Improving Ad Hoc Routing for Future Wireless Multihop Networks

Erik Weiss*, Markus Frewel*, Guido Hiertz*, 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*: Nowadays Ad Hoc Routing Protocols have been developed and evaluated using several different simulation tools, i.e. NS-2. However, all these investigations do not consider the fact that future wireless networks are capable to adapt their behaviour to the channel situation. These adapting functionalities haven't been developed to be used in Multi-Hop Ad Hoc Networks. Therefore the performance of Ad Hoc Routing using IEEE 802.11a turned out to be unexpected inefficient. This paper presents a new concept to improve Ad Hoc Routing Protocols exploiting IEEE 802.11a Link Adaptation capabilities. The IEEE 802.11a Link Adaptation information is used to predict the link stability and link lifetime. After introducing the IEEE 802.11a MAC Layer and its transmission modes, the paper reveals some insights of the IEEE 802.11a Link Adaptation behaviour. Based on the Link Layer Information, new route maintenance Protocol ERU (Early Route Update) is proposed to improve the active route maintenance in Ad Hoc Networks.**

1 Introduction

Internet access is becoming increasingly important. Furthermore, 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 work at the 5 GHz band, supporting transmission rates up to 54 Mbit/s. Due to the high attenuation at 5 GHz the coverage is limited. To extend the coverage, multi-hop routes have to be established. Being wireless enables the user to be mobile; therefore the network has to deal with the mobility, and all the effects introduced by a dynamic changing network topology.

High transmission rate and limited transmission range makes WLAN systems reasonable for areas with a high population density and users with the need for high data rates. Such places are called Hotspots like airports or fairs. Figure 1 shows the idea of the future Mobile Internet.

Due to the limited transmission range the needed density of Access Point/Router has to be very high. The deployment of such a high number of Access Points would be economically infeasible. This could be reduced by either increasing the transmit power or enabling intermediate terminals to forward the data to users outside the access point range.

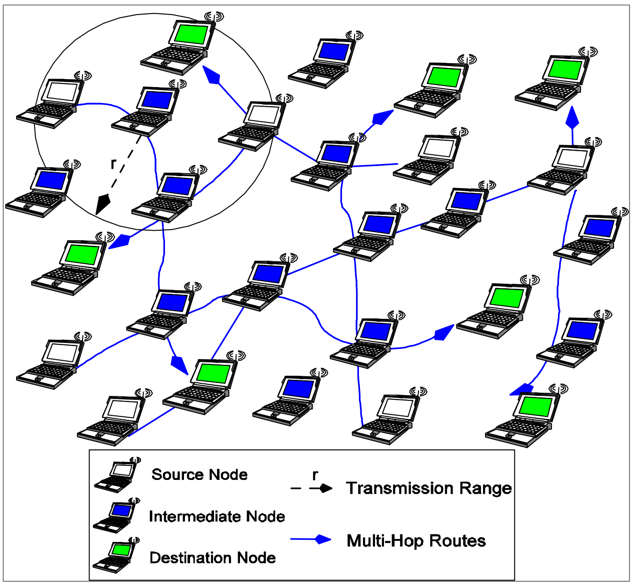

Figure 1: Wireless Ad Hoc Network

Increasing the transmit power burdens the batteries of the mobile node and increases exposure of operators to radio waves along with their yet undetermined health risk.

State of the Art

The solution is to expand the fixed infrastructure using multi-hop connections. To handle the mobility and fast topology changing on the network, Ad hoc Routing Protocols have been developed. Routing protocols are divided in two groups, the proactive and reactive protocols. The reactive protocols request a route when needed. Whereas proactive protocols permanently maintain routes to all network members. Thus, proactive approaches can use the route when requested, therefore minimizing the packet delay. Reactive protocols avoid to maintain unneeded routes, but with a higher route discovery and packet delay. Furthermore, hybrid approaches have been developed.

All current routing protocols have been developed using IEEE 802.11. The next evolution step is IEEE 802.11a working at 5 GHz. The main extensions during the evolutions steps are the implementation of more than one transmission modes "*PhyModes*". However, no routing protocol considers the impact of these PhyModes. The PhyMode adaptation has not been standardized by the IEEE group, but its impact on the IP Layer and especially to the ad hoc routing turned out to be immense.

