Paper

A static test-bed for the evaluation and optimization of multihop wireless network protocols

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Abstract—We investigate the performance of multicast transmissions in a simple stationary wireless multihop ad hoc network test-bed. We compare several methods for MANET multicast using implementations for the protocols MOLSR, SMOLSR and SMF with an approach that uses explicit multicast and link-layer retries for reliable multicast. Results from the test-bed are compared with simulation results. We find that implementing a combination of explicit multicast with a retry mechanism gives the most promising results in test-bed and simulation compared with other approaches.

Keywords*— *MANET, mobile ad hoc network, multihop wireless network, multicast, wireless test-bed, simulation, explicit multicast.

1. Introduction

Multihop wireless networks, namely wireless mobile ad hoc networks (MANET) and wireless mesh networks (WMN), are objects for a multitude of current research efforts. They are also of high military relevance, as was found in the "NATO network enabled capability feasibility study" [1] particularly for MANETs. Their independence from existing network infrastructure makes them suitable for assessment in destructed or unstructured areas as well as in urban and rural areas where infrastructure support by local authorities might not be available or does not meet operational requirements.

One challenge of ad hoc network protocol design is the efficient use of the wireless channel. Especially the family of IEEE 802.11 wireless LAN protocols, prominent in civilian wireless networks, are not designed for efficient multihop communication and can impose a significant constraint on wireless network performance. On the other hand, their widespread civilian use increases the interest to explore their military potential. Furthermore, their high availability makes them an easily to deploy research foundation to investigate challenges imposed by future military wireless broadband communication standards.

For our research on military aspects of multihop ad hoc networks we developed a protocol framework called WNet that is designed for efficient multihop transmission of multi- and unicast data, allowing for the test and analysis of various MANET routing techniques [2]. One of the key features is its ability to be used both in a real-life network and in the ns-2 network simulator.

In this paper we concentrate on the application of a real-life network for MANET analysis. We present a basic test-bed that consists of stationary nodes which form a wireless ad hoc network using their IEEE 802.11a/b/g wireless interfaces. Although this test-bed is not suited to study effects of mobility on the communication, it is a valuable research tool to evaluate the real-life characteristics of wireless multihop communication. The static nature of this test-bed, with its immutable topology and constant radio conditions, permits measurements with a high degree of reproducibility that is hard to gain in experimental setups that use vehicles or personnel to add mobility. The drawback of this approach is the limited possibility to create topology changes, so tests for the flexibility of the routing mechanism are restricted. Routing aspects are therefore not assessed in this paper.

With our test-bed we studied multihop multicast transmissions using WNet and other ad hoc routing protocols. The results from these studies are compared to results from a simulated environment.

2. Related work

There has been plenty of research on ad hoc networks during the past years, but for protocol design and evaluation, network simulators have been the main – and often only – research tool for a long time. Even though simulation is indisputably an essential part of network research, most simulations lack the possibility to properly take into account the influence of radio propagation, interference, bit errors and other effects of the physical and medium access control (MAC) layers [3]. In fact, some researchers have instead opted for a test-bed to evaluate wireless network protocols, e. g., to survey routing metrics [4].

We decided to use the perfect reproducibility and flexibility of a network simulation as well as study the real-life effects found in a wireless test-bed and compare results.

The following section contains further related work concerning the ad hoc protocol features we address and implementations we used in our work.

3. Routing protocols

A vast amount of wireless multihop routing protocols has been designed in the last years. They are often classified as proactive or reactive, depending on their approach to find routes in the network either in advance (mostly using management frames to announce link states to their neighbors and other nodes) or on demand (in most cases using broadcasts to find a route to the destination). We assess proactive protocols with their potential for fast reaction to varying conditions, especially to high mobility, to be of increased relevance for wireless tactical networks. Therefore, our research concentrates on proactive protocols, the most prominent example for unicast transmissions being optimized link state routing (OLSR) [5]. Reactive protocols, on the other hand, can be an alternative, especially for operational scenarios where fast connection start-up and immediate reaction to topology changes – i. e., fast access to other network nodes – are not as important as the possibility to maintain radio silence even in short periods of inactivity.

3.1. Proactive MANET multicast protocols

Since one of our main concerns is the efficient transmission of multicast data traffic, we integrated several multicast enabled MANET protocols in our test-bed. For this paper, we used the following ones:

MOLSR (version 0.2 for OOLSR 0.99.16). A multicast extension for OOLSR, the OLSR implementation from INRIA (FR) [6]. MOLSR takes a source tree based approach for multicast. For broadcast messages flooding is done using the multi-point relay (MPR) flooding mechanism of OLSR.

