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Abstract. We propose and investigate Multi-Channel Extremely Opportunistic Routing (MCExOR) which is a protocol that extends Extremely Opportunistic Routing by utilizing multiple RF channels in multi-hop wireless networks. Large numbers of transmissions per end-to-end delivery combined with interference are the main reasons for the low capacity of wireless multi-hop networks. 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 an algorithm for packet forwarding and show with the help of simulations that MCExOR outperforms traditional protocols like ad-hoc on-demand distance vector routing through the simultaneous use of multiple RF channels. In combination with realistic radio propagation models a further increase in the throughput is observed due to the opportunistic feature of MCExOR. 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. Finally, MCExOR is more robust than traditional protocols since it offers a higher end-to-end packet delivery.

Keywords: Algorithms, Computer networks, Communication system routing, Wireless LAN.

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1. Introduction

Wireless multi-hop mesh networks play an increasingly important role as backbones for sensor networks and as community networks that provide Internet access in urban areas [7]. Nevertheless, one of their biggest challenges is the insufficient scalability with increasing number of nodes and users [1]. The most important reason for this phenomenon can be found in the structure of a multi-hop network: a node is responsible not only for the transmission of its own data, but also for forwarding packets of other nodes. No less significant 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 without interference resulting in a positive impact on overall network throughput. Although routing protocols that use multiple channels have been studied before [4][6], they are not applicable in most 'real' IEEE 802.11 multi-hop installations 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 IEEE 802.11 hardware is capable of switching the RF channel within a fixed delay of 80 µs [4]. Extremely Opportunistic Routing (ExOR) is a promising approach for improving the throughput of wireless multi-hop networks [2]. 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, with a certain non-zero probability. This brings up the opportunity that a packet might skip a few nodes on its forwarding path if current radio propagation conditions are favorable.

The main contributions of this paper include: (1) a high throughput forwarding scheme which incorporates the use of multiple channels and opportunistic routing in a straightforward manner, (2) a compressed slotted acknowledgment for an IEEE 802.11 like MAC, (3) a multi-channel solution which solves "deafness" for single RF transceiver devices and allows both flow and node channel assignment, (4) an efficient candidate set selection algorithm for multi-channel opportunistic forwarding.

2. Related Work

Many routing protocols are known today which were developed particularly for multi-hop mesh networks. For example, AODV [8], as well as protocols especially designed for wireless mesh networks like ExOR. Recently, new protocols for the use of multiple RF channels like multi-channel routing protocol (MCRP) [6] 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.

2.1 Extremely Opportunistic Routing

Figure 1 demonstrates the principles behind ExOR [2]. Many routes exist between node A and D. It is possible for A to transmit a packet to D directly in one hop. However, because the probability of a successful transmission from A to D is very low, a packet will likely be retransmitted multiple times. Alternatively, A can send a packet via B and C towards the final destination D. In this case, a packet must be transmitted multiple times too (multi hop), but possibly without many retransmissions. When transmitting a packet from A to B towards D, it is possible that the packet is successfully received not only by B, but also by C or even D. In this case an additional transmission of the packet from B to C is unnecessary. Instead, the node that is closest to the final destination should continue the forwarding process. Similarly, if A tries to send a packet directly to D and the transmission fails, it is likely that the packet reached B or even C. Hence, it could make sense to transmit the packet from B or C to D instead of retransmitting it from A. This mechanism was first introduced by ExOR. ExOR uses a so-called 'candidate set' which contains all nodes useful for the forwarding of the packet towards the destination.

In contrast to traditional protocols ExOR uses multiple potential nodes for the next hop. 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.

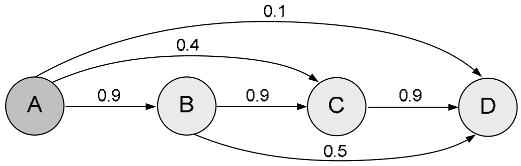


Figure 1: Network with delivery ratios (e.g. the probability of a successful transmission from node A to C is 0.4).

2.2 Multiple Channel Routing

A promising approach to increase the capacity of wireless multi-hop mesh networks is the simultaneous use of multiple RF channels for packet transmissions. With the use of multiple channels the capacity is increased even further because of the reduction of packet loses due to interference (collisions). However, this approach introduces new problems. For example, it is not possible for a node with only one RF transceiver to operate on multiple channels at the same time. Hence, we will use devices with only one transceiver that are able to switch from one channel to another within a short time. Finally, the additional expense of channel management needs to be considered. Routing protocols have to deal not only with route discovery and packet forwarding, but also with the assignment of a proper channel to each node.

