Coping with Communication Gray Zones in IEEE 802.11b based Ad hoc Networks

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ABSTRACT

Our experiments with IEEE 802.11b based wireless ad hoc networks show that neighbor sensing with broadcast messages introduces “communication gray zones”: in such zones data messages cannot be exchanged although the `HELLO` messages indicate neighbor reachability. This leads to a systematic mismatch between the route state and the real world connectivity, resulting in disruptive behavior for multi-media data transfer over ad hoc routing protocols. Concentrating on AODV we explore this issue and evaluate three different techniques to overcome the gray zone problem. We present quantitative measurements of these improvements and discuss the consequences for ad hoc routing protocols and their implementations.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*wireless communication* ; C.2.2 [**Computer-Communication Networks**]: Network Protocols—*routing protocols*

General Terms

Design, Experimentation, Measurement, Performance

Keywords

Communication gray zone, gray zone, IEEE 802.11b, MANET, mobile ad hoc networks, real-world experiment, routing protocols

1. INTRODUCTION

Wireless ad hoc networks consist of autonomous mobile nodes which provide a joint network service. The involved routing protocols must detect multihop paths and, in the range of a few seconds or below, react on changes in the topology. Such timing requirements and the characteristics of wireless links make conventional Internet routing protocols inappropriate for ad hoc networks.

Several ad hoc routing protocols like DSR [6], AODV [13] or OLSR [5] have been proposed in the last 5 to 10 years. These protocols have been subject to intensive evaluations through simulation, but far less effort has been documented on the evaluation of the corresponding protocol implementations. When we measured the performance of our own fully conformant AODV implementation (called AODV-UU [2]), we observed an unexpected high amount of packet loss, especially during route changes. We found that the increased amount of packet loss coincided with specific geographic locations that we call *communication gray zones.* Inside gray zones the packet loss is severe and applications with continuous packet flow, like streaming multi-media and large file transfers, will suffer severe performance losses under such circumstances.

Reproducing our tests and comparing them with the behavior of the implementations of OLSR [12] and LUNAR [8] confirmed AODV-UU’s poor results. OLSR and LUNAR were chosen for comparison because of their availability and their different routing strategies. AODV is a reactive protocol which discovers and maintains routes on demand. When a route to an unknown node is needed AODV broadcasts a route request that is disseminated through the network. If the destination, or a fresh route to the destination, is found a route reply is unicasted back to the source. During this process routes are set-up inside the traversed nodes’ routing tables. In addition, periodic broadcast `HELLO` beacons are used to sense neighboring nodes and based on this routes can be added, deleted or updated. OLSR is a proactive protocol which senses the network topology in the 10-second range using broadcast messages. LUNAR is a hybrid protocol as the on-demand discovery is combined with a proactive route re-discovery every third second. As with AODV, the route requests are broadcasted while the route replies are sent via unicast.

In this paper we show that gray zones are linked to the difference between messages that are broadcasted (e.g., AODV’s `HELLO` messages) and the other unicast data packets. Three different schemes counteracting the communication gray zones were added to AODV-UU, and their effectiveness was validated through controlled real world measurements with Ping, MP3 streaming and intermittent HTTP traffic. We discuss these findings and how they relate to other ad hoc routing protocols in general.

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The rest of the paper is outlined as follows. In Section 2 we explain the gray zone problem and why it appears. In Section 3 we describe three mechanisms that reduce or eliminate the gray zone problem. Results from experiments with the enhanced AODV-UU implementation are reported in Section 4 before discussing and concluding our findings in Sections 5 and 6, respectively.

2. COMMUNICATION GRAY ZONES

Comparisons of MANET routing protocols based on simulations, which often present AODV in a favorable manner with good performance, are readily available, such as those in [4] and [7]. However, these findings could not be reproduced in real world: We observed strange performance problems of the AODV-UU implementation. In this section we explain how the problem of "communication gray zones" manifests itself and why AODV's standard `HELLO` messages are inappropriate for neighbor sensing when using IEEE 802.11b. We also discuss why this problem is not evident in simulations using ns-2.