SMOLSR. A simple variant of MOLSR above, using simple flooding instead of a multicast tree. SMOLSR is also from INRIA and integrated into the MOLSR code.

SMF (NRL version 1.0a3). The simplified multicast forwarding protocol (SMF) for MANET as described in [7]. This is the prospective multicast and flooding protocol from the IETF MANET Working Group. We used an implementation from the US Naval Research Lab (NRL) that interfaces with the NRL OLSR implementation (version 7.7) for efficient MPR flooding.

3.2. WNet

Since most of the available protocol specifications address only single aspects of efficient multihop communication – either quality-aware routing, or multicast traffic, or congestion management – we decided to design our own framework, termed WNet, to be able to integrate multiple of these mechanisms.

At the moment, this framework implements an OLSR-like proactive MANET routing with additional provisioning for multicast transport, link quality estimation, quality-aware routing and congestion management [2]. In contrast to other MANET routing protocols WNet is implemented on layer 2 of the ISO/OSI network model and thus transparent for IP traffic. To enhance reliability, WNet uses link-layer acknowledgments and a retry mechanism that is used even for multicast transmissions. This feature is optional and can be disabled. Alternatively, multicast transmissions can use flooding instead of the above explicit multicast approach.

Furthermore, WNet employs rate selection on the WLAN MAC to choose the most effective modulation for the intended next hop recipients of a transmission. In combination with multicast acknowledgments, a necessary packet retry will use the best modulation (i.e., the fastest data rate) possible to reach exactly those nodes that did not acknowledge reception of the data packet.

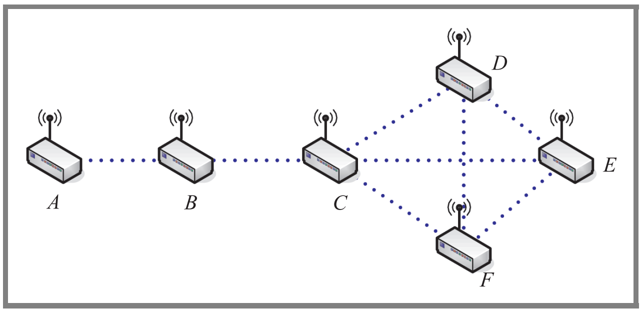

Fig. 1. Schematic test setup.

WNet also offers multiple link metrics that can be activated to find optimal routing paths with respect to a predefined quality metric. This includes received signal strength, the packet reception loss rate and the radio link utilization. In our test setup, mainly the signal strength based metric is used. Although our scenario does not offer many alternate routes, routing decisions might have a small influence when a link becomes unavailable. This can happen due to congestion at the "fan-out" from node *C* to receiving nodes *D*, *E* and *F* in Fig. 1. Node *C* might then decide to route packets over one of the remaining receivers.

3.3. MFP

We also compare our approach with the reactive MANET forwarding protocol (MFP) that is described in [8]. To improve multicast performance, MFP implements an optional mechanism that uses (multiple) unicast transmissions on a hop when the number of receivers on that hop is lower than a given threshold [9]. The default for this threshold is 3. This way, MFP can take advantage of the link layer transmissions of IEEE 802.11 for unicast frames.

4. Test setup

4.1. Hardware

Our test-bed consists of six wireless nodes, set up with connectivity as seen in Fig. 1. The nodes are PC-like embedded servers running GNU/Linux with kernel 2.6.18. Each server is equipped with IEEE 802.11a/b/g WLAN PC cards and an external omni-directional antenna. The WLAN cards are set up in IEEE 802.11g mode. The nodes use MAD-WiFi WLAN drivers [10] for all protocols except WNet, which brings its own MADWiFi-based kernel driver to ease layer 2 access.

The connectivity laid out in Fig. 1 is realized with nodes set up in different rooms next to one of our office hallways. The topology demonstrates a sender, followed by a simple chain of wireless relays that end in a bundle of multicast receivers. Because it is not practicable to accomplish physical distances large enough to attain the desired network topology, we use RF attenuators between each WLAN card and its antenna. Signal strength is effectively reduced to about -75 to -85 dBm at the receivers for the connections between nodes A and B; B and C; C and $D/E/F$, respectively. This leads to a modulation corresponding to 6 Mbit/s data rate, so that the multi-rate mechanism of WNet and the "multicast over unicast" mechanism of MFP can not gain an advantage over the IEEE 802.11 broadcast-based protocols that will never use more than the 6 Mbit/s modulation, the lowest data rate for 802.11g mode operation. For links with a higher signal quality, we would expect an additional performance gain for protocols like WNet which implement a multi-rate feature. Connections between nodes D, E and F show higher signal strength values and therefore higher data rate modulations, but this should be of small relevance due to our traffic model.