2.2.1 Channel Assignment - Nodes vs. Flows

Using multiple RF channels in one wireless network requires new algorithms for channel assignment and management. From [6] 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. If this information is available the sending node can transmit packets by switching to the channel of the destination node. However, nodes operating on different channels create a new problem: ‘deafness’ [3]. Deafness occurs if two nodes cannot communicate with each other because they operate on different channels. As we will see later, this problem is less pronounced in MCExOR which uses multiple nodes (a candidate set) as potential next hop nodes. 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 [5][1][12]. If multiple packets are transferred along a path, self-interference reduces the number of simultaneously active links. If too many links are active, collisions will occur that provoke retransmissions. Therefore, we will focus on the assignment of channels to nodes independently of packet flows and independently of the routing function.

3. 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 a main advantage of MCExOR is its low complexity which is a prerequisite for a practical application. In this section we will focus on the packet forwarding algorithm of MCExOR. Finally, we illustrate the modifications to IEEE 802.11 MAC layer. Algorithms for link probing and route discovery are omitted due to space limitations [14].

3.1 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 neighbors. Data packets are sent on the home channel of the receiving node. Hence MCExOR is not restricted to a fixed channel assignment. So the following approaches are only examples. The random strategy assigns channels to nodes in a random fashion. Alternatively a node chooses its channel based on the decision of its neighbors. It selects the least utilized channel in order to minimize the influence of neighboring nodes. Furthermore, the observed link quality of a channel could be taken into account [10].

3.2 Packet Forwarding

Within this section, we address the problem of selecting a route and forwarding the packet along this path. 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. With MCExOR the additional problem of choosing a transmission channel is introduced. We subdivided the mentioned problems into two tasks. At first, candidate sets for every RF channel are constructed and finally, the most promising candidate set along with its channel is selected for transmission. Both tasks are covered in detail in the following two sections.

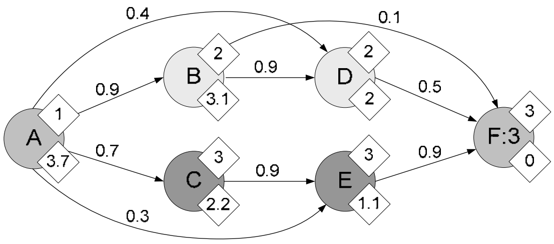


Figure 2: Network with link delivery probabilities shown along the edges; RF channels indicated by the number in the upper right corner

and the expected transmission count to node F from each node of the graph indicated by the number in the lower right corner.

3.2.1 Construction of Candidate Sets per Channel

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 [9]) for the current node and each neighbor node towards the destination is calculated. Only neighbors with a better metric than the current node are further considered. Thereafter the candidates are grouped according to their home channels. Finally the most promising candidate set together with its home channel is selected for transmission. There are two alternative algorithms which differ in their knowledge about the current network's state they use to make a decision. A detailed description of one algorithm is presented in the following section.

3.2.2 Algorithm for the Selection of a Candidate Set

In the previous section we have seen how to construct a candidate set per channel. Now we address the problem of choosing the most promising one. 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. An alternative metric for opportunistic routing is presented in [16].

For a detailed description of the algorithm we have to formulate the problem more precisely: A wireless mesh network is a collection of directed links connecting transmitters, forwarders, and receivers. Such a communication network may be represented by a directed graph $G=(V,E,f)$ with a vertex set $V=\{A_1,\ldots,A_n\}$ and an edge set $E\subseteq V\times V$. Further a non-negative number $f(e)$ is associated to each link $e\in E$, called the link delivery probability of e. Based on this graph we can define the expected transmission count $g(x,y,z)$ for traditional shortest path routing. Given a path from node x followed by node y to destination node z function g is calculated as follows:

$$g(x,y,z)=\sum_{e\in sp(x,y,z)}\frac{1}{f(e)}, \quad \text{where } x,y,z\in V,(x,y)\in E \tag{1}$$

