AN OPPORTUNISTIC CROSS-LAYER PROTOCOL FOR MULTI-CHANNEL WIRELESS NETWORKS

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ABSTRACT

In this paper, we propose a new multi-hop forwarding scheme for wireless multi-hop networks, denoted Multi-Channel Extremely Opportunistic Routing (MCExOR), that efficiently exploits radio channel characteristics and makes use of multiple RF channels. MCExOR reduces the overall number of transmissions in wireless multi-hop networks by opportunistically skipping nodes in a packet's forwarding path. The use of multiple non overlapping RF channels contributes to the reduction of overall interference. In contrast to other approaches MCExOR only needs one RF transceiver per device. We present algorithms for route discovery and packet forwarding. In contrast to other multi-channel protocols the packet forwarding is decoupled from route discovery. Therefore, both protocols have low complexity and can be addressed separately. With the help of simulations we show that MCExOR significantly outperforms traditional protocols like AODV through the simultaneous use of multiple RF channels and its opportunistic behaviour. With the increasing number of RF channels the overall throughput increases superproportionally. MCExOR with 2 RF channels surpasses AODV by an average of 140%. Unlike other multi channel approaches even a single packet flow can benefit from the existence of multiple channels.

I. INTRODUCTION

Wireless multi-hop mesh networks play an increasingly important role as backbones for sensor networks and as community networks that provide Internet access. One of their biggest challenges is the insufficient scalability with increasing number of nodes and users [1]. An important reason for this is the fact that wireless network nodes in close proximity interfere with each other because they share the same medium. IEEE 802.11 provides several non overlapping RF channels. If multiple channels are used within one region multiple transmissions can take place simultaneously. Although routing protocols that use multiple channels have been studied before [2,3], they are not applicable in most 'real' IEEE 802.11 multi-hop deployments because they require nodes with more than one transceiver. Most 802.11 devices are equipped with only one transceiver. This leads to the problem that nodes which operate on different channels cannot communicate with each other. Nevertheless, devices with just one transceiver can still make use of multiple channels by quickly switching to the channel of the intended receiver. Today's hardware is capable of switching the RF channel within a fixed delay of 80 μs [2].

The main contributions of this paper include: (1) route discovery algorithms for a (multi-channel) opportunistic routing protocol, (2) a forwarding scheme realized by a compressed slotted acknowledgment for an 802.11 like MAC, (3) a multi-channel solution which solves 'deafness' for single RF transceiver devices.

II. RELATED WORK

Many routing protocols are known today which were developed particularly for multi-hop mesh networks. For example, AODV [4], as well as protocols especially designed for wireless mesh networks like Extremely Opportunistic Routing (ExOR) [5]. Recently, new protocols for the use of multiple RF channels like multi-channel routing protocol (MCRP) [3] were introduced. In this section we present the idea on which MCExOR is based – an opportunistic routing protocol that utilizes multiple RF channels in wireless multi-hop networks.

A. *Extremely Opportunistic Routing*

A new and interesting communication idea for wireless multi-hop networks that inherently respects radio channel aspects is the notion of multi-user diversity (MD) [6]. The idea here is to communicate with "good" users (nodes) by exploiting wireless channel variations and selecting the "best" users (nodes). The diversity idea, through user data broadcasting, was further improved by ExOR [5]. While most wireless network models use wire-like point-to-point links that try to mask the fact that wireless transmissions are broadcasts by nature, ExOR uses this fact to its advantage. All packet transmissions can potentially be received by every remote node. This brings up the opportunity that a packet might skip a few nodes on its forwarding path if current radio propagation conditions are favourable. In contrast to traditional protocols ExOR uses multiple potential nodes, the so-called 'candidate set', for the next hop towards the destination. Candidate nodes acknowledge the successful reception of a packet in a prioritized manner, i.e. a candidate with higher priority sends its acknowledgement before any lower prioritized candidate. Among all nodes of a candidate set that successfully received a packet, the node with the highest priority will forward the packet.

B. *Multiple Channel Routing*

Using multiple RF channels in a wireless network requires new algorithms for channel assignment and management. From [3] we know at least two approaches: In the first approach, channels are assigned to nodes independently of packet flows. A node along a path only needs to know the next node towards the destination as well as the channel this node is operating on, its so-called home channel. However, nodes operating on different channels create a new problem: 'deafness' [7]. Deafness occurs if two nodes cannot

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communicate with each other because they operate on different channels. Deafness is the main reason why MCRP uses a second approach to channel assignment and management: channels are assigned to flows. After the successful establishment of a route from the source to the destination all nodes along this route have to be assigned the same channel as long as the flow exists. However, assigning channels to flows has a significant disadvantage: The available capacity along a path is substantially reduced by self-interference [8,1,9]. Therefore, we will focus on the assignment of channels to nodes independent of packet flows and independent of the routing function.