In addition to the wireless network interface, all nodes provide fast Ethernet network adapters that allow out-of-band remote control access and time synchronization.

4.2. Test software

For network traffic generation, we use a modified version of the *iperf* bandwidth measurement tool [11]. Our modification implements an additional logging facility that records packet sequence number and size as well as sender and receiver time stamps for every successfully received packet. Network time protocol (NTP) clients on all nodes allow time synchronization with an NTP server in the LAN, connected over the fast Ethernet adapters. We can obtain a synchronization below 100 μs relative to the NTP server, which proves to be well under the observed end-to-end delays within the wireless network in the range of some 1 ms and more, so that packet time stamps can be used for delay calculation.

4.3. Test execution

Preceding to our tests, we did measurements of the received signal strength of transmissions on all nodes for several days, using only WNet management traffic. We found that at night, radio conditions were stable to a very high degree, with quite low variances between different nights, whereas during office hours we could observe short- and long-term variations in the order of multiple dBm, as seen in Fig. 2. They were probably caused by opening and closing doors and moving people. We thus decided to conduct our tests only during the night hours when the surroundings of the test-bed were devoid of people and the environment was static. Rounds of the night watchmen did not have measurable influence.

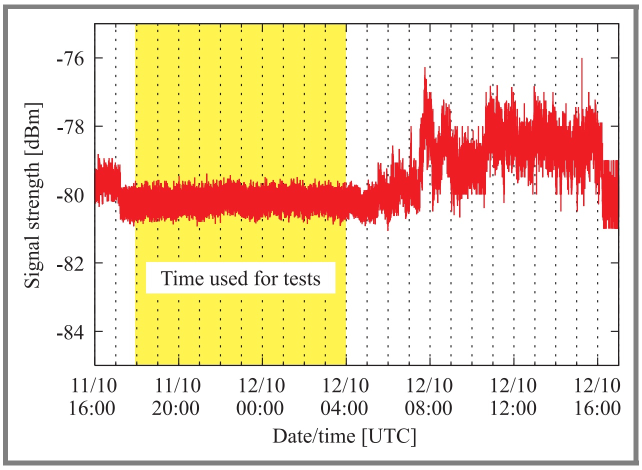

Fig. 2. Example for received signal strength from node B on node C during 24 hours. Signal strengths are averaged over 10 s; time is UTC (coordinated universal time).

We use *iperf* constant bit rate (CBR) multicast user datagram protocol (UDP) traffic from sender node A to receiver nodes D, E and F, varying either the data rate or the payload size. Every set-up is run for 10 minutes, with an additional 10 second holding time after the last *iperf* packet was transmitted.

5. Test results

The goodput ratio from every test run is measured as the total of all successfully received *iperf* packets on a single receiver, divided by all packets sent by *iperf*. Goodput ratios for the three receivers D, E and F are then averaged and a standard deviation is calculated. In contrast, packet delays for a test run are averaged for all successfully received packets on a single node and the standard deviation is also calculated. These values are then averaged again for the three receivers, including the standard deviations. The delay error resulting from the imperfect NTP synchronization amounts to less than 100 μs, as mentioned above, and has been neglected.

Most test runs were performed multiple times to check for consistency, but results are only shown from one test run for each setup.

5.1. Data rate variation

In Figs. 3 to 6 we see results from a test suite that applied increasing load to the network. For these measurements, we used a constant payload size of 1000 bytes and data rates between 100 and 1500 kbit/s.

Figure 3 shows the relative data goodput measured in *iperf*, i.e., the net percentage of successfully received data packets in relation to sent data packets. As can be easily seen, the WNet variant using the standard signal strength metric and link-layer acknowledgments with retries (*WNet Ret*) yields a high goodput even for increased network load and under congestion. This is mainly due to the retry mechanism of WNet. The MFP implementation that uses unicast transmissions for multicast packets also takes advantage from retries, but those integral to the IEEE 802.11 MAC layer. The other protocols begin to suffer from very high losses already for moderate load.

