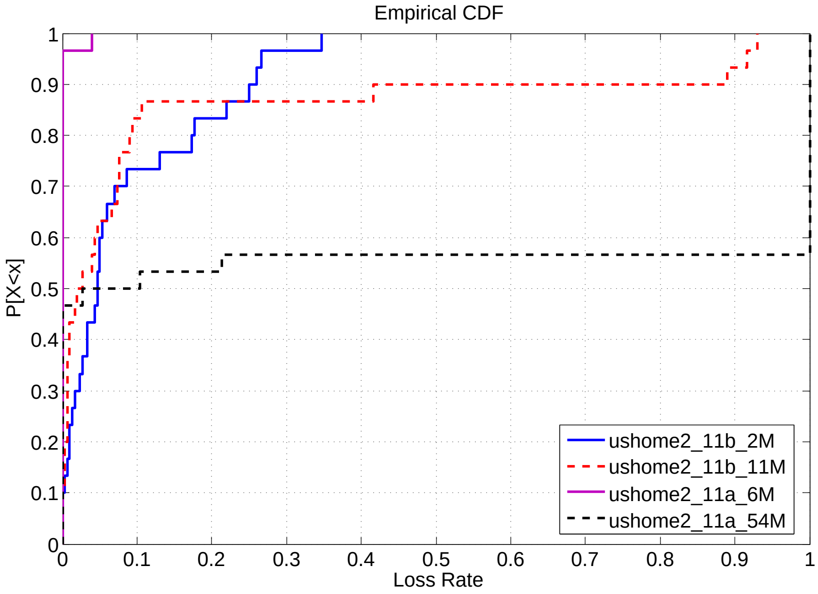

(b)

Fig. 14. Cumulative density function of loss rates under IEEE 802.11b and IEEE 802.11a in (a) *ushome1* and (b) *ushome2*.