Performance Analysis of AODV on Top of IEEE 802.11a and the Impact of the 5GHz Channel

Erik Weiss*, Guido Hiertz*, Sven Hischke+, Bangnan Xu+
* : Communication Networks, Aachen University of Technology, Kopernikusstr.16, D-52074 Aachen, Germany
+: T-Systems, Technologiezentrum, Am Kavalleriesand 3, D-64295 Darmstadt, Germany
Ph: +49 241 8028575, Fax: +49 241 8022242, Email: erik.weiss@comnets.rwth-aachen.de

Abstract-- *This paper analyses performance of AODV (Ad hoc On Demand Distance Vector) routing protocol in IEEE 802.11a multi-hop ad hoc networks. IEEE 802.11a operates in the 5GHz band and offers 8 different coding schemes. Each coding scheme has a specific behavior according to the error probability and supported data rate. The impact of the coding schemes (PhyModes) of IEEE 802.11a on the performance of AODV is evaluated using computer simulation. The traffic performance and network connectivity using different PhyModes are evaluated. Optimized PhyModes resulting in best traffic performance and high network connectivity can be derived from the simulation results.*

Index Terms-- *IETF, IPonAir, IEEE 802.11, AODV, Coding schemes, Ad Hoc Networks, Link Adaptation, Ad Hoc Routing*

1 Introduction

Internet access is becoming increasingly important. The trend is towards the wireless world, providing public access to the Internet via wireless devices at high data rates. *Wireless Local Area Networks* (WLAN) like IEEE 802.11a with transmission rates up to 54Mbit/s are increasingly important for the wireless access. Due to the high attenuation at the used 5GHz frequencies the wireless coverage is limited. Multi-hop ad hoc networks can be used to extend its coverage. To realize multihop transmission, a route between source and destination must be found. One of the most promising ad hoc on demand routing protocol to establish an end-to-end route is AODV. The paper is structured as followed. First we give a brief introduction of the medium access control and its physical layer of IEEE 802.11a. Then the main issues of AODV (Ad Hoc On Demand Distance Vector) are described. The simulation results of AODV with different PhyModes are presented in the following Sections. Finally we conclude the paper and give a short outlook.

2 IEEE 802.11 Medium Access Layer

IEEE 802.11 specifies the Medium Access Control (MAC). 802.11a, 802.11b and 802.11g extend the basic modulation and encoding schemes. 802.11a [1], operating at 5GHz, defines eight coding schemes, called "*Phy-Modes*" (see Table 1). IEEE 802.11 has specified a distributed MAC protocol, the *Distributed Coordination Function* (DCF) The 802.11 standard also defines a *Point Coordination Function* (PCF) but no vendor has ever implemented it. The DCF is based on *carrier sense multiple access with collision avoidance* (CSMA/CA). As mobile nodes (MN) are not able to monitor the air interface while sending, the DCF uses backoff and Request-To-Send / Clear-To-Send (RTS/CTS) mechanisms to avoid collisions. Details of the IEEE 802.11 MAC protocol are shown in [3].

3 IEEE 802.11 5GHz Channel

IEEE 802.11a has up to eight different PhyModes. The standard itself does not specify any rules for selecting the PHY mode.

