# 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 some 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.

## 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 [5], AODV [11] or OLSR [4] 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 conformant AODV-UU implementation [1], we experienced an unexpected high amount of packet loss, especially during route changes. Reproducing our tests and comparing them with the behavior of the implementations of OLSR [10] and LUNAR [12, 7] confirmed AODV-UU’s poor results. We found that the increased amount of packet loss coincided with specific geographic locations that we call *communication gray zones*.

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 demonstrated through controlled real world measurements. We also discuss these findings and how they relate to other ad hoc routing protocols in general.

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 [3] and [6]. However, these findings could not be reproduced in real world: We observed strange performance problems of our conformant AODV 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 Plain AODV

Our AODV-UU implementation was subject to thorough tests under several different conditions and configurations using the APE testbed[8, 2]; As a point of reference, we compared the performance of AODV-UU with those for OLSR [10] and LUNAR [12, 7] in identical scenarios.

In most cases AODV-UU performed better than OLSR, but that was what we expected because OLSR suffers from a 10 second 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 as *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 looses contact with its next hop.

Our measurements were made with a simple mobility scenario that we call *“Roaming node”* (see Figure 1 and Table1). It consists of a a total of four nodes where three of them are stationary (GW, C1 and C2), while a forth mobile node (MN) “roams” the network and is constantly communicating with the gateway node GW: The MN will theoretically always have a possible route towards 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.

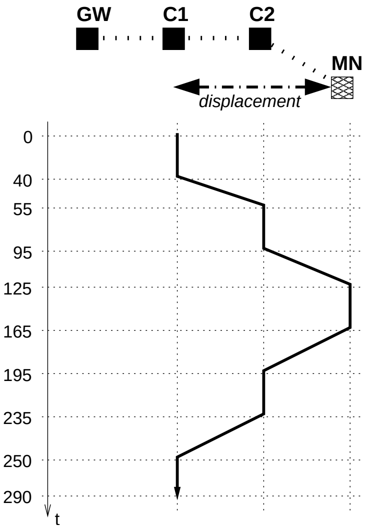

Figure 1: A simple “roaming node” scenario for a wireless multihop stub network.

## 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”.

**a) Different Transmission Rate:** In IEEE 802.11b, broadcasting is always done at a bit rate of 1 Mbit/s 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 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

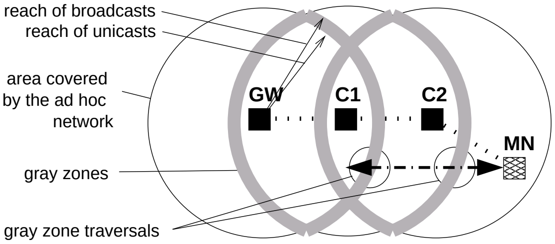

Figure 2: Communication gray zones for the "roaming node" scenario.

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 loosing contact to the gateway node GW and when loosing 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 presented in Section 4.

### 2.4 Unrealistic ns-2 simulations

The implementation of IEEE 802.11b in ns-2 [9] 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 in 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 incorporated the suggested modifications into 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 bidirectionality.

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 plain AODV would.

## 4 Results

We present results from experiments using the neighbor sensing extensions discussed in Section 3. Experiments have been repeatedly conducted using the "Roaming node" scenario and the analysis focuses on gray zones and packet loss. Data traffic load consists of node MN sending 512-byte ping 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 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 success ratio indicates the range and severity of the gray zones. In the following discussion we present one representative testrun for each approach –averaged numbers obtained from repeated testruns can be found in Table 1.

### 4.1 Plain 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. It is clear from inspecting figure 3 and the logfiles that AODV-UU did not live up to such expectations: The ping success ratio for the unmodified 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 success varies from 12% and 100%. During time 172 to 193 the ping success goes down to at minimum of 50%. During the short time period between 242 and 243 there is a complete loss of packets. The overall ping success ratio is 93%. 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

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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.

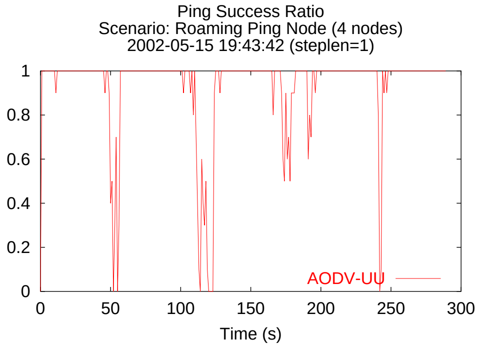

Figure 3: Unmodified AODV-UU

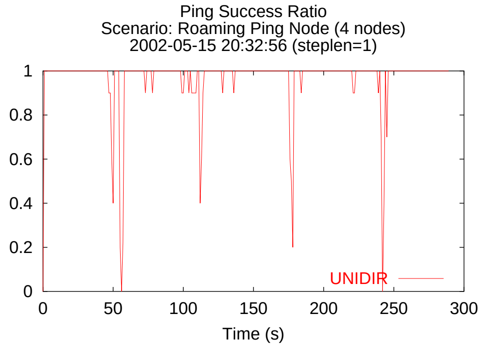

Figure 4: AODV-UU with exchanging neighbor sets

from approximately 5 to 20 seconds.