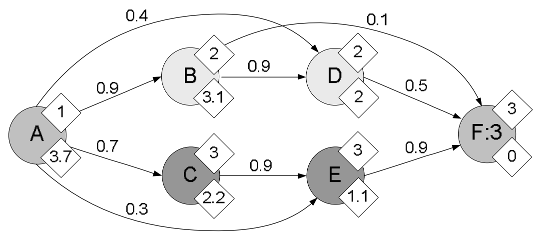


Figure 1: Example network with link delivery probabilities shown along the edges; home channels indicated by the number in the upper right corner and the estimated transmission count to node F from each node of the graph indicated by the number in the lower right corner.

III. MCExOR

MCExOR extends ExOR by utilizing multiple RF channels. It improves the network performance by choosing the RF channel with the most promising candidate set for every transmission. In contrast to other multi-channel protocols like MCRP, packet forwarding is decoupled from route discovery. In this section we will focus on the route discovery algorithms used by MCExOR. Finally, we illustrate the modifications to the 802.11 MAC layer. A detailed description of packet forwarding is omitted due to space limitations [10].

A. *RF Channel Assignment*

In MCExOR the channel assignment for nodes is decoupled from the routing protocol. MCExOR merely needs the information about a node's assigned home channel to construct a candidate set. Therefore each node announces its home channel to its neighbours. Data packets are sent on the home channel of the receiving node. Hence, MCExOR is not restricted to a particular channel assignment scheme and the approaches that follow are just examples. One such approach, the random strategy, assigns channels to nodes in a random fashion. In an alternative strategy, a node chooses its channel based on the decision of its neighbours. It selects the least utilized channel in order to minimize the influence of neighbouring nodes. Furthermore, the observed link quality of a channel could be taken into account [11].

B. *Local Neighbour Discovery*

Nodes discover neighbours through link probe packets. Every node periodically broadcasts link probes and neighbouring nodes receive them. The link delivery probability is calculated similar to ETX [12], except that links are considered unidirectional. Within a link probe packet the calculated delivery probabilities of all neighbors are locally distributed so that every node knows the adjacent nodes and corresponding delivery probabilities within the hop count distance of 2. Furthermore, MCExOR is a multi-channel protocol. Adjacent nodes do not necessarily operate on the same RF channel. For this reason consecutive link probes are broadcasted on different channels in a round robin manner.

C. *Route Discovery*

MCExOR offers two different route discovery algorithms: proactive and reactive. Proactive route discovery results in knowledge about the global network topology. However, it does not scale with the number of nodes in the network. It is also not applicable in highly dynamic networks where routes change frequently. Here, reactive route discovery is used instead. The overhead of reactive route discovery is low compared to that of proactive algorithms. However, a node only knows a subset of the network topology. For traditional routing protocols like DSR [13] this is not a problem, but as we will see this is a problem for opportunistic protocols (D.1).

1) *Reactive Route Discovery*

Reactive route discovery algorithms work 'on-demand'. The difference to single channel protocols is that route requests (RREQ) are sent via multi channel broadcast. This is necessary because network nodes can operate on different RF channels. During a multi channel broadcast, a node emits a RREQ not only on one channel, but on all available channels[1]. Thereafter it quickly returns to its home channel. The following example illustrates the route discovery process (Figure 1). For a packet transmission from A to F, A starts a route discovery with the creation of a route request: A creates a RREQ packet and adds itself together with its home channel (1) in the packet's routing header. Then A performs a multi channel broadcast and switches back to its home channel. On receiving a RREQ a node adds its address together with its home channel to the packet's header and multi-channel broadcasts the packet further. In our example, node F will eventually receive the RREQ on channel 3 and reply with a RREP packet. In contrast to traditional reactive protocols the RREP is opportunistically forwarded back to the originator of the RREQ (Section D). This is important since otherwise a simple source routed packet could encounter a 'deaf' node, leading to cascading route discoveries (Section D.1).

2) *Proactive Route Discovery*

Basically, the proactive version of the MCExOR route discovery algorithm can be understood as the natural extension of the local neighbor discovery algorithm (Section B). The algorithm works as follows: Each node periodically broadcasts discovery packets containing its home channel as well as the link delivery probabilities to its neighbours. On receiving such a packet each node stores the home channel of

[1] If a node has neighbors operating only on a small fraction of available channels a broadcast on all channels is unnecessary. Instead, the broadcast should only consider channels used by neighboring nodes.

the node initiating the discovery, updates its link table and forwards this packet via broadcast on all available RF channels. Eventually this discovery packet will be received by each node in the network (flooding).