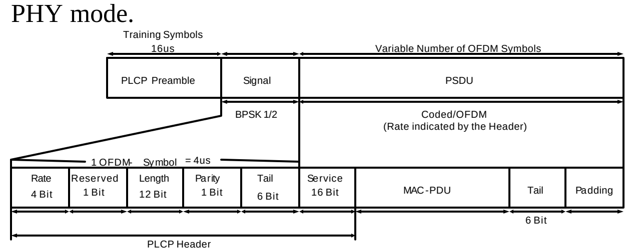

Figure 1: Physical Layer Frame Structur of IEEE 802.11a

Figure 1 shows the physical layer packet data unit (PDU) of IEEE 802.11a. The first four bits within the preamble refer to the PhyMode with which the data is coded. Figure 2 shows the Packet Error Rate (PER) versus C/I (Carrier to Interference Ratio). Higher PhyModes are capable to deliver higher data rates. Nevertheless, they also need a remarkable higher C/I. In Table 1 the available PhyModes are listed together with the maximum data rate and the number of bits per OFDM symbol. Based on the relation between C/I and the useable transmission mode, IEEE 802.11a allows changing the PhyMode when the channel quality is decreasing. Channel quality may decrease due to several reasons. In Figure 3 the maximum reachable data throughput is shown with DCF and the RTS/CTS mechanism of the 802.11 MAC protocol. It can be seen that with the PhyMode QAM-64, IEEE 802.11a can achieve a throughput of around 36 Mbit/s.

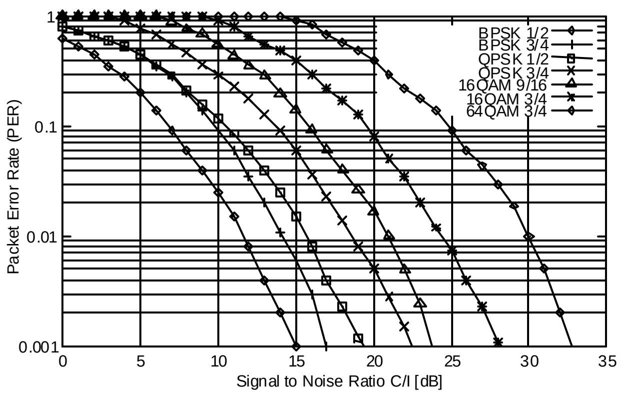

Figure 2: Packet Error Rate versus C/I

The IEEE 802.11a system offers the opportunity to choose an appropriate PhyMode. For every connection and each data packet, the PhyMode can be chosen separately, depending on the received C/I. The idea is to take the envelop in Figure 3 by choosing always the PhyMode with the best balance of throughput and PER. Terminals in a real system cannot measure the C/I, since each terminal only receives 'Energy'. The terminal cannot determine between signal power and interference power. Two ways to estimate the C/I ratio exist. Terminals can either measure the interference power within breaks or the terminals count successfully received and lost packets.

Data rate (Mbit/s)	Modulation	Coding rate (R)	Data Bits per Symbol
6	BPSK	½	24
9	BPSK	¾	36
12	QPSK	½	48
18	QPSK	¾	72
24	16-QAM	½	96
36	16-QAM	¾	144
48	64-QAM	2/3	192
54	64-QAM	¾	216

Table 1: PhyMode dependent Parameters

With the ratio of the number of received to lost packets the current C/I can de derived from Figure 2. At the Chair of Communication Networks a simulation tool was built to simulate IEEE 802.11a/e together with HiperLAN/2 for coexisting investigations. IEEE 802.11a uses a Link Adaptation (LA) based on the number of successful/lost packets. To improve the protocol performance, an easy but valuable approach is implemented in the simulation tool. After successfully receiving a predefined number of packets, the current PhyMode changes to that with a higher date rate and vice versa the PhyMode changes to that with a lower data rate after losing a predefined number of packets. The main advantage of the implemented LA algorithm is the fast reaction to link changes. But some unnecessary changes may occur. Because even when the LA has found an optimum PhyMode it tries to improve it further, although this trials will fail.