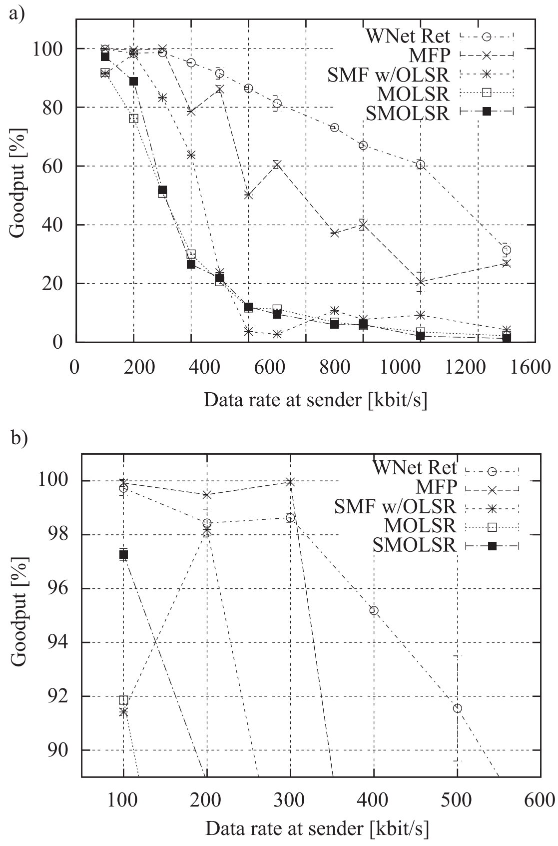

Fig. 3. (a) Measured goodput versus data rate at 1000 bytes packet size; (b) a view zoomed in at high goodput and low data rates.

The positive effect of WNet retransmissions can clearly be seen in Fig. 4. The graphs show results from different protocol variants of the WNet framework: *WNet NoRet* uses the same signal strength based metric as *WNet Ret*, but does not use multicast acknowledgments and no link layer retransmissions. The *WNet Ret+LR* variant combines the signal strength metric with a loss rate based metric. We discussed the options for a combination of these metrics in [12]. The retry mechanism is also activated in this variant. The same test conditions as above were applied. Apparently, acknowledgments and retries counteract the losses caused by interference and increase the success rate significantly, especially for low data rates. For high data rates, congestion effects prevail. The usage of retries under very high load is not beneficial and only increases congestion. Due to this effect *WNet NoRet* achieves a higher goodput than the other variants at 700 to 1000 kbit/s. Comparing *WNet Ret* and *WNet Ret+LR*, the usage of the loss rate metric is beneficial, especially under medium and higher load, as it presumably counteracts the effects of congestion.

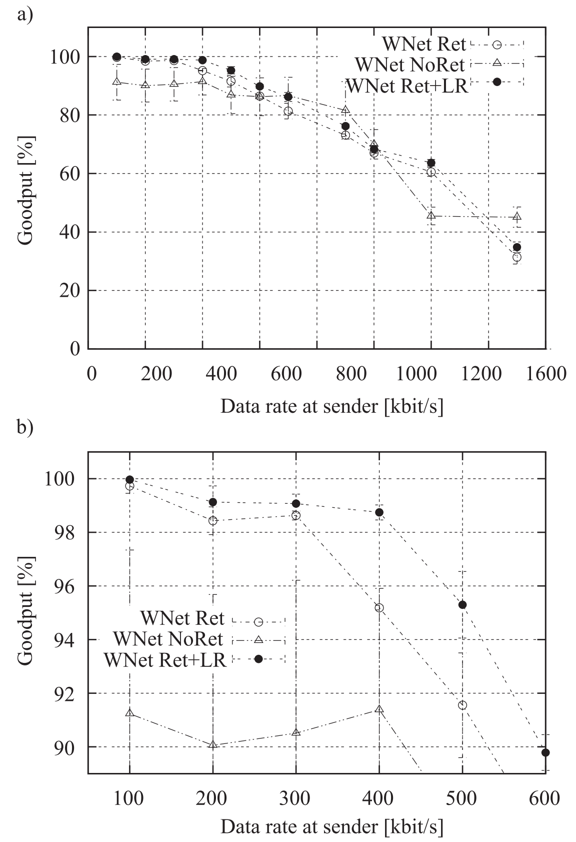

Fig. 4. (a) Measured goodput versus data rate for three WNet variants at 1000 bytes packet size; (b) a view zoomed in at high goodput and low data rates.

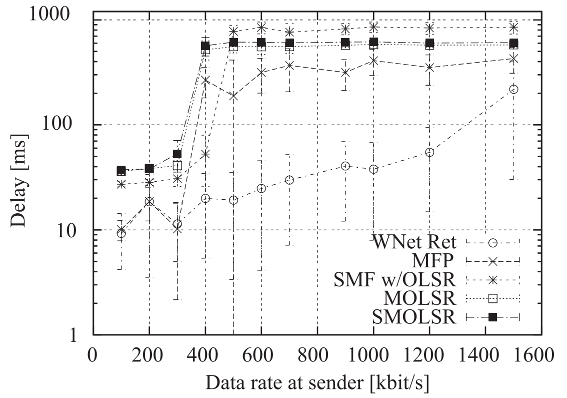

Fig. 5. Measured delay versus data rate at 1000 bytes packet size.