2.1 Performance Problems of Original AODV

We compared the performances of AODV-UU with those for OLSR [12] and LUNAR [8] in identical scenarios. In most cases AODV-UU performed better than OLSR, but that was what we expected because OLSR suffers from a 10 seconds re-route time. LUNAR and AODV-UU were approximately on par in most tests, but as the LUNAR implementation indicated some problems in stressed multi-hop configurations we had expected AODV-UU to win those contests. However, a more careful analysis of the AODV-UU results indicated that in some specific locations a node could have a valid route in its routing table, but no data got through to that next hop. We call the areas where we experienced this problem *communication gray zones*. In such gray zones, a node will experience considerable packet loss. The magnitude of the packet loss is larger than what can be explained by the re-routing that would occur when a node loses contact with its next hop.

Our measurements were made with a simple in-door mobility scenario that we call *"Roaming node"* (see Figure 1). The scenario is strictly choreographed and the experiments were performed using the APE testbed [3, 9]. The experimental setting consists of a total of four nodes where three of them are stationary (GW, C1 and C2), while a forth mobile node (MN) is moving at a speed of approximately 1 m/s and "roams" the network. The MN is constantly communicating with the gateway node GW and will theoretically always have a possible route towards the GW. The scenario is run in a time period spanning 290 seconds: During this time traffic is routed over one, two and three hops via intermediate stationary nodes C1 and C2. This scenario lets us isolate and examine the route change phenomenas that we had experienced in testruns under various other conditions and configurations.

2.2 Conditions for the Forming of Communication Gray Zones

AODV relies on neighbor sensing to keep track of those nodes which are used as relay points for data transmissions. The neighbor sensing algorithm must therefore be able to detect when a link to a neighboring node can forward data. To this end, AODV uses periodic `HELLO` messages. These `HELLO` messages have several salient properties that differentiate them from data packets and that contribute to the occurrence of "gray zones": while `HELLO` messages can be heard, the same is not true for data packets to be exchanged between two "neighbors".

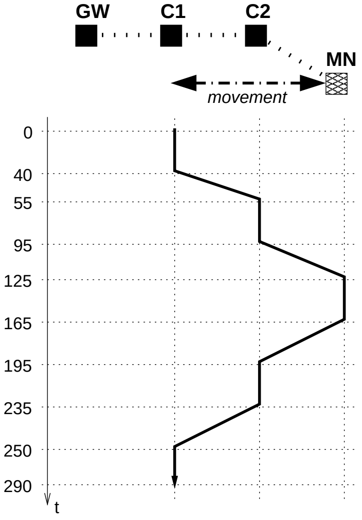

Figure 1: A simple "roaming node" scenario for a wireless multihop stub network.

a. **Different Transmission Rate** – In IEEE 802.11b, broadcasting is always done at a basic bit rate while data transmissions normally are sent at higher rates (up to 11 Mbit/s in IEEE 802.11b). Transmissions at lower bit rates are more reliable and can reach further than at higher rates. As `HELLO` messages are broadcasted, this is the main cause to why gray zones appear.

b. **No Acknowledgments** – Broadcast messages in IEEE 802.11b are transmitted without acknowledgments. `HELLO` messages are therefore not guaranteed to be sent over bidirectional links i.e., receiving a `HELLO` message is no indication that transmissions are possible in the opposite direction.

c. **Small Packet Size** – The size of a `HELLO` message is small compared to a data packet. Small packets are less prone to bit errors since there are less bits to transfer than in large packets. Also, they have a smaller probability of colliding with the usually longer data packets. This makes it more likely for a `HELLO` message to reach a receiver than a data packet, especially over weak links.

d. **Fluctuating Links** – At the transmission borderline, communication tends to be unreliable due to fluctuating quality of links. This leads to spurious `HELLO` messages which, once received, do not reflect correctly whether consistent communication between two nodes is possible or not. As a consequence this means that stable and longer routes can be replaced by shorter but unreliable ones.

All these elements together contribute, in various degrees, to the occurrence of communication gray zones.