D. Candidate Selection and Packet Forwarding

Within this section, we shortly address the problem of route selection and packet forwarding. The main idea of MCExOR as well as ExOR is to use a set of forwarding candidates instead of only a single forwarder. Especially in dense networks it is possible to construct many different candidate sets. The algorithm for the construction of a candidate set is similar to the one used by ExOR. Unlike ExOR, in MCExOR we have to construct a candidate set per channel. Our algorithm works as follows: At first the cumulated expected transmission count (ETX) for the current node and each neighbour node towards the destination is calculated. Only neighbours with a better metric than the current node are further considered. Thereafter the candidates are grouped according to their home channels. The optimal candidate set cannot be calculated efficiently. Therefore we propose a heuristics which considers only the first hop as opportunistic. For the remaining hops the traditional ETX metrics is used. The metric of a candidate set is the sum of the ETX values of each contained candidate weighted according to the probability that the candidate successfully receives the packet. The detailed description can be found in [10].

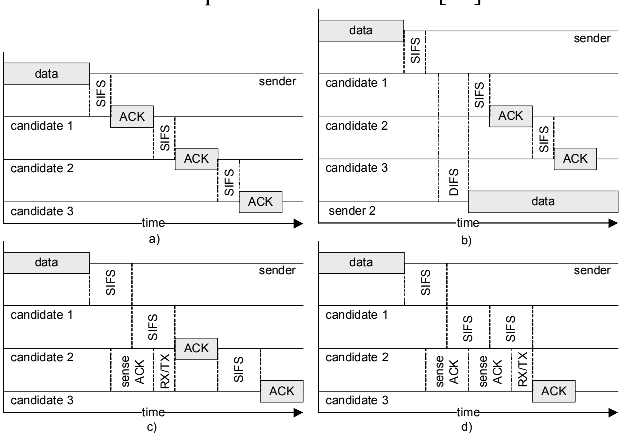


Figure 2: a) Slotted acknowledgement with three candidates. b) Slotted acknowledgement with the first ACK missing. Subsequent ACKs collide with a data transmission started within the delay of the missing ACK. c) Compressed slotted acknowledgement with first ACK missing. d) Compressed slotted acknowledgement with first and second ACK missing.

1) Opportunistic Routing with Fallback-Route

As described in Section C we can freely choose between proactive and reactive route discovery. In case of the reactive route discovery we have to make some further restrictions on the selection of forwarding candidates. This is required to avoid cascading route discoveries due to the properties of opportunistic forwarding. For example, it is not always possible to send a RREP along the inverted route of the associated RREQ due to the existence of asymmetric links. Furthermore it is very likely that an opportunistically transmitted data packet will be received by a forwarding node which has not a valid route to the destination. In both cases an additional route discovery would reduce the overall performance of the network. That's why an additional restriction on the selection of a forwarder has to be made when the reactive route discovery algorithm is used: Each node in the candidate set has at least one neighbour which is listed in the fallback route with a better ETX metric towards the destination than the current node. This restriction together with the information obtained from the fallback route and the local neighbour discovery algorithm (Section B) guarantees that each forwarder is able to calculate the next forwarder without possibly initiating a new route discovery process.

2) Compressed Slotted ACK

MCExOR uses a modified version of slotted acknowledgements (SLACK) [5] to determine which candidate forwards the packet. The packet transmission starts with a channel switch, if necessary. Within this period, the node is deaf. The sender transmits the data packet after contending for medium access. The highest prioritized candidate sends the first ACK with a delay of *SIFS* after packet reception. The other candidates send their ACK in order of decreasing priorities, each separated by *SIFS*. The next forwarder is determined using an additional field in the ACK packet which contains the identification of the highest prioritized candidate which successfully received the packet. A slotted acknowledgement with 3 candidates is depicted in Figure 2a. SLACK works well with simple propagation models, but in more realistic settings like shadowing a serious problem arises. If a candidate misses the data packet and does not send an ACK the medium is idle for more than DIFS. Therefore other nodes contending for medium access start their transmissions within the acknowledgement process (Figure 2b). We address this problem by refining the mechanism presented in [5] to a compressed slotted acknowledgement (CSLACK). If a candidate detects that an ACK from a higher prioritized candidate is missing, it prematurely sends its ACK. This way spaces where the medium is idle are kept smaller than *DIFS* (for a candidate set of a fixed size), as could be seen in Figure 2c and Figure 2d. In order to prevent collisions between ACK packets, the points in time when a candidate prematurely sends its ACK are ordered by decreasing priority. A detailed description of CSLACK could be found in [10].