The end-to-end packet delays (Fig. 5; please note the logarithmic scale) are low in WNet up to data rates of 1000 kbit/s. Under congestion, though, frequent collisions lead to a higher number of retries, increasing the load even more. Other protocols suffer from high delays even under lower load. The unicast approach of MFP can keep the delays significantly lower than for other protocols with the exception of WNet. It is noticeable that the *multicast-over-unicast* approach with link layer retries from IEEE 802.11, as used by MFP, shows no advantages over the WNet multicast retry mechanism which has no "true" link layer support due to implementation restrictions. Of course, MFP has to send every packet n times for n next hop receivers, regardless of how many receivers are in fact within radio range.

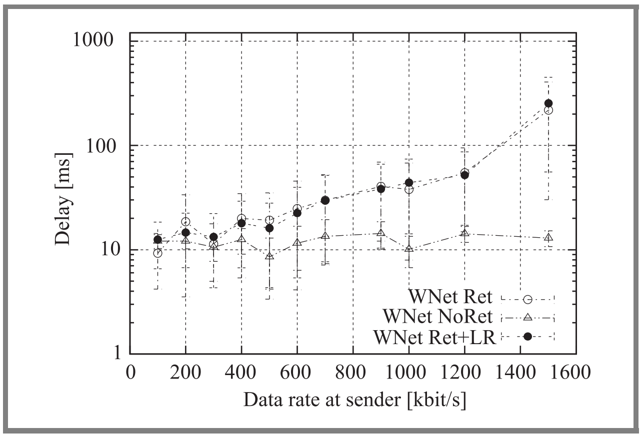

Fig. 6. Measured delay versus data rate for three WNet variants at 1000 bytes packet size.

The downside of the WNet retry mechanism is apparent in Fig. 6. Activating retries generally increases end-to-end delays. For low to medium load, though, the delay difference is moderate and may be a reasonable price to pay for higher multicast transport reliability. Nevertheless the delay increases significantly under high load and under congestion. Taking the goodput into account, it is questionable whether a retry mechanism should be active under very high load conditions. But considering the gain in goodput, it is advisable to enable retries for low and medium load, especially if transmissions over more than three hops occur. We expect an increased influence of the retry mechanism if the hop count increases, since the loss rates of the links are multiplied along a path and the retry mechanism reduces these loss rates. This remains subject to further investigation using other network topologies.

5.2. Packet size variation

In another test suite, we vary the payload size for our packets, keeping the *iperf* data rate at a constant 200 kbit/s. It should be noted that this leads to higher network load for smaller packet sizes, since the packet frequency and thus the payload overhead increases. Figure 7 shows the *iperf* goodput for the different protocols. For MOLSR, SMOLSR and SMF, packets with sizes beyond the MTU size of 1500 bytes are dropped, because the implementations can not handle packet fragmentation. The last significant measurement for these protocols is at 1400 bytes payload size. We also had problems to gain reasonable results for very small packet sizes ($\lesssim$ 50 bytes payload). We expect these problems to be due to implementation problems in the network device drivers, but this issue has to be further investigated.

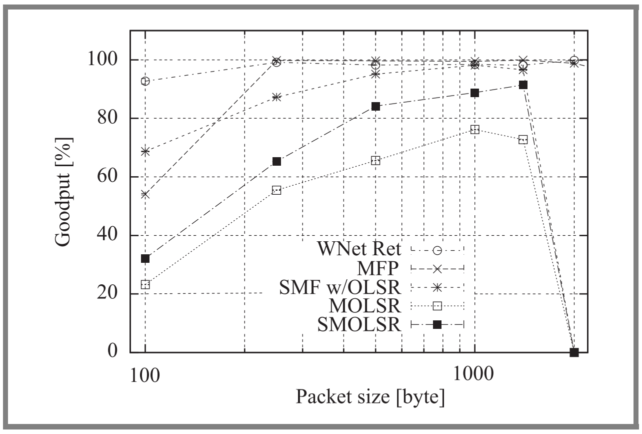

Fig. 7. Measured goodput versus packet size at 200 kbit/s.

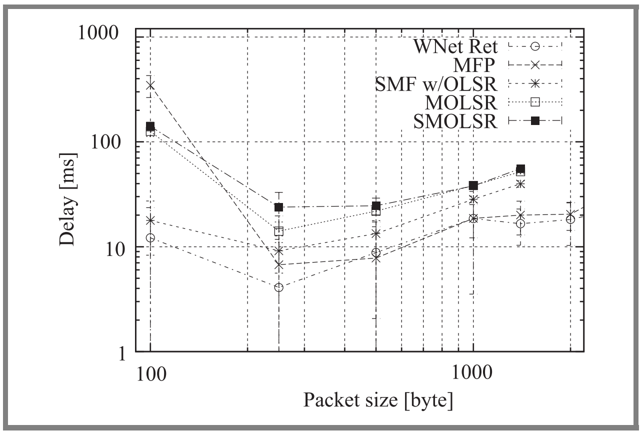

Fig. 8. Measured delay versus packet size at 200 kbit/s.