### 4.2 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 success ratio are smaller than in the unmodified version. The overall ping success ratio raised from 91% to 97%.

### 4.3 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 reduced amount of lost packets during the “moving back” periods i.e., when the mobile node regains contact and switches to a shorter route: during the gray zone traversals, packet loss is now below 10% on average. The plain 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 success ratio in this particular testrun was 99% but other repeated testruns have shown slightly less success.

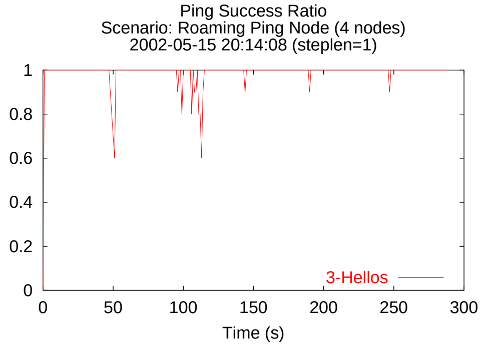

Figure 5: AODV-UU with 3-Hello extension

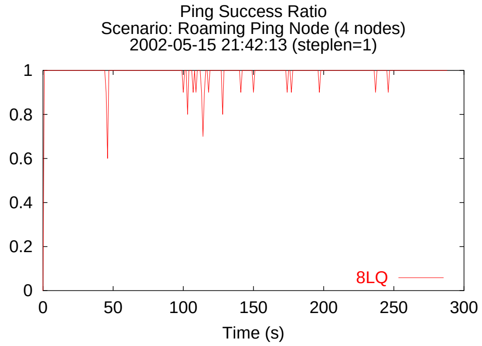

Figure 6: AODV-UU with SNR threshold for control packets=8 dBm

### 4.4 SNR–Threshold for Control Packets

Discarding `HELLO` packets that are below some signal quality 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, we can still 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 success ratio of 50%, but only during a one second interval. During time 101 to 118 there are several small occurrences of packet losses but they are mostly around only 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.

## 5 Discussion

Table 1 shows a summary of the total packet losses 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 Success Ratio for the AODV-UU modifications ("Roaming node" scenario).

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

As a point of reference, Table 2 show the corresponding delivery ping success ratios for OLSR and LUNAR. With the addition of the SNR-threshold scheme to AODV-UU we removed a major performance problem that became obvious in a setting that is as simple as the "roaming node" mobility scenario. The ratio of 99% successful ping delivery leaves little leeway for further optimization, at least for this scenario.

Table 2: Protocol specific Ping Success Ratio ("Roaming node" scenario).

| | |
|---|---|
| OLSR | 89.0% |
| AODV-UU | 91.9% |
| LUNAR | 96.5% |
| AODV-UU + SNR threshold | 99.1% |

### 5.1 Protocols without Gray Zone Problem

It seems that OSLR and LUNAR are not sensitive to communication gray zones for two different reasons.

Although OLSR uses broadcasts to disseminate its routing table data, it seems 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 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 garbage collects routing table entries after three seconds and restarts the discovery of an individual delivery path for a given destination if there are still pending send requests. Creating 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), plain AODV also adds routing table entries that are 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.

### 5.2 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, will have to be revisited and need 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. However, we do not expect this choice to be critical as its main purpose is to logically reduce the reach of the longer-ranging broadcasts: reducing that reach too much could prevent some otherwise acceptable communications, but will not introduce new instabilities or delays in the neighbor discovery process.

## 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 our AODV-UU software. Their effect was evaluated in controlled experiments which showed that all three modifications substantially increase the packet delivery ratio. The approach that introduces a signal quality threshold for AODV control packet acceptance almost totally eliminates the effect of communication gray zones.

In conclusion we state that ad hoc routing protocols which operate over IEEE 802.11b need to explicitly address communication gray zones, either by design of the protocol using broadcasts *and* unicasts in appropriate ways, or by artificially limiting the range of broadcast messages.

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