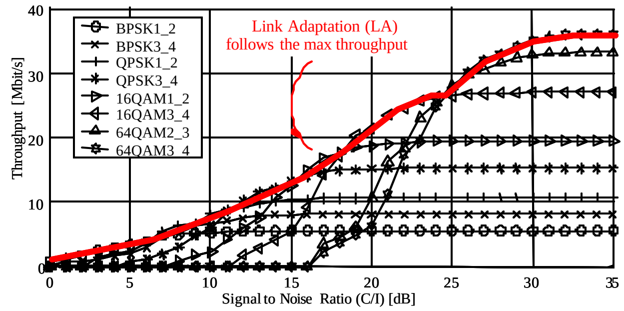

Figure 3: Max. Reachable Throughput per PhyMode

4 Ad hoc Routing

Routing protocols can be divided into two groups, proactive and reactive protocols. Proactive approaches maintain all routes, therefore minimizing the packet delay. Whereas reactive protocols have to create routes upon request, and respectively the signaling overhead can be minimized. This paper analyses the performance of AODV operating on top of IEEE 802.11a. Particularly this paper focuses on the interaction between different PhyModes and the ad hoc routing protocol.

4.1 Ad Hoc on Demand Distance Vector Routing (AODV)

Currently AODV is one of the most discussed ad hoc routing protocols. Due to the proactive nature of AODV if no route is available, the protocol introduces a higher delay at connection begin than reactive protocols; the route has to be established [5].

Route Discovery

When a node wants to sent packets to its destination, it checks its routing table for a valid route. If a route exists the packets are forwarded to the appropriated next hop. If the node can not find a valid route it initiates a route discovery process. The source node sends a route request (RREQ) and the RREQ floods the network (cf. Figure 4). The RREQ contains source and destination IP addresses and a sequence number from the source node and also the last known sequence number from the destination node. Additionally the RREQ packet contains a broadcast ID. The broadcast ID is incremented with each broadcast by the source node. Therefore, the combination of source IP address and broadcast ID uniquely identifies each RREQ. After receiving the RREQ a node checks whether it is the destination or whether its routing table has a valid entry to the destination. If the destination is unknown the node increments the RREQ hop count and rebroadcasts the RREQ. Additionally the node builds a new reverse route towards the source node. In this route entry the source IP address of the RREQ, the according sequence number and hop count are stored together with the IP address of the last node that has sent this RREQ.

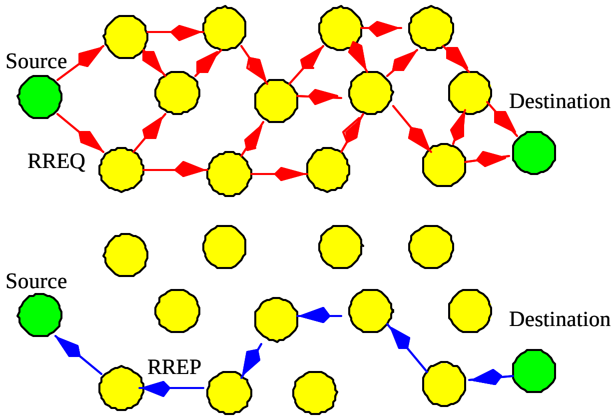

Figure 4: AODV Route Discovery Process

Hence, the node has a route to forward a Route Reply (RREP) to the source node if one arrives. If the node itself is the destination or it knows a valid route, it compares the sequence number from the RREQ with the number stored in its routing table. If the stored sequence number is higher than that indicated in the RREQ, the node responds by unicasing a RREP packet. The RREP contains source and destination IP addresses. In case that the responding node is the destination it inserts the current sequence number and sets the hop count to zero in the RREP. If an intermediate node replies, it inserts the stored sequence number into the RREP and adapts the hop count to the actual hop count.
Each node receiving the RREP builds a *forward path* entry containing the destination IP address, the neighbor IP address of the last RREP sender and the hop count to the destination. The table entry also contains the 'lifetime' of the RREP. Each time the entry is used the lifetime is updated. Otherwise it expires after its lifetime. To limit the overhead an expending-ring search mechanism is proposed in [5]. The first route request is sent using a limited time-to-life (TTL). After a certain time the route request attempt expires. Then the TTL is increased and the RREQ is rebroadcasted. Thus flooding the whole network is avoided. Although the route discovery process with expending-ring search takes more time to find a route.