For instances, all approaches only react when the link is already broken. This leads to a high packet loss as well as an increase of route rediscovery and packet delay. This paper presents a new approach. Our proposal reacts before the link breaks. Based on Link Adaptation information the link state is predicted. The route will be rearrange before the link breaks. The lower layer, especially the Link Adaptation, provides information that allows predicting the link conditions. We present a new route rearrangement protocol based on the prediction, the Early Route Update (ERU). ERU prevents unnecessary signalling, avoids packet loss and minimizes packet delay. Therefore, our approach uses the Ad Hoc Network capacity more efficiently than existing protocols. We structured the paper as follows:
First we start with a brief overview about the IEEE 802.11. To explain the fundamental for the prediction we focus on the IEEE 802.11a Link Adaptation behaviour in section 3. Section 4 presents simulation results visualizing the correlation between Link Adaptation behaviour and upcoming link breaks. Finally, the ERU signalling is presented to use the link prediction effectively. Finally the last section concludes our paper.

2 IEEE 802.11a Medium Access Layer

The IEEE 802.11a Medium Access Control (MAC) layer is mainly the same as the MAC layer of 802.11b and the legacy 802.11. The main difference to 802.11a are the transmission modes [1]. 802.11a can chose between eight PhyModes (cf. Table 1). IEEE 802.11 uses a distributed MAC protocol; the *Distributed Coordination Function* (DCF) based on *carrier sense multiple access with collision avoidance* (CSMA/CA) [1][2].

IEEE 802.11a Transmission Modes

The standard itself does not specify any rules for selecting the PhyMode. Figure 2 shows the Packet Error Rate (PER) versus C/I (Carrier to Interference) for all usable PhyModes. Higher transmission modes are capable to deliver higher data rates, but nevertheless, they also need a remarkable higher C/I. In Table 1 the available modes are listed together with the maximum data rate and the bits per OFDM symbol. For instance a 2000 byte data packet sent with 64-QAM 3/4 needs 75 OFDM symbols for the data and transported with BPSK ½ the packet needs 667 OFDM symbols. Hence transmitting with BPSK ½ takes approx. 8.5 times longer, compared with 64-QAM 3/4. Due to the dependence between C/I and useable PhyModes. The IEEE 802.11a system offers the opportunity to choose an appropriate PhyMode (Table 1). For every connection and every single data packet, the PhyMode is chosen separately, de pending on the received C/I. This task is done by the Link Adaptation (LA). Terminals in a real system cannot measure the C/I, since each terminal only receives 'Energy'. Terminals cannot differentiate between signal power and interference power. Thus two ways to estimate the signal-to-noise ratio exist. Terminals could either measure the interference power within breaks or count the successful received

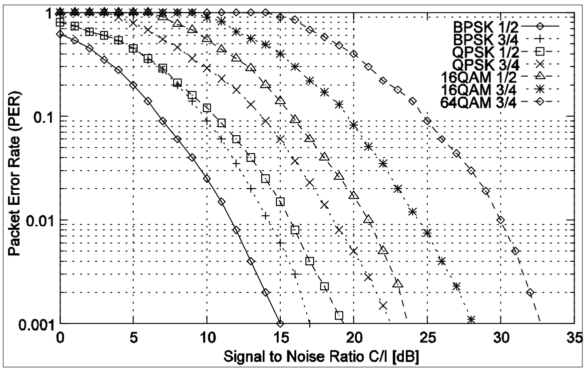

Figure 2: Packet Error Rate versus C/I

and lost packets. The ratio between successful and lost packets, in combination with the mapping to Figure 2 leads to the current C/I.
At the Chair of Communication Networks a simulator was built to simulate IEEE 802.11a/e together with HiperLAN/2 for coexisting questions.

Data rate (Mbit/s)	Modulation	Coding rate (R)	Data Bits per Symbol
6	BPSK	1/2	24
9	BPSK	3/4	36
12	QPSK	1/2	48
18	QPSK	3/4	72
24	16-QAM	1/2	96
36	16-QAM	3/4	144
48	64-QAM	2/3	192
54	64-QAM	3/4	216

Table 1: Mode Dependent Parameters

3 IEEE 802.11a Link Adaptation

The link adaptation functionality has not been standardized by the IEEE group. Each vendor can chose detailed implementation by itself. This section describes our proposed link adaptation in detail. It has been developed to meet the special requirements of Ad Hoc Networks.