2.3 The Shape of Communication Gray Zones

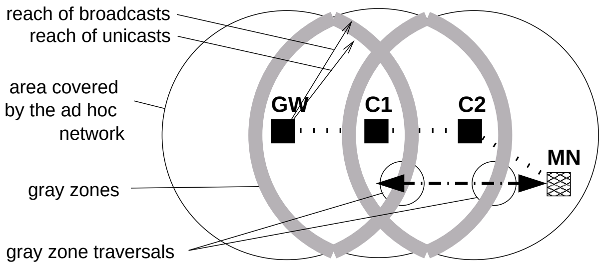

Figure 2: Communication gray zones for the "roaming node" scenario.

Figure 2 depicts in an idealized way where in the "roaming node" scenario communication gray zones can be experienced (the union of the three circles shows the area where the mobile node potentially can route to any of the three stationary nodes). In its journey from the place of C1 over C2 to its rightmost position, the mobile node will traverse two gray zones, namely when losing contact to the gateway node GW and when losing contact with the intermediate node C1. Similarly, two gray zone traversals are experienced when moving back, namely when regaining contact with C1 and GW, respectively.

These four traversals are easily found in the ping success charts shown in the appendix and discussed in Section 4.

2.4 Unrealistic ns-2 simulations

The implementation of IEEE 802.11 in ns-2 [11] does all transmissions at a bit rate of 2 Mbit/s, whether it be unicast or broadcast transmissions. Connectivity is also implemented as an on/off switch, where transmission suddenly breaks at a specified distance. In such a model, all properties mentioned above (except c) are not represented. This leads to uniform transmission ranges regardless of transmission rate, type and time, effectively preventing communication gray zones to emerge.

3. ELIMINATING GRAY ZONES

In this section we present three different modifications to AODV-UU that we experimented with to help neighbor sensing and reduce gray zones. The modifications are not in the AODV draft, but to some degree have all been proposed and discussed on various mailing lists, such as the AODV Implementors list or the IETF MANET mailing list.

We have added the suggested modifications to the AODV-UU implementation and then evaluated them in the APE testbed. In Section 4 we will then present how these modifications affect the performance of AODV.

3.1 Exchanging Neighbor Sets

To address the problem of unidirectional links when using broadcast `HELLO` messages, nodes exchange their neighbor set in an extension field of the `HELLO` messages. A node receiving such a `HELLO` message can then tell, by looking for its own address, if the link to the sender is bidirectional.

A new potential problem is introduced insofar as `HELLO` messages become variable in size, which in turn makes the success rate of `HELLO` messages depend on how many neighbors a node detects. Furthermore, using a neighbor set extension will introduce a handshake-like procedure into the neighbor detection system of AODV. When two nodes discover each other as neighbors, they must acknowledge the other node's `HELLO` message through the neighbor set extension before the detection process is complete. This will introduce a latency which may affect AODV's ability to quickly adapt to changes in connectivity. Finally, this approach does not address the difference between unicast and broadcast transmissions.

3.2 N–Consecutive `HELLO`s

It has been proposed to request that a node should receive N consecutive `HELLO` messages from the same source before accepting it as a neighbor. N is typically set to 2 or 3. The idea is to bring stability into the changes in neighbor sets and ultimately the routes. On the other hand, this will introduce a latency which may hurt the on-demand properties of the protocol. This approach is again based on broadcasts only and is not sensitive to unicast/broadcast differences. However, it addresses the problem of fluctuating links.

3.3 SNR Threshold for Control Packets

The third way to improve neighbor sensing that we have evaluated is to use signal quality from the IEEE 802.11b driver as a criteria for "weak" control messages: control packets are discarded when they are received with a signal quality that is below some threshold[1]. Intuitively this will counteract the gray zone problem, by forcing AODV to detect a longer route when link quality is so bad that data supposedly cannot get through while `HELLO` messages still can. Using a link quality criteria for broadcast messages will also minimize the probability of unidirectional links being present, although it cannot guarantee links to be bidirectional.