Route Maintenance

Once a route has been discovered, it is maintained as long as needed. If the source node moves it reinitiates the route discovery process. When either the destination or an intermediate node moves and the route breaks a Route Error (RERR) packet is sent to the source node. This RERR is sent by the node on the source side of the breakage (upstream). A neighbor node receiving the RERR marks the according route entry as invalid (hop count is set to infinity) and broadcasts the RERR to all neighbors that are affected by the broken link. The source node reinitiates the route when it receives the RERR. In addition to the approach described here AODV introduces a method to repair broken routes locally.

Local Repair

Additional to the above described approach AODV introduces a special route maintenance method to repair broken routes. When a link and accordingly the route breaks the upstream node decides either to repair the route or to send a RERR message. To repair the broken route the node sends a RREQ. It is important to notice that the repair RREQ will not reach the source node to prevent loops. Further details can be found in [5].

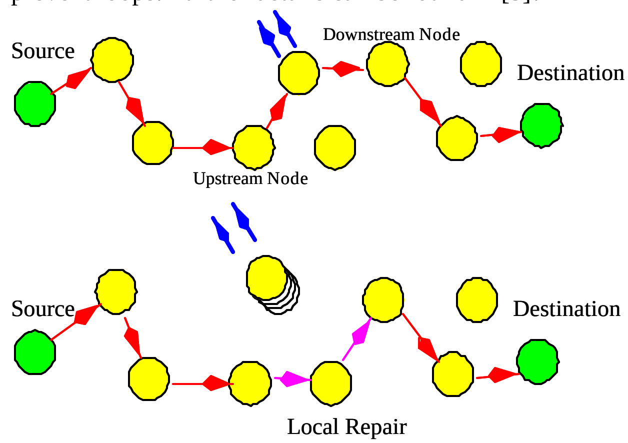

Figure 5: AODV Route Repair shown for Unicasting

After starting the repair process the node waits for a discovery period. If the repair attempt fails, a RERR message is sent back to the source node. Otherwise it updates its routing entry and compares the stored hop count with the recently received one. If the new hop count to the destination is larger, the node creates a RERR message for the source node. To distinguish the repair RERR from the standard RERR the 'N' flag must be set. After receiving the repair RERR, a node will update the corresponding route entry instead of deletion. However, when the source node receives the *repair RERR,* it may decide to initiate a new route discovery process to avoid unnecessarily long and inefficient routes.

5 AODV Performance with IEEE 802.11a

To evaluate the interaction between AODV and the used PhyModes we present the simulation results according to the scenario below.
The simulation scenario contains 20/40 Stations (STA) and 3 Routes, all loaded with 100 kbit/s Constant Bit Rate (CBR with a packet size of 512 bytes. Figure 6 shows the general setup. At the beginning of the simulation all nodes are distributed as shown in Figure 6. All light grey colored nodes will move following the Random Way Point Model, the simulated velocity per simulation varies from 0.5 to 5m/s. The set up scenario allows building routes between the sources and destinations at the beginning.

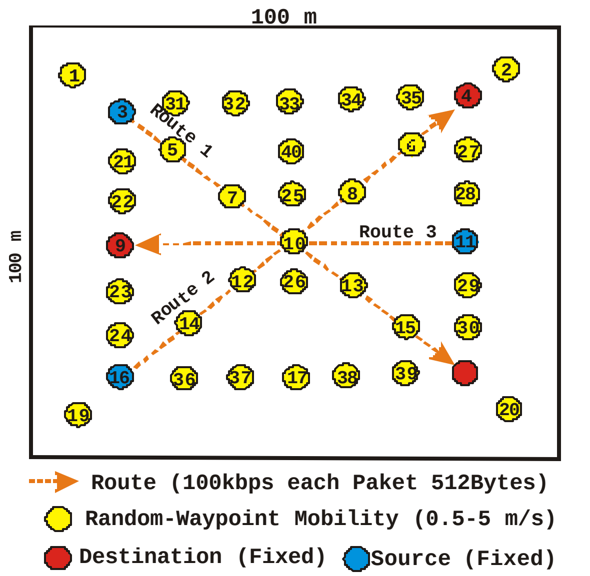

Figure 6: Scenario with 40 Stations, 3 Routes each 100kbit/s

These routes will break soon depending on the mobility and the velocity. Contrary to a pure Random Way Point Model where all stations are moving we decided to fix the source and destination nodes.