To understand how routing protocols profit from LA information, it is important to understand how the LA works. The LA is based on counting the number of successfully transmitted and lost packets within a certain number of packets. This certain numbers of packets are referred as packet windows (PW). To keep the LA reaction fast and tolerant to short term failure, three different PWs have been defined. Figure 3 shows the working principles of the developed LA. For each receiver the link is adapted separately, the LA for each link contains three windows and an expiration timer.
The windows are labelled with short (PW_s), medium (PW_m) and long packet window (PW_l). The error ratio in each packet window is calculated separately (ER_s, ER_m, ER_s).
For each new receiver, the LA must start in a special initialization state (Init State) until all three windows are filled (Figure 3). At the beginning the LA has to react fast to avoid expiration of the IEEE 802.11 retry counters [2].

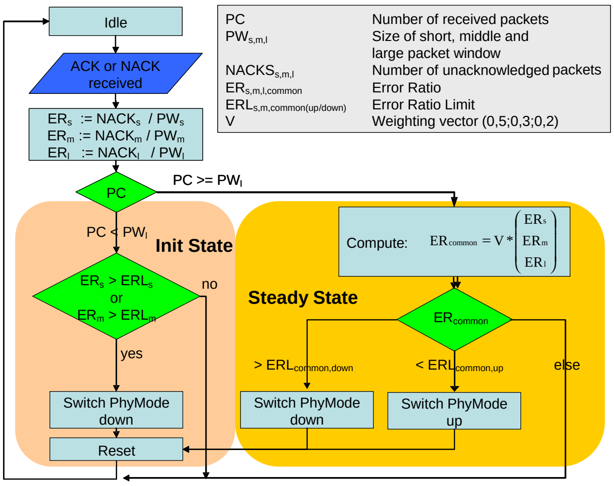

Figure 3: Link Adaptation Working Principle

Thus the first packets are transmitted using a predetermined PhyMode. Medium PhyModes seem to be a good start. At the initialization state the LA only evaluates the short or medium PW, if one of them is over the defined error ratio limit ($ERL_{s,m}$) the LA decreases the PhyMode. The initialization phase is finished after PW_l is filled and the LA has reached its steady state. At ready state the error ratio within each packet window is calculated and all three ERs are weighted (weighting vector V) and summed up to ER_{common}. As the error ratio increases and the ER_{common} reaches a lower limit ($ERL_{common,down}$), the LA decrements the PhyMode and vice versa when the upper limit ($ERL_{common,up}$) is reached the PhyMod is incremented.

To prevent using stale information each LA instance is associated with an expiration timer for the stored information. Timer expiration means, that the connection was idle for a certain time period. The Timer expiration causes the LA instance to reset this link adaptation process back to the initialization phase.

4 Link-Layer-Information for the Ad Hoc Routing

Link Adaptation information could improve the ad hoc routing performance. The information about the chosen PhyModes in the past and in the present makes it capable to predict the near future of the link. Figure 4 presents a simple scenario used to simulate the channel usage shown in Figure 5. The Scenario consists of 40 nodes and 3 Routes. The traffic load is 100 kbit/s per route. Random-Way-Point (RWP) Mobility [4] is used for all nodes except source and destination nodes. This will ensure multi-hop connections. Figure 5 presents all successful packets sent by node 3, source of the first route. As already mentioned node 3 as source node of route 1 is fixed.. Hence several route breakages occur. Please note, Figure 5 shows the view from node 3 regarding the first route only. Thus only link breaks in the direct neighbourhood of node 3 are recorded on the link layer. Breakages also occur on every link along the whole route. Each link breakage results in a new route discovery process and in a new next hop for node 3.