The down-side of this approach is that when cutting off AODV control traffic, AODV might not always be able to do a "best effort" attempt at delivering messages over a poor link, when no other alternative is available. Therefore one could expect that although the overall experience of the routing is smoother, there are times when AODV using link quality bias will not be able to deliver data while original AODV would.

4. RESULTS

We present results from experiments using the neighbor sensing extensions discussed in Section 3. For each protocol and each protocol variant dozens of test runs were performed and analyzed for establishing the qualitative basis of our findings. The actual quantitative numbers are extracted and averaged from two test series using the "Roaming node" scenario (see Figure 1).

The analysis focuses on gray zones and packet delivery success. First we analyze Ping delivery success in detail and compare the unmodified AODV-UU with the proposed neighbor sensing extensions. Next, we examine how gray

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[1] In our implementation we had to approximate this behavior: the 802.11b driver does not provide SNR values for individual packets wherefore we read the last value recorded for a given sender. Although we do this for each broadcast packet received, there is a slight chance that the SNR value belongs to some unicast packet that was received more recently.

zones affect two potential ad hoc networking applications: MP3 streaming and HTTP-based webpage requests. The active communication session in these experiments is always between the MN and the GW node.

4.1 Ping Delivery Success

Here we present detailed results of round trip packet delivery success when running a Ping application. Data traffic load consists of node MN sending 512-byte pings with the Record Route option which sums up to 580-byte IP packets (including IP header) to the GW node, at a rate of 10 packets/s. As this is a moderate traffic load and pings are sent at larger intervals than the round trip time, we know that packet losses are not due to the load put on the network. Ping delivery success ratio is calculated as the number of received ping replies divided by the number of sent ping requests during a one-second interval. The breadth and the depth of the dips in ping delivery success ratio indicates the range and severity of the gray zones. In the following discussion we present one representative testrun for each approach (see appendix for figures) –averaged numbers obtained from repeated testruns can be found in Table 1.

4.1.1 Original AODV-UU

Theoretically one would expect close to zero packet losses throughout the test because there is no self–colliding traffic and connectivity is always available. In order to verify this, we have modeled the “roaming node scenario” in ns-2 and have placed the AODV-UU code into the simulation environment. The (preliminary) results are that AODV-UU should successfully deliver more than 98% of the ping traffic. However, it is clear from inspecting figure 3 and the log files that AODV-UU running in the real world experiment did not live up to such expectations: The ping delivery success ratio for the original AODV-UU implementation documents severe packet losses during all moving periods.

Detailed inspection of the logs reveals the following. Between time 49 and time 56 it loses 10% to 100% of the packets. The second dip is between time 110 and time 124 where the ping delivery success varies from 12% and 100%. During time 172 to 193 the ping delivery success goes down to a minimum of 50%. During the short time period between 242 and 243 there is a complete loss of packets. The overall ping delivery success ratio is 91%. During three of the four gray zones we experience a complete drop out of packet delivery, while in one case it drops to 50%. Gray zones seem to stretch from approximately 5 to 20 seconds.

4.1.2 Exchanging Neighbor Sets

Including the neighbor set in `HELLO` messages should avoid uni-directional links as it requires the incoming `HELLO` messages to contain its own address, otherwise the sender is not considered to be a neighbor. In fact, we can see in Figure 4 that both the breadth and the depth of most dips in ping delivery success ratio are smaller than in the original version. The overall ping delivery success ratio raised from 91% to 97%.

4.1.3 3-Consecutive `HELLO`*s*

A visual comparison between the Figure 4 and Figure 5 clearly indicates less packet loss for the 3-Hello approach. Both the depth and breadth are significantly smaller. Specifically, one can see a reduction in packet loss during the period when the mobile node MN is moving back and switches to a shorter route: during the gray zone traversals, packet loss is now below 10% on average. The original AODV-UU suffers from spurious `HELLO` messages in these cases because it directly installs new routes that not necessarily indicate stable and reliable transmission capability. The 3-consecutive `HELLO` approach successfully addresses this problem as it requires the new, shorter routes to become stable before replacing the existing ones. The overall ping delivery success ratio in this particular testrun was 99% but other repeated testruns have shown slightly less success.