With this deployment we force the creation of multi-hop routes and the distance between source and destination node is always the same. By placing the nodes like described we can evaluate the effectiveness of AODV separated by the different PhyModes and different terminal velocities.

5.1 Average Throughput

Figure 7 shows the average throughput for route 1, that is loaded with 100 kbit/s. It is obvious that raising the velocity decreases the throughput as the high mobility of the nodes increases the routing protocol signaling. From

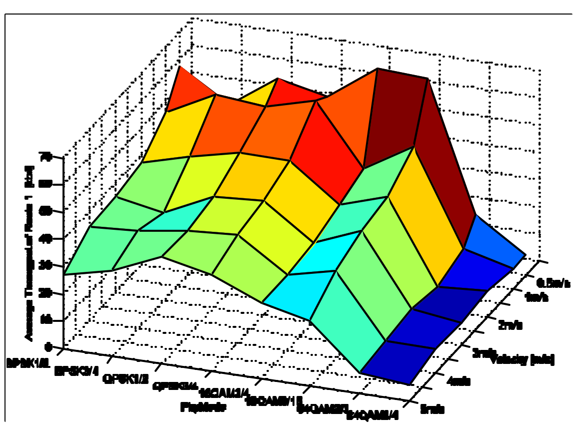

Figure 7: Average Throughput for an offered load of 100kbit/s (20 Stations)

Figure 7 we can also see the impact of PhyModes on the throughput performance. With a higher PhyMode, the one hop throughput increases accordingly. However the end-to-end throughput decreases to approx. 10kbit/s with the highest PhyMode QAM-64. Because increasing the PhyModes per hop means on the other hand decreasing the communication range. Thus the network connectivity decreases with a higher PhyMode. Figure 8 indicates the average throughput with the scenario of 40 stations. After a comparison of Figure 8 with Figure 7 we can see that the average throughput with 40 stations is much higher than that with 20 stations.

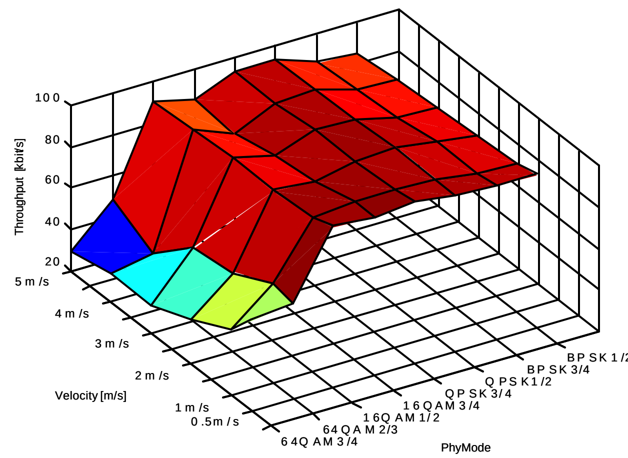

Figure 8: Average Throughput per Route (40 Stations)

The reason is that the network connectivity increases accordingly to the node density. With increasing the number of stations the throughput increases. From the simulation results shown in Figure 7 and 8 we can derive an important conclusion that higher PhyModes do not lead to higher end-to-end throughput in IEEE 802.11a multihop ad hoc networks due to low network connectivity with higher PhyModes. Hence it is not profitable in ad hoc networks/multi-hop networks to use exclusively the high coding schemes.