Furthermore $sp(x,y,z)$ calculates the shortest path $(e_1,\ldots,e_n)\in E^n$ in the network from node x followed by y ($(x,y)\in e_1$) to z regarding to the link delivery probability f. In order to allow communication between two nodes in the network we define a flow c as $(u,v)\in V\times V$, where $u=source(c)$ is the source of c and $v=sink(c)$ is the sink of c. Our algorithm $chooseCs(c,w,CSS)$ calculates for a given flow $c=(u,v)$, a forwarding node w and a set of available candidate sets $CSS:P(V^n)$ the candidate set with the lowest metric towards the destination node $v=sink(c)$, where $P(V^n)$ denotes the power set of V^n:

$$chooseCs\left(c,w,CSS\right)=cs, \quad \text{where} \quad \forall cs'\in CSS: csm\left(c,w,cs'\right)\geq csm\left(c,w,cs\right) \tag{2}$$

Whereas $csm(c,w,cs)$ associates a non-negative number to each candidate set cs selected by a node w to a given flow c, called the metric of the candidate set:

$$csm\left(c,w,cs=\left(c_1,\ldots,c_n\right)\right) = \sum_{i=1}^{n} g\left(w,c_i,\mathrm{sink}(c)\right)\frac{pcs\left(w,i,cs\right)}{1-pncs\left(w,cs\right)} \tag{3}$$

Further $pcs(w,i,cs)$ calculates the probability that the i-th node in the candidate set cs will be the next forwarder when the packet is transmitted by node w, i.e. all higher prioritized candidates $c_1,\ldots,c_{i-1}$ failed to receive the packet. Furthermore $pncs(w,cs)$ is the probability that the packet was received by none of the nodes in cs:

$$pncs\left(w,cs=\left(c_1,\ldots,c_n\right)\right)=\prod_{j=1}^{n}1-f\left(w,c_j\right) \tag{4}$$

$$pcs\left(w,i,cs=\left(c_1,\ldots,c_n\right)\right)=f\left(w,c_i\right)\prod_{j=1}^{i-1}1-f\left(w,c_j\right) \tag{5}$$

Consider the network illustrated in Figure 2, where node A needs to forward a packet to node F ($c=(A,F)$). It constructs the following two candidate sets: (D,B), when channel 2 is used and (E,C), when channel 3 is used:

$$csm\left(\left(A,F\right),A,\left(D,B\right)\right) =\left(\frac{1}{0.5}+\frac{1}{0.4}\right)\frac{0.4}{0.94}+\left(\frac{1}{0.5}+\frac{1}{0.9}+\frac{1}{0.9}\right)\frac{0.54}{0.94}=4.33 \tag{6}$$

$$csm\left(\left(A,F\right),A,\left(E,C\right)\right) =\left(\frac{1}{0.3}+\frac{1}{0.9}\right)\frac{0.3}{0.79}+\left(\frac{1}{0.7}+\frac{1}{0.9}+\frac{1}{0.9}\right)\frac{0.49}{0.79}=3.95 \tag{7}$$

$$chooseCs\left(c=\left(A,F\right),w=A,CSS=\left\{\left(B,D\right),\left(E,C\right)\right\}\right) =\left(E,C\right) \tag{8}$$

Therefore node A would decide in favor of (E,C). This is true in the case of only one single RF channel, but in case of multiple channels some further work is required. The reason is that MCExOR tries to reduce self-interference. If multiple packets are transferred along a path, self-interference between these packets reduces the number of simultaneously active transmissions. That's why MCExOR tries to minimize the use of identical RF channels along a path. To achieve this not only the metric of the candidates in the candidate set is considered, but also their RF channels. Reconsider the example of Figure 2. Imagine further that the nodes A, E and C operate on the same channel 1 and that node A receives a packet from a preceding node X on its home channel. In this case (E,C) is not a good choice, since a packet will be forwarded on the same channel (here 1) twice: From node X to A on channel 1 and from node A to (E,C) on channel 1. To avoid multiple successive transmissions on the same channel, each opportunistically forwarded packet contains the RF channels of the last j hops, where j is the number of available channels. If a packet is forwarded j-times on the same channel then the observed bandwidth is smaller than B/j. The metric of a candidate set is increased by a factor of j+1 if the packet was forwarded j-times on the same channel before:

$$csm'(c, w, cs, p) = uch(p, ch(cs)) \cdot csm(c, w, cs) \tag{9}$$

A natural number *ch(cs)* is associated to each candidate set $cs \in V^n$ which represents the home channel of the candidates. Further *uch(p,i)* calculates how often the packet *p* was transmitted on channel *i* plus one. Therefore node A would calculate:

$$\begin{aligned} &csm'((A,F), A, (E,C), p) \\ &= uch(p, ch((E,C))) \cdot 3.95 = 2 \cdot 3.95 = 7.9 \end{aligned} \tag{10}$$

So it makes sense to use *(D,B)* and therefore to transmit the packet on channel 2.