4.1.4 SNR–Threshold for Control Packets

Setting the SNR threshold to 8 dBm and discarding control packets below this level produces the least packet loss of the three different approaches (see Figure 6 and Table 1). This can be explained by the fact that not only the problem of longer transmission range for broadcasted `HELLO` messages is addressed but also the problems of unidirectional links and spurious `HELLO`s: the probability of links being unidirectional decreases as we have logically shrunk the transmission border. Furthermore, spurious `HELLO` messages do not necessarily disrupt communication anymore. If logically we have an unstable link, indicated by the reception of spurious `HELLO`s, chances are still good to successfully transmit data packets to the next hop. Thus, this SNR threshold approach decreases the probability that installed routing entries do not reflect the true communication capabilities.

Detailed log inspection reveals the following. At the first dip we observe a ping delivery success ratio of 50%, but only during a one second interval. During time 101 to 118 there are several occurrences of minor packet loss but they are mostly around 10%. Although we are ignoring control messages below some signal quality threshold, we can see in our logs that the route change does not occur until time 113 which indicates that we could increase the threshold even more. However, further experiments with different threshold values have not produced significantly better performances. This indicates that it is hard to obtain completely smooth route changes when switching to longer routes. During route changes while moving back there are only singular packets lost at two occasions.

4.1.5 Ping Experiment Summary

Table 1 shows a summary of the total packet delivery ratio for the different approaches, averaged over several repeated testruns. We see that all three modifications to AODV-UU increase the delivery success ratio significantly. Most effective is the SNR threshold approach although it does not achieve lossless route changes.

Table 1: Overall Ping Delivery Success Ratio for the AODV-UU modifications (“Roaming node” scenario).

AODV-Original	91.9%
AODV-Neighb. set	97.7%
AODV-3-Hellos	98.0%
AODV-SNR thresh.	99.1%

4.2 Continuous MP3 Streaming

In this setting we continuously send MP3 music from the GW node to the MN node throughout the testrun. The MP3 music file used was encoded at 128 Kbit/s. We measured the percentage of successfully and in-order delivered MP3 packets. Apart from testing a real application, MP3 streaming differs from Ping in that the MP3 sessions are one-way only and do not accept out-of-order delivery of packets. There was not a single MP3 packet delivered out-of-order in any of the experiments. In comparison, the original AODV-UU had a few out-of-order deliveries during the Ping experiments.

Table 2: Overall MP3 packet delivery success ratio for AODV-UU modifications ("Roaming node" scenario).

AODV-Original	97.9%
AODV-Neighb. set	98.6%
AODV-3-Hellos	98.9%
AODV-SNR thresh.	99.7%

Table 2 shows the results from continuous MP3 streaming in the Roaming node experiment. The perceived playback quality during the testruns corresponds well to the results in Table 2: the SNR threshold and 3-HELLO approaches sounded very good with only minor "glitches" (<1s) in the music while the glitches in Neighbor Set Extension and Original AODV occurred more often and overall had longer duration (1-3s).

4.3 Intermittent HTTP Requests

Although not as conclusive as with Ping and MP3 experiments, we report on the AODV's routing performance using HTTP traffic. Our simple web user model uses a static think time of 8 seconds and a data set size of 34 KB. These values are loosely based on [10] and [1] (10 to 15 seconds median user think time and 10 to 39 KB average data transfer). We counted the number of successful cycles and measured the request completion time. If the node is located in a gray zone at the moment it requests the webpage the TCP SYN packet will potentially not reach the destination. TCP will try to re-send the SYN packet after 3 seconds, 9 seconds, 21 seconds – after 30 seconds the request fails. This affects the number of successful requests as well as the average access time.

Table 3: Overall number of successful webpage accesses and average access time for AODV-UU modifications ("Roaming node" scenario).