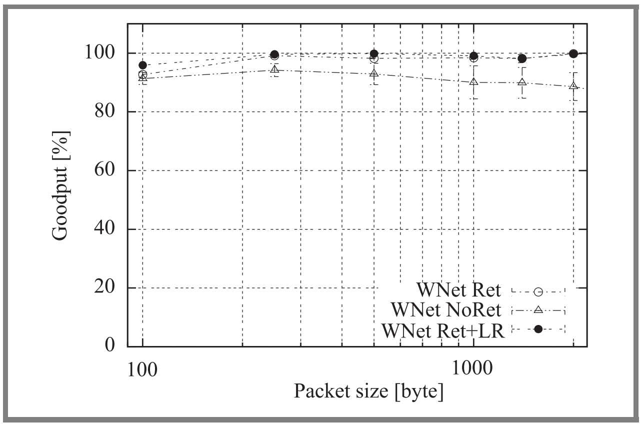

Fig. 9. Measured goodput versus packet size for three WNet variants at 200 kbit/s.

WNet Ret with link layer retransmissions and MFP with its IEEE 802.11 retries again show the best overall performance, with MFP revealing a considerable decline at high load conditions caused by small packets. The performance impairment of MFP correlates with increased end-to-end delay, as can be seen in Fig. 8. Without this exception, WNet and MFP show quite low delays. All other protocols show significant decrease in the goodput and higher delays for all packet sizes, SMF being closest to a satisfying performance for medium packet sizes.

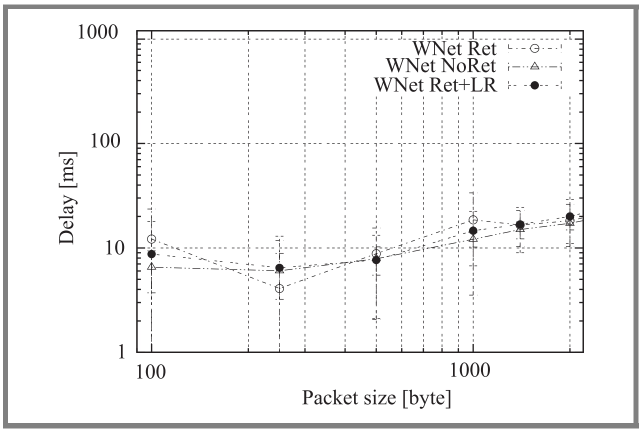

Fig. 10. Measured delay versus packet size for three WNet variants at 200 kbit/s.

Switching off the WNet retry mechanism, as seen with *WNet NoRet* in Fig. 9, decreases the success rate considerably for all packet sizes. In contrast to the high load scenarios in Fig. 6, the retry mechanism has no significant influence on the delay for varying packet sizes, all WNet variants showing constantly low delays (Fig. 10).

6. Simulation setup

To complement our results from the test-bed, we perform network simulations for the same static topology and with the same WNet variants as above. For other protocols used in the test-bed, simulation results are unfortunately not yet available.

We use the ns-2 simulator [13] in version 2.29 with an enhanced version of the IEEE 802.11 ns-2 implementation published by the University of Bonn [14]. This implementation eliminates some known inaccuracies of the current implementation included in ns-2 that lead to frequent failures with higher data rates.

Many MANET simulations use simplified radio propagation models, resulting in disk-shaped radio ranges with fixed radius for each node, and are far from modeling a real-world scenario [3]. To obtain better results in contrast to these simpler models we use the log-distance model for large-scale fading and Ricean fading as a small-scale fading model [15]. The path-loss exponent for the log-distance model is set to 3.5, resembling an environment with multiple smaller obstructions like in our office environment.

The Ricean fading model is based on the assumption that in addition to a dominant signal component (e.g., line-of-sight) there is a large number of multi-path components at the receiver which can lead to attenuation or amplification, depending on the phase shifts caused by the signal propagation times along different paths. The Ricean K factor specifies the ratio between the signal strength of the dominant component and that of the multi-path components. To find a suitable K factor for our simulations, we evaluated the signal strength variations observed during measurement periods in the test-bed (from 6 pm to 4 am in Fig. 2). This data was used to fit to a Ricean signal strength probability distribution and estimate the K factor to 40.