Sometimes it is possible that the algorithm makes suboptimal decisions. Reconsider the original example illustrated in Figure 2. According to the algorithm we would decide in favor of *(E,C)* (3.95 < 4.33). However this is not a good decision since the home channel of *(E,C)* and the final destination (F) is 3: Packet forwarding by *(E,C)* would lead to two successive transmissions on the same channel (3). For the evaluation of different candidates the improved version of this algorithm considers not only previous hops together with the next hop but also uses a look-ahead algorithm to punish candidates which will lead to successive transmissions on the same channel [14].

3.2.3 Packet Transmission

In MCExOR a packet transmission starts with a channel switch, if necessary. Within this period, the node is deaf. After the RF hardware proceeded the channel switch, the state of the MAC is reset (back-off, collision window, retry counter, mode, etc.). The network allocation vector (NAV) is not reset because of the risk of collisions. Instead the MAC tries to adapt the NAV to the new channel through advancing the NAV by the transmission time of the maximum fragment size. So the packet is not sent until the NAV is updated. Slotted acknowledgements [2] determine which candidate forwards the packet. Every candidate sends an acknowledgement packet (ACK). The highest prioritized candidate sends the first ACK with a delay of *SIFS* after the data packet was received. The other candidates send their ACK in order of decreasing priorities, each separated by *SIFS*. A slotted acknowledgement with 3 candidates is depicted in Figure 3a. The ACK packet additionally contains an identification of the highest prioritized candidate which did successfully receive the packet. With reaching the assigned time slot the candidate sends the ACK with the previously determined forwarder. This way the ACK packets propagate in a multi-hop fashion from the highest prioritized candidate to the sender.

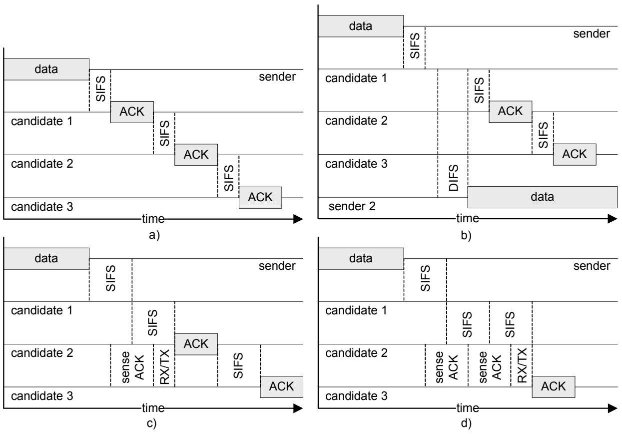


Figure 3: a) Slotted acknowledgement with three candidates. b) Slotted acknowledgement with the first ACK missing. Subsequent ACKs collide with a data transmission started within the delay of the missing ACK. c) Compressed slotted acknowledgement with first ACK missing. d) Compressed slotted acknowledgement with first and second ACK missing.

A serious problem arises with the usage of slotted acknowledgements. In the traditional IEEE 802.11 MAC an ACK is sent after a delay of *SIFS*. Since the ACK packet has a constant size the initial sender could determine whether to retransmit the packet after a fixed delay. Another node willing to transmit a packet has to sense the medium for a period of *DIFS* which is larger than *SIFS*. Thus the contention based medium access does not allow that another node starts to send a packet within the delay between data reception and ACK transmission. But using the slotted acknowledgement the mentioned problem may occur if a candidate misses the data packet and does not send an ACK. Since an ACK packet is larger than *DIFS* another node may experience an idle medium and decide to start a transmission which will collide with subsequent ACK packets. The described scenario is depicted in Figure 3b. We address this problem by refining the presented mechanism [2] to a compressed slotted acknowledgement. The main idea is the following. 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). In order to prevent collisions, the points in time when a candidate prematurely sends its ACK are ordered by decreasing priority.

The compressed slotted acknowledgement works in the following way: With a delay of *SIFS* after the data packet was received the highest prioritized candidate sends the ACK packet. From that point in time all other candidates wait for the period *P = SIFS – RX/TX* whether they ‘hear’ the recently sent ACK (The receive/transmit turnaround *RX/TX* delay occurs when the radio turns from receive to transmit mode.) Because not all candidates necessarily receive this ACK, we use signal strength as an indicator. If within the waiting period the signal strength did increase significantly, the ACK packet is considered as