Protocol	*HTTP cycles*	*avg. access time (sec)*
AODV-Original	33	0.84
AODV-Neighb. set	34.5	0.43
AODV-3-Hellos	33	0.90
AODV-SNR thresh	34	0.54

Table 3 shows a summary of the HTTP request experiments. The higher average access times for the Original AODV-UU and the 3-`HELLO` extension is due to HTTP request failures. The Neighbor Set and SNR threshold extensions had a few TCP SYN retransmission but no failures. If we instead consider the median access time we can see in our log files that it only differed by 0.02 seconds among all the different approaches. We conclude that short intermittent traffic bursts are not as sensitive to gray zones as traffic with continuous data flows.

5. DISCUSSION

In this section we present results from comparisons with OLSR and LUNAR. Furthermore, we discuss the implications of gray zones for OLSR and LUNAR as well as for ad hoc protocols in general.

5.1 Comparison Against OLSR and LUNAR

We repeated all tests with the OLSR and LUNAR protocols, as a point of reference. Figure 7 and 8 show the Ping delivery success charts for OLSR and LUNAR, respectively. Table 4 summarizes the comparison results from all three experiments (Ping, MP3 and HTTP access).

Table 4: Comparison against OLSR and LUNAR for all three experiments ("Roaming node" scenario).

	success ratio		*HTTP*
Protocol	*Ping*	*MP3*	*cycles*
OLSR	89.0%	91.9%	32.5
LUNAR	96.5%	96.8%	31.5
AODV-UU	91.9%	97.9%	33
AODV-UU+SNR	99.1%	99.7%	34

5.2 Protocols without Gray Zone Problem

It seems that OLSR and LUNAR are less sensitive than AODV to communication gray zones for two different reasons.

Although OLSR uses broadcasts to disseminate its routing table data, it is possible that a mobile node does not stay sufficiently long in the gray zone for OLSR to be able to react (wrongly) on this. Thus, OLSR's low overall Ping/MP3 success ratio is mainly due to the slow discovery of topology changes because of its proactive routing approach.

LUNAR does not rely on a broadcast neighbor sensing algorithm. Instead, it re-discovers delivery paths every third second. Thus, the creation of new routing table entries is *solely* based on *unicast* route replies, which mitigates the gray zone problem for LUNAR. Note that AODV too creates routing table entries based on unicast `RREP` messages. However, when using `HELLO` messages (instead of link layer notification), original AODV also adds routing table entries based on broadcasts. The lower overall performance of LUNAR can be explained by its 3-seconds "forget and re-learn" approach which potentially leads to longer packet loss periods.

An interesting future research topic is the problem of handling (intermediate) nodes which happen to be permanently located in a gray zone or which stay there for an extended period of time. In such cases it would be useful to make routing decisions based on the end-to-end quality of the routing path instead of local decisions only.

5.3 IEEE 802.11b is not Bidirectional

Successful reception of messages over IEEE 802.11b does not always imply that links are bidirectional. We have shown for AODV that such an assumption, currently built into simulation models, has adverse performance effects. Routing protocols that, without access to link level notifications, have to use `HELLO` like broadcast messages, need to be revisited and have to explicitly cope with communication gray zones. This can be in form of a mixed broadcast/unicast approach as in LUNAR, or signal quality based measures as we experimented with for AODV. One problem of the latter is that determining the exact cut-off level could be context specific. Ideally we would like the cut-off level to always logically reduce the range of broadcasts to match the range of unicasts. Reducing the range too much may prevent some otherwise acceptable communication, but will still make AODV resistant to communication gray zones.

6. CONCLUSIONS

In this paper we provide evidence for IEEE 802.11b based wireless ad hoc networks suffering from “communication gray zones”: In such zones it is possible to receive broadcasts but it is unlikely to successfully send or receive unicast messages. This leads to invalid routing table entries for protocols that establish their neighbor set using `HELLO` beacons, as e.g. AODV.