In contrast to the test-bed, we can easily obtain our topology without simulated antenna attenuation, using larger distance between the nodes. A connectivity comparable to our test-bed, with similar received signal strengths and resulting modulations, is achieved with a distance of 150 m between adjacent nodes (except D to E and E to F, respectively, where distances are 77.6 m).

The traffic model corresponds to the traffic produced with *iperf*, using CBR multicast UDP traffic from node A to nodes D, E and F. To increase statistics and decrease probability for synchronization effects between agent traffic and WNet management traffic, simulations are repeated 5 times with small variation (jitter) in the traffic starting time. Additionally, results are averaged over all three receivers.

For the WNet protocol, the same code base is used for the simulation and the test-bed implementations.

7. Simulation results

Figure 11 shows the simulated goodput for varied data rates, corresponding to Fig. 4 for the test-bed. Although we achieved a high similarity between the simulated environment and the test-bed, the simulation results show considerable differences. The goodput is generally better, and congestion effects appear at significantly higher loads. Especially *WNet NoRet*, the WNet variant where the retry mechanism is disabled, shows major differences to the test-bed results from Fig. 9 and an astonishing stable behavior up to very high loads. Additional simulations could show that congestion starts at approximately 2000 kbit/s with *WNet NoRet*. Nevertheless, goodput for low to medium loads is almost as mediocre as in the test-bed. In contrast to the test-bed, the advantage gained by the added loss rate metric in *WNet Ret+LR* does not exist in the simulation.

The decreasing goodput for higher load corresponds clearly with higher delays, as seen in Fig. 12. The emerging congestion at about 800 kbit/s is abundantly clear.

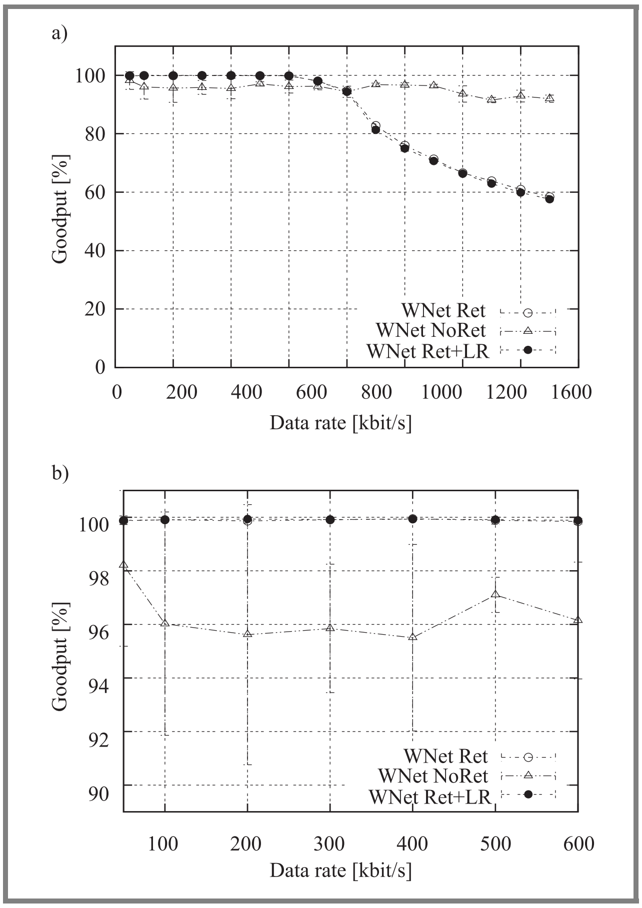

Fig. 11. (a) Simulated goodput versus data rate for three WNet variants at 1000 byte packet size; (b) a view zoomed in at high goodput and low data rates.

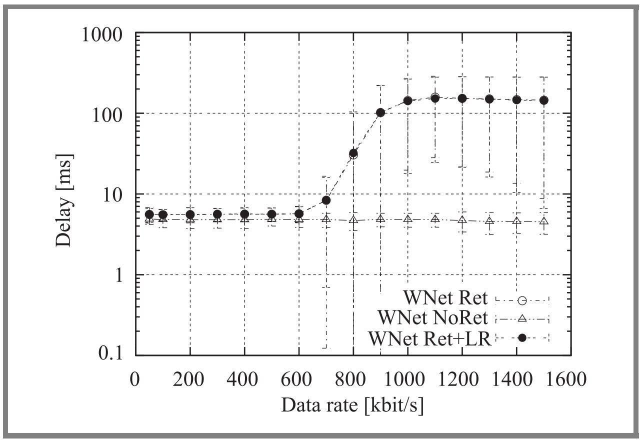

Fig. 12. Simulated delay versus data rate for three WNet variants at 1000 byte packet size.