IV. SIMULATION

We implemented a prototype of MCExOR using the JiST/SWANS [14] wireless network simulator. Therefore we extended the simulator by a more realistic radio propagation model (shadowing [15]). Furthermore, we realized a simple multi-channel radio without cross-channel interference. The radio is extended by a fixed number of RF channels. Switching from one channel to another is possible within a fixed delay. Within this period of time the radio is not able to process any packets, hence the node is deaf.

The simulation scenario consists of a grid of nodes. Within a field with a fixed dimension the nodes were placed using a fixed density. The RF channels were uniformly assigned to all nodes. We used a simple communication model for our simulations with a constant number of traffic flows. The source and destination of a flow are placed on the left and right borders of the grid. The flows are uniformly distributed in the horizontal dimension of the grid. Moreover, we used constant bit-rate UDP traffic with packet sizes of 1400 bytes and all reported results are averages over multiple simulation runs.

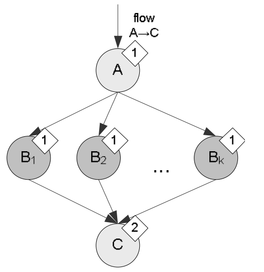


Figure 3: Network with one packet flow from node A to C with the help of the forwarding nodes ($B_{1..k}$).

A. Results and Discussion

Multi-channel protocols known so far benefit from the multi-channel advantage at the expense of highly increased complexity. Because no adequate implementation for those protocols is available we focused on the comparison with well-known protocols like AODV and ExOR. In the following sections we show how MCExOR handles deafness and the impact of multiple channels on the latency of route discovery. Finally, we compare the throughput of MCExOR with AODV and ExOR.

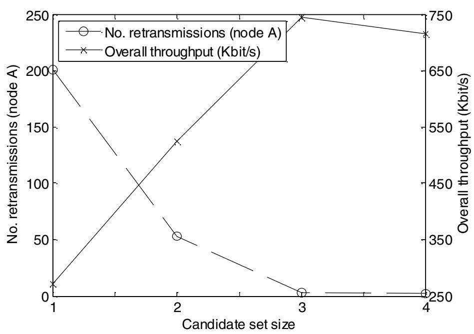


Figure 4: Diagram shows the impact of candidate set size on the throughput of the packet flow of the network in Figure 3.

1) Deafness

MCExOR uses for the next hop a set of forwarding nodes with the same home channel. However, at the time of receiving a packet it is possible that some of these nodes have changed to another channel and are unable to receive the packet. This problem is handled in the following way. Instead of choosing only one next hop, MCExOR selects a set of potential forwarding candidates (next hops) to reduce 'deafness'. This means that the use of multiple candidates does not only increase the single channel performance (the *opportunistic advantage*) but also contributes to overcome the deafness problem. Consider the example from Figure 3. There is a packet flow from node A to C with the help of the forwarding nodes ($B_{1..k}$). The first hop (A to $B_{1..k}$) is on channel 1, whereas the last hop ($B_{1..k}$ to C) is on channel 2. Therefore each forwarding node ($B_{1..k}$) has to switch from channel 1 to 2 in order to transmit the packet to node C. During the transmission on channel 2 each forwarding node is 'deaf'. The idea behind MCExOR is that is very unlikely that all nodes in the candidate set are 'deaf' at the same time. The impact of the candidate set size on the overall throughput is depicted in Figure 4. With increasing number of candidates the throughput of the flow increases. It seems that at least 3 candidates are required to overcome 'deafness'. Additional candidates do not further increase the performance. Furthermore, the number of retransmissions at node A decreases. Finally, an increased channel switching delay (> 80 µs) does not significantly reduce the observed throughput.

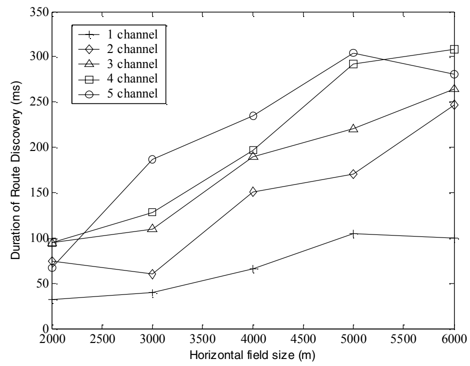


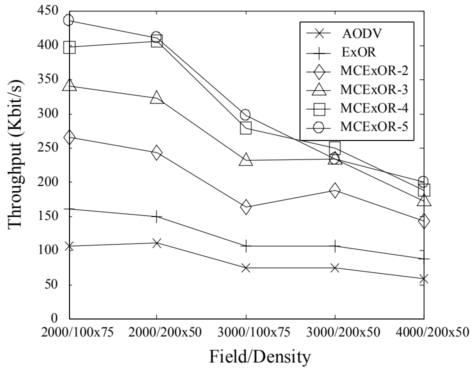
Figure 5: Delay in the reactive route discovery due to the support of multiple channels (example network with constant vertical field size of 200m).