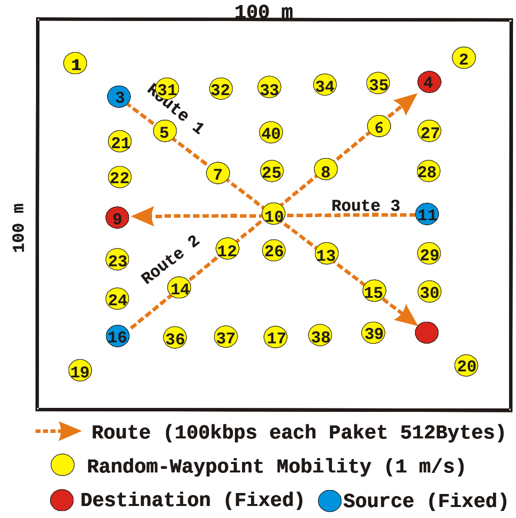

Figure 4: Ad Hoc Example

We emphasis three particular points in Figure 5 that symbolizes a typical LA behavior before a link failure. Breakages between node 3 and the next node on the route are marked with a dash-dotted vertical line. The node speed was set equal to 1 ms/s for all moving nodes.

Figure 5 contains two levels. The upper level presents the channel view from 650 to 1350 seconds and shows how the LA works. The LA switches several times to higher PhyModes when the link conditions improve and vice versa when the conditions are decreasing.

Three typical situations are highlighted (grey block) in Figure 5 and presented in detail below. The subplot at the lower left corner presents the typical channel pattern that can be observed in advance of a link breakage. The second subplot, highlighting second 1000 to 1040 presents a somehow interfered pattern, although the pattern could be still found. The third subplot on the right side shows the pattern in advance of a link break as well. In addition, the third subplot presents one of the problems that we have to deal with. The first part of the third subplot presents a pattern as a breakage is coming, although no break occurs. Contrary the LA increases the PhyModes again. This could be observed several times and depends on the used mobility model. For instances, with RWP mobility the node moves away, reaches its drawn point and returns, on his way back it might come closer again but then the node disappears. The described movement result in the LA pattern shown in the right subplot.

All three subplots show that if the node departs from its communication partner the link quality decreases. The LA adapts whenever necessary the PhyMode to avoid a connection interruption. Due to this behaviour we are able to predict the link breakage. Continuous decreasing of the PhyMode is a hint for the network layer that the link may break soon. This information triggers a routing instance to change and to adapt the route for the actual situation. Being able to predict a link breakage has a large benefit. The usual routing protocols can only react after the link is broken, while with LA information they can act before the breakage occurs.