We have explored this problem and implemented three different gray zone work-arounds in the AODV-UU software. Their effect was evaluated in controlled real world experiments which showed that all three modifications substantially increase the packet delivery ratio. Only by enabling these modifications we were able to obtain real world performance figures that matched the simulation results. The approach that introduces a signal quality threshold for AODV control packet acceptance almost totally eliminates the effect of communication gray zones. In mobile scenarios, this gray zone elimination is most important for applications with continuous, real-time packet flows e.g., multi-media streaming.

In conclusion we state that ad hoc routing protocols which operate over IEEE 802.11b need to explicitly address communication gray zones. It could be by design of the protocol using broadcasts *and* unicasts in appropriate ways, by artificially limiting the range of broadcast messages or by basing routing decisions on the end-to-end quality instead of relying on local decisions.

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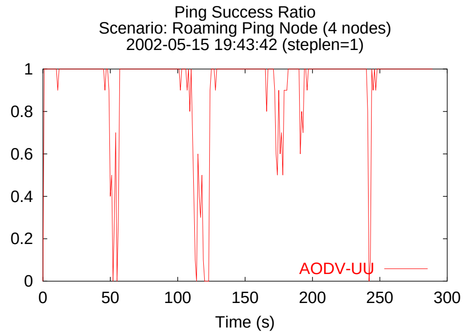

Figure 3: Original AODV-UU

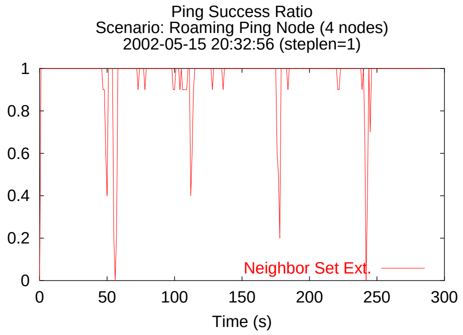

Figure 4: AODV-UU with exchanging neighbor sets

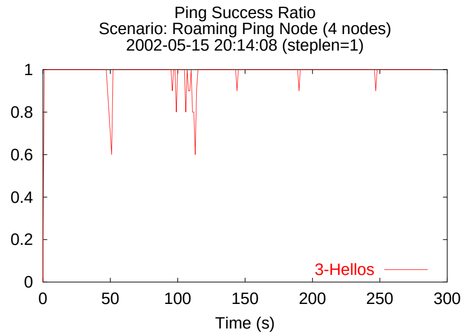

Figure 5: AODV-UU with 3-Hello extension

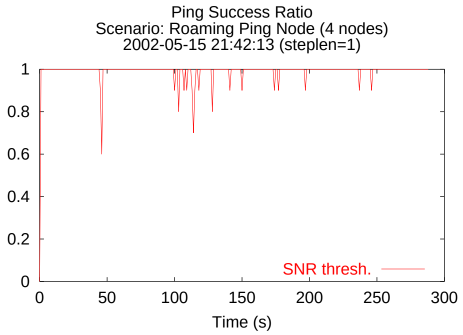

Figure 6: AODV-UU with SNR threshold for control packets=8 dBm

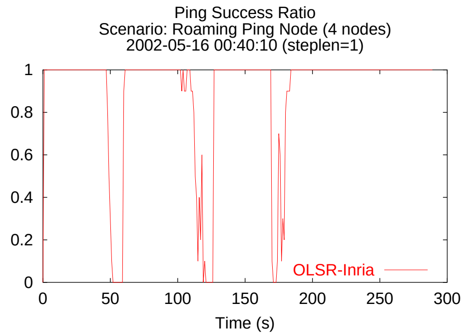

Figure 7: OLSR

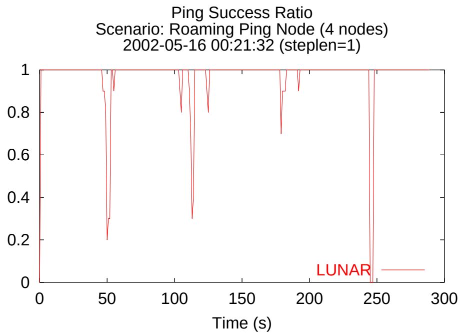

Figure 8: LUNAR