5.2 Average Hop Count versus PhyMode

Figure 9 shows the percentage distribution between the different hop counts for route 2. Accordingly to the stability and the short communication range with higher PhyModes more hops are needed to reach the destination. Whereas lower PhyModes need less hops to reach their destination, due to the larger communication range. AODV defines a mechanism to locally repair a broken route, called 'Local Repair' (cp. Section 4.1).

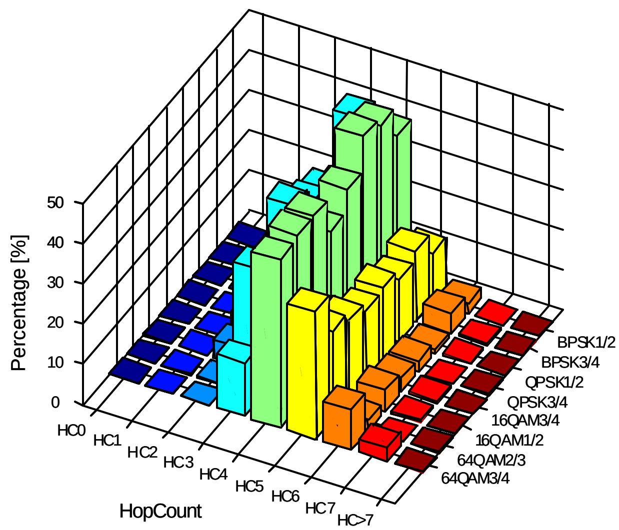

Figure 9: Average Hop Count used for Route 2 without Local Repair (40 Stations, Velocity 1 m/s)

Figure 10 shows the resulting hop count with local repair. As expected the hop count tends to increase especially for the higher ordered PhyModes. But the increase is very slight. This means that Local Repair does not increase the hop counts significantly. The results in Figure 11 indicate that the throughput is not negatively affected by the local repair mechanism.

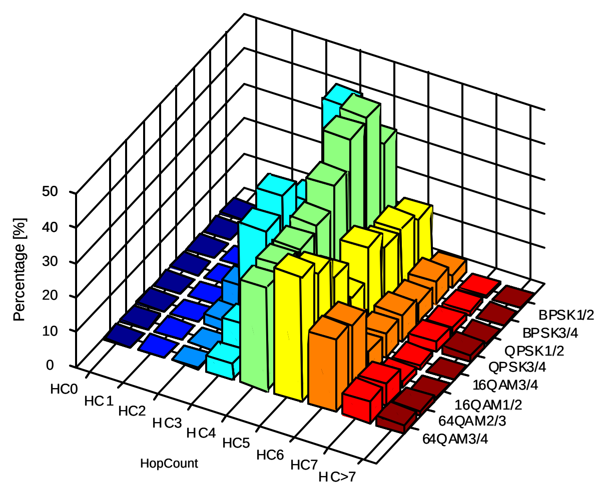

Figure 10: Average Hop Count used for Route 2 with Local Repair (40 Stations, Velocity 1 m/s)

In difficult connection situation, for instances with high PhyModes, the local repair increases the throughput. With higher PhyModes the probability for route breakage is larger therefore the local repair effect is more obvious. Thereby higher PhyModes profit more form introducing the local repair mechanism than lower ordered PhyModes.

The simulation results show that the local repair mechanism can improve the traffic performance if higher PhyModes are used. But the average throughput decreases using higher PhyModes. Hence, the PhyMode should be selected according to the network connectivity of the Ad Hoc Network. As long as the traffic load is not close to the system limit the lower ordered PhyModes are delivering the highest amount of data.