2) Latency due to Reactive Route Discovery

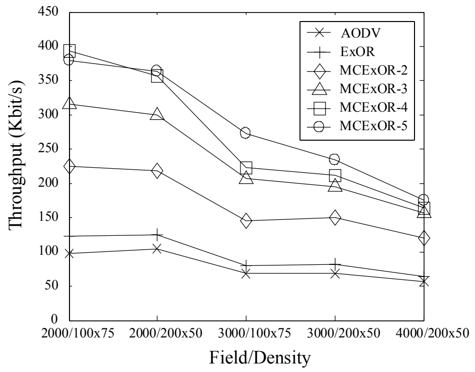
In section III.C.1) we described the reactive route discovery algorithm used by the reactive version of MCExOR. The problem was that due to the multi channel feature there is a noticeable delay in the route discovery. Figure 5 presents the latency in the route discovery in regard to the number of channels used. With the increase of the number of channels the delay also increases. However the delay per channel does not increase with the number of channels.

3) Throughput of AODV, ExOR, and MCExOR

The throughputs of AODV, ExOR, and MCExOR are displayed in Figure 6. The simulation took place on regular grids with the horizontal dimension of 2000m, 3000m and 4000m, a constant vertical dimension of 300m and different field densities. Furthermore, the proactive route discovery was used. Figure 6a shows the achieved throughput for AODV, ExOR and MCExOR for a single flow. ExOR outperforms AODV, but the gain is not as high as expected. These observations were confirmed in [16]. In turn, MCExOR with 2 RF channels outperforms ExOR by an average of 64%. The most interesting point is that MCExOR with 2 channels surpasses AODV by an average of 140% – doubling the number of channels results in more than doubling of the observed throughput. From the practical point of view the case with 3 channels is of interest since IEEE 802.11b/g only offers 3 non-overlapping channels. In this case MCExOR outperforms AODV by 210%. Finally, MCExOR also performs very well with an increasing number of simultaneous flows.

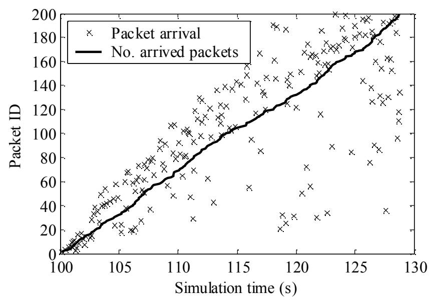


(a) 1 flow

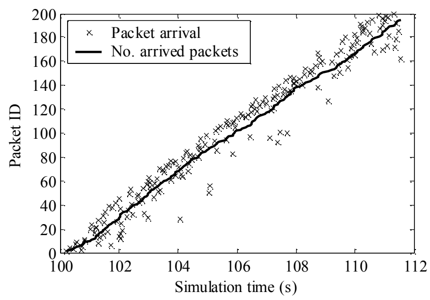


(b) 4 flows

Figure 6: AODV, ExOR and 4 versions of MCExOR with 2, 3, 4 and 5 RF channels and (a) 1 flow and (b) 4 flows.



(a) ExOR



(b) MCExOR with 3 channels

Figure 7: Packet arrival time and number of arrived packets for ExOR (a) and MCExOR with 3 RF channels (b).

4) Packet Ordering

Opposite to AODV, ExOR as well as MCExOR use multiple routing paths towards a destination. The ordering in which packets are sent is not necessarily the same in which they arrive. Figure 7 illustrates the ordering in which packets arrive at the destination for an example network. The problem of ExOR and MCExOR is packet reordering which could lead to problems with TCP/IP. However, with MCExOR the variation of the packet arrival time is smaller than in ExOR.

V. CONCLUSIONS

We introduced the route discovery and the forwarding scheme of the MCExOR protocol which enables devices with only one transceiver to operate on multiple channels. The simulation results show that MCExOR significantly outperforms AODV by the simultaneous use of multiple RF channels. With the increasing number of RF channels the observed overall throughput super-proportionally increases. In contrast to other multi-channel approaches MCExOR assigns channels to nodes and not to flows. Hence, a single flow can benefit from the existence of multiple channels.

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