For the packet size variation, the simulation results offer less surprises. The packet goodput ratio from Fig. 13 shows the same decrease when WNet retries are disabled as in Fig. 9. The performance with retries enabled is nearer to 100 percent, though.

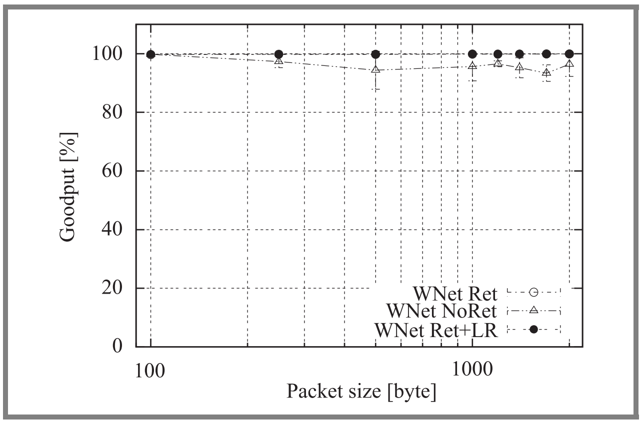

Fig. 13. Simulated goodput versus packet size for three WNet variants at 200 kbit/s.

Delays for varying packet sizes also show the same overall behavior in Fig. 14 as they show in Fig. 10, although they are in general some milliseconds lower.

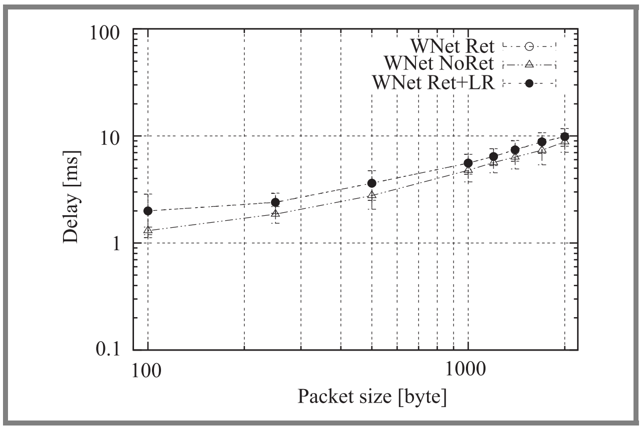

Fig. 14. Simulated delay versus packet size for three WNet variants at 200 kbit/s.

8. Conclusion

We have shown that for multicast transmissions in an ad hoc network based on IEEE 802.11, improvements to the link layer are strongly advisable.

The positive influence of link layer retries for multicast packets on the overall network goodput is obvious, at least for our scenario. Simulation results confirm these findings as far as the scenarios are comparable. Addition of link layer acknowledgements and retries, like those applied to IEEE 802.11 unicast transmissions, would be a feasible approach, but must be combined with explicit multicast forwarding to determine the next hop recipients. Also, an implementation of multicast over unicast can improve the delivery rate in our scenario, but it increases the network load even when not needed. For high-density networks and large multicast groups, ACK implosions will probably counteract the positive effect of these features.

Efficient flooding mechanisms, like those that can be integrated with SMF, are supposed to attain major advantages for scenarios that offer multiple paths between source and destinations, higher node densities or increased mobility. For the simple relay chain scenario presented here, the flooding approach appears detrimental. Even when link layer retries are not activated, as it is the case with *WNet NoRet*, goodput and especially delays are significantly better with explicit multicast than with flooding.

All in all, we have reproduced the main effects seen in the test-bed with our simulations. But compared with the real-life test-bed results all simulations show a more consistent and "smooth" behavior that can not be explained simply by better statistics.

Future work. Although the results from our simulations show a reassuring similarity to our test-bed results, there are still obvious differences that should be resolved. Delays for small packets are significantly lower in simulation than in the test-bed, congestion effects show earlier in the test-bed. Apparently, the models used still lack a certain amount of applicability for the validation of test-bed results. But the reliability and stability of the network drivers and hardware can as well be a source of otherwise unexplainable variation. This should be clarified, where possible.

On the other hand, different scenarios should be tested, both static and mobile. Whereas node mobility can be easily added in simulation, designing a real-world mobile test-bed with high reproducibility presents a hard to meet challenge. In addition, a suitable mobility model has to be found that can be viewed as a practical application of mobile communication in tactical environments.

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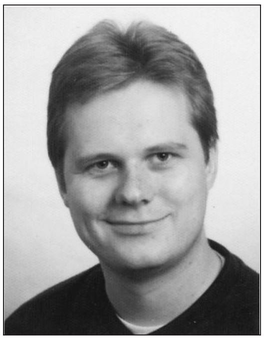

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