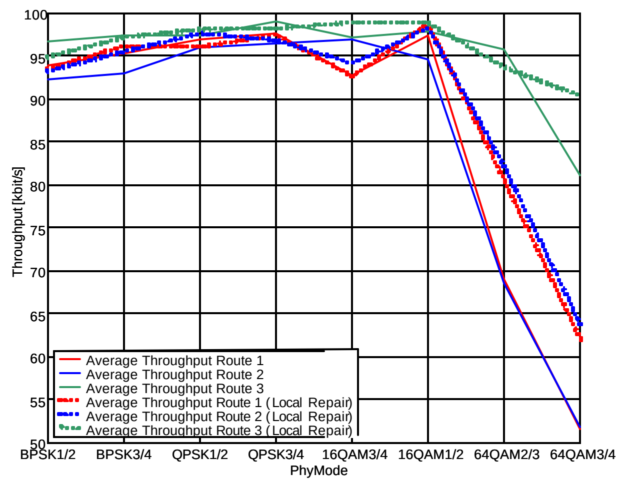

Figure 11 : Throughput with and without local repair (40 Stations, Velocity 1 m/s)

5.3 Packet Latency versus PhyModes

Besides the throughput and hop count the packet delay is another important factor to evaluate the performance of an ad hoc network. Figure 12 shows the experienced delay with different PhyModes. The delay is measured from the packets of route number 2; the average hop count of route 2 is between 3 and 5 hops (without local repair) depending on the used PhyMode. Figure 12 shows the complementary cumulative distribution function of the packet delay of the route 2. The delay curves in Figure 12 can be divided into three parts. The first part contains all packets that are sent to the destination when a route was available when the packet appears. The produced delay in this part results mainly from the MAC backoff at each hop and the packet sending duration. The second part is a delay gap, either an arriving packet finds a route immediately or the packet has to wait until a route is found.
Therefore a packet delay between 30 and approx. 300 ms is very rare. The third part consists of packet arrivals when the source has no valid route to the destination. Hence the packets have to wait until a new route is established. The last section shows two steps originated by the expending ring search mechanism of AODV [5].

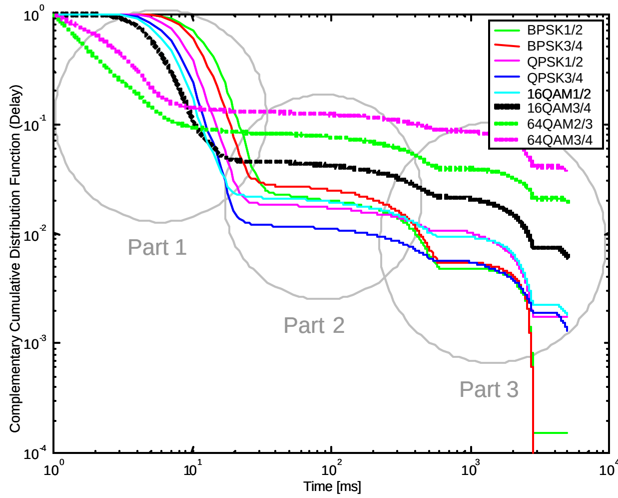

Figure 12: Packet delay with different PhyModes without Local Repair (40 Stations, Velocity 1 m/s)

The first route request is sent with a TTL=3 (time-to-life). It is increased in 3 hop steps. The effect of this range extending can be seen in the latency steps. Figure 13 also shows as well the packet latency. However these are the results after using the local repair mechanism. It can be observed that the first part grows.

Obviously using the local repair mechanism increases the average lifetime a route exists, hence the probability that an arriving packet can be sent with an already established route is also increasing. Another interesting change can be seen in the second part, the former approx. horizontal part is now declining. Repair attempts occur either to repair a small gap or to repair a larger interruption. Therefore the former clear separation in the packet delay curves between existing routes and routes that have to be reestablished becomes now ambiguous. The steps in the curves caused by the expending ring search could be also seen.