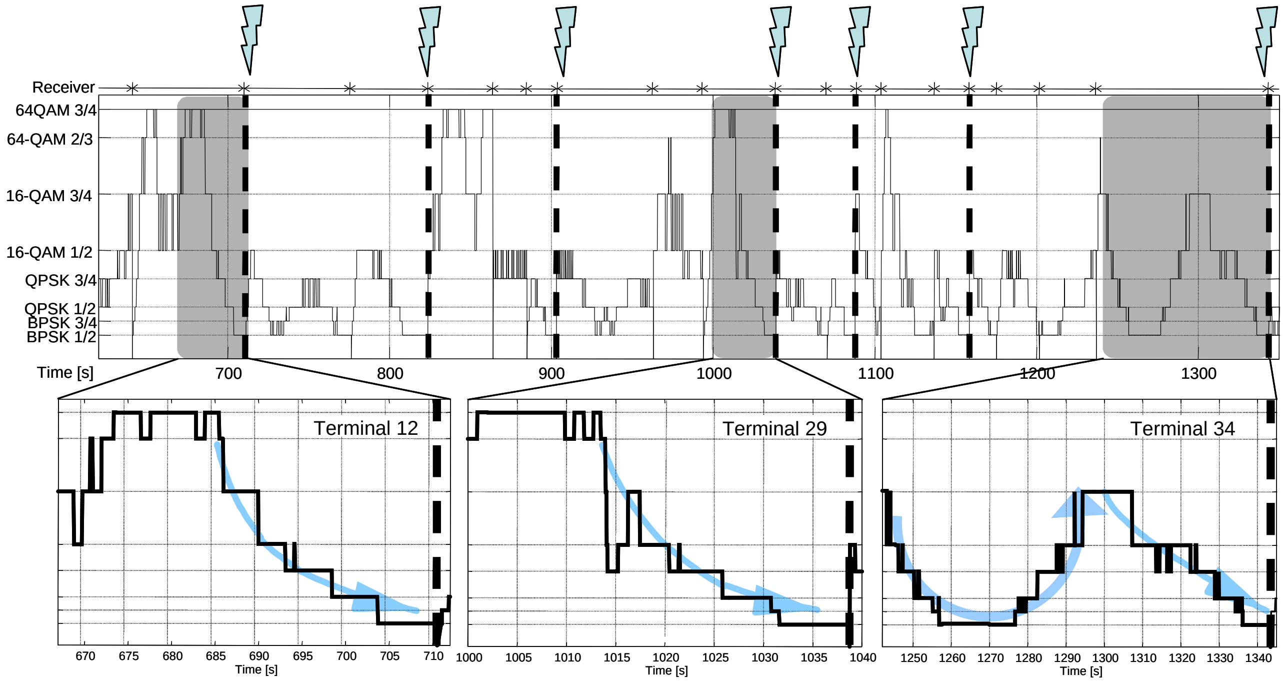

Figure 5: PhyMode dependent Channel Monitoring for Multihop Ad-Hoc Networks

Above we show a channel dump presenting three examples of a particular LA behavior resulting in a downstair pattern. The next step is to evaluate the relation between this "downstair pattern" and a route breakage. Therefore we define a weighting vector that weights the importance of a PhyMode step related to the breakage (cf. Figure 6) as changing from BPSK ¾ to BPSK ½ (weight 7) is more important for the breakage prediction than a switching from 64 QAM ½ to 16 QAM ¾ (weight 2).

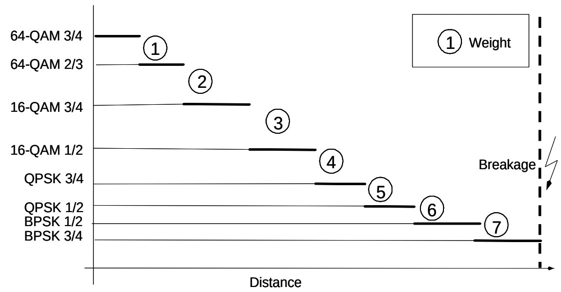

Figure 6: Weighting Steps

We add up all switch steps within certain time period. Switching down is valued as negative and up as positive. Whenever a breakage occurs, we sum-up the weighted switch steps in a certain time before the link breakage. The result will be evaluated, describing the clearness and speed of the "downstair-pattern".

Figure 7 presents a histogram for the correlation between "downstair patterns". The presented distribution shows clearly the coherence between "downstair pattern" and link breakage. Seven different windows sizes have been used to totalize the LA switching in advance to the link break.

First of all we can clearly identify that most breakages occur after the LA has decreased the PhyModes because the most links break with a negative sum and only few with a positive value. Positive values indicate that the breakage occurred after the PhyMode has been increased. Therefore Figure 7 proves the assumption that a breakage prediction is feasible when looking for LA "downstair pattern".

Furthermore Figure 7 gives a good overview about the window size influence. Summations in small windows more often result in zero, the window is chosen to small, and contains only one PhyMode. On the other side large windows are resulting with an higher probability in positive summations because the PW contains not only the 'downstair pattern', but also a 'upstairs pattern'.

The presented approach to weigh the LA steps and to sum up the weightings within a certain period is a very simple method. It confirms the assumption that a prediction is possible. More complex approaches can be used to raise the link breakage detection rate. We have proved that a breakage prediction is feasible, and future publications will show the accurateness.

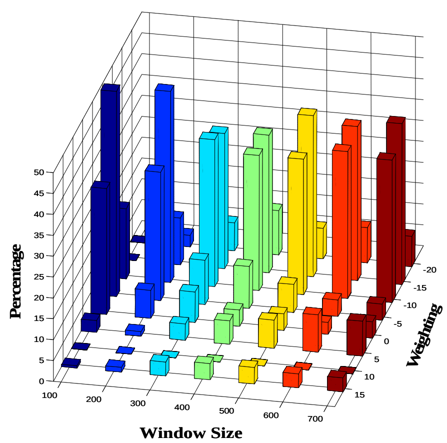

Figure 7: Histogram showing the sum-up results of different window sizes, representing the percentage of predictable link breakages

In additional to the LA information, information about the number of retransmissions is available and able to further increase the detection rate. The prediction is not only feasible at the sending node, but at the receiving node as well.