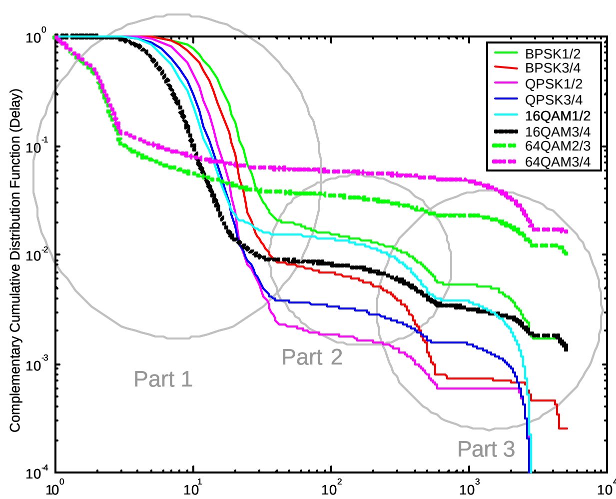

Figure 13: Packet delay with different PhyModes using Local Repair (40 Stations, Velocity 1 m/s)

5.4 Impact of the traffic load

All results presented so far have been investigated with 100 kbit/s traffic per route. Figure 14 shows the average throughput for all three routes each loaded with 300 kbit/s. In comparison with the results in Figure 8 with 100 kbit/s (cp. Figure 8) the lower ordered PhyModes have serious problems and cannot provide a sufficient throughput. The bandwidth consumption by lower ordered PhyModes is too high. Hence the wireless medium is congested.

The higher PhyModes suffer from their instability, the main problem occurring during the route discovery phase. The route requests are broadcasted therefore not acknowledged. Thus the drawback using higher ordered PhyModes is immense. As Figure 14 shows that the throughput performance with middle PhyModes is the best because of the optimized tradeoff among stability, communication range and bandwidth capacity in the high traffic load case.

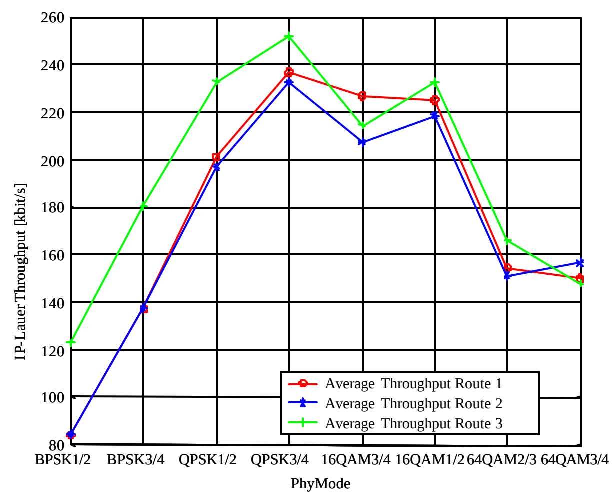

Figure 14 : Increasing the Traffic per Route to 300kbit/s (40 Stations, Velocity: 1 m/s)

6 Conclusion

This paper shows that the choice of the PhyMode has a significant impact on the traffic performance and the routing behavior in ad hoc networks. The Impact of PhyModes on the average throughput and packet delay has been evaluated using AODV routing protocol and IEEE 802.11a. The simulation results indicate that under low traffic load lower PhyModes seem to be the best choice. However the best delay characteristic may be achieved using middle PhyModes. The traffic performance with middle PhyModes is best in the high load cases.

7 Outlook

Apart from the presented results for AODV on 802.11a, as mentioned before the standard IEEE 802.11a does not specify any rules for selecting the PhyModes. However a function called "Link Adaptation" is used to choose a PhyMode for each transmitted data packet. Thus, for each hop-by-hop connection the PhyModes are adapted for the best suitable balance between packet error rate and throughput. Therefore the Link Adaptation has to choose lower ordered PhyModes to keep the link connection in case that the link quality degrades. In the ongoing investigation we will consider the link adaptation and the priorities provided by IEEE 802.11e. Furthermore we will consider to split up the coding schemes depending on the messages, thus all route request messages for instances are sent with different fixed PhyModes whereas the date packet are adapted continuously to the link quality.

8 Acknowledgement

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