4.1 Proper Actions for upcoming Link Break

Assuming that the Link Adaptation delivers the necessary information about the link state characteristics, this information triggers appropriate actions, either to rescue the link and prevent the expensive route rediscovery or to guarantee a required link quality by finding a new route. Several proper actions are conceivable.

Here we present one of them. The node that monitors the incoming and outgoing links knows if one of them, none of them or both are being adapted. This enables the node to distinguish three different cases.

1) The node recognizes that the outgoing link is adapting the transmission mode but the incoming link is stable. Thus, the next node on the route seems to move.

2) The node recognizes that the incoming as well as the outgoing links are adapting the transmission modes. Hence, the node itself seems to move.

3) The incoming link is adapting to changes but the outgoing link remains constant. Therefore, the previous node on the route seems to move.

In the scenario depicted in Figure 8 all three cases could be found. Node 2 experiences case 1, node 3 experiences case 2 and node 4 experiences case 3. Due to the observed changes one node starts the route maintenance procedure.

Early Route Update (ERU)

This section presents an approach that uses the existing link across the upcoming link break. Thus, according to the link layer information the nodes are able to figure out the upcoming link break but the upstream node (node 2) can still communicate with the downstream node (node 4) behind the expected interruption. Additionally we assume that the lower layers are permanently sensing the channel. Therefore, each node has an up-to-date list of its neighbourhood. This feature assists the routing.

However, neighbour discovery messages are also useable. Figure 8 shows the fundamental steps of the Early Route Update approach. Node 2 monitors its link to node 3. Node 2 notices that the PhyMode for this link is decreasing. Therefore, node 2 expects an interruption and requests a route update by adding an ERU_PATCH_INFO message to a regular data packet[i] for the destination (node 7). The ERU_PATCH_INFO message contains the neighbour table from node 2, a breakage hop counter (BHC) field set to 1, a unique sequence number identifying the route and the ERU initiator. Node 3 also observes the changing link condition; it receives the piggybacked ERU_PATCH_INFO from node 2. Within its routing layer, node 2 monitors the incoming and outgoing link as well.

At this point, node 3 determines whether it should forward the information or if it receives the information. This decision is based on the behaviour of its outgoing link. For example, in Figure 8 the link from node 3 to 4 is also decreasing the modes. Therefore, node 3 forwards the neighbour table to node 4 and increments the BHC field by one. Node 4 separates the neighbour table from the data packet and broadcasts a ERU_REQ message with the TTL set to two according to the BHC. If node 4 would also move rapidly it would increment the BHC and forward the ERU_PATCH_INFO to the next downstream node (node 5). However, in Figure 8, finally, node 4 broadcasts the ERU_REQ message with a chosen TTL of two and containing the neighbour table from node 2.

When a node receives the ERU_REQ message and knows one of the neighbour nodes, the initiator node or the source node (cf. Figure 8, node 8), it replies with an ERU_REP towards this node (cf. Figure 8, note 9 forwards the ERU_REP to node 2). This ERU_REP together with the broadcasted ERU_REQ creates the alternative path. When node 2 receives the ERU_REP from one of its neighbours, an alternative reverse path [3] is built.Depending on the alternative route hop count (AHC) and the conditions for the old link, the node may confirm the reverse path by using it. The AHC always counts the distance to the destination. Using the reverse path builds the forward path and rearranges the route. Note that the maximum hop count for the alternative route is the number of node with decreasing links (here node 3) along the route, as well as node 2 (Figure 8; maximum hop count is four).When the hop count has changed the initiator node has to inform the source node using an ERU_INFO message containing the new hop count. The ERU approach gives the opportunity to check the length of the upcoming link break, thereupon the TTL for the alternative route search (ERU_REQ) is set accordingly to the BHC. Due to sending the ERU_REQ attached to a normal packet, the signalling overhead is further minimized. In addition, the TTL calculation for the locally broadcasted ERU_REQ depends on the breakage size. Hence, only the absolute minimum numbers of broadcasts are initiated. This increases the routing protocol performance. As the signalling packets can be reduced, most of route breakages can be avoided, thus the delay is minimised. Finally, the network capacity can be used more efficiently using routing protocols with link prediction and ERU.

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[i] To limit the overhead the message is piggybacked, hence this is only feasible when the data packet plus neighbour table size is smaller or equal to the max PDU size (IEEE 802.11 2304 bytes)

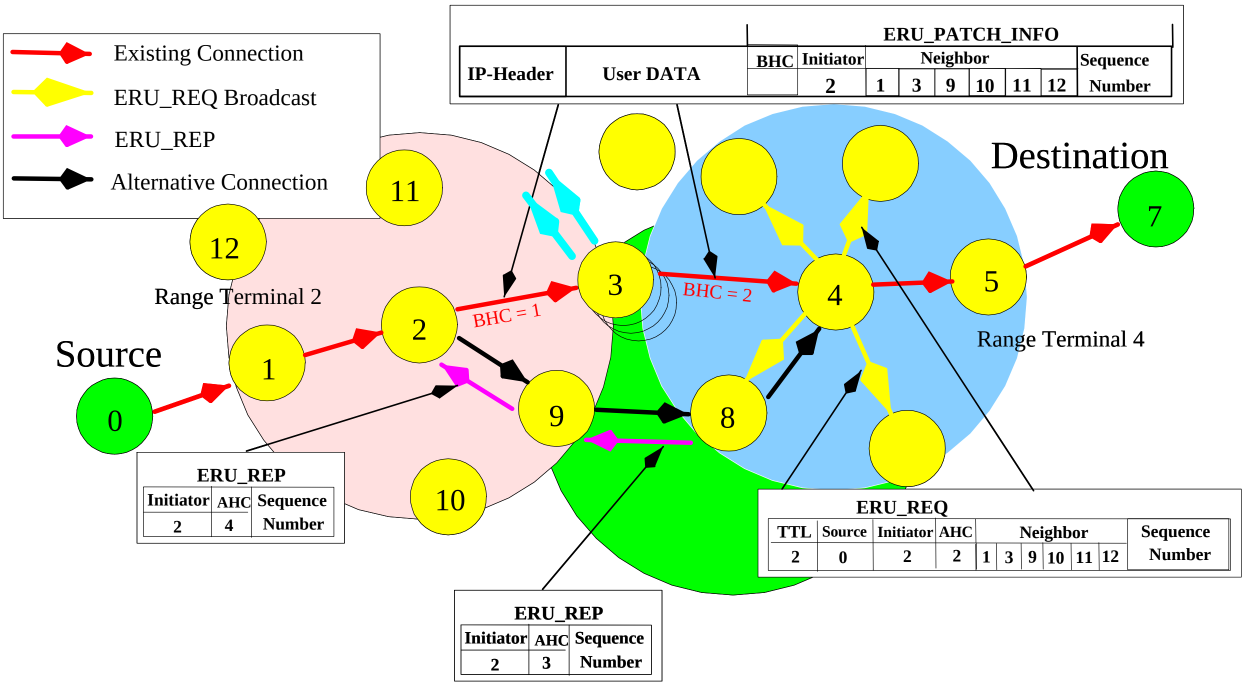

Figure 8: Early Route Update (ERU)

5 Conclusion

This paper shows how ad hoc routing profits from methods by adapting the transmission modes. The LA and their behaviour contain information, which are essential for the network layer. We propose the information exchange between LA and network layer. Based on this information the network layer is able to predict the link state and to initiate the proper actions to prevent the link break or to optimize the route.

The presented approach limits the necessary signalling overhead to maintain a route to a minimum. Through avoiding link breaks both of the number of lost packets and the packet delay decreases. Using the link prediction unnecessary network flooding is avoided. Hence, network capacity could be used more efficiently with link prediction.

We have shown that predicting link breaks is feasible. But the actual aim is behind the pure breakage prediction, situation where a single hop consumes an over proportional part of the bandwidth should be avoided. Using low data rate, e.g. BPSK resulting in an inefficient route is such an situation and further work will focus on the discovery and maintenance of efficient route in terms of bandwidth and date rate.

6 Acknowledgement

This work was supported by T-Systems under the German research project “IPonAir”, partly funded by the German Ministry for Education and Research (BMBF). The authors would like to thank the members of the project for the valuable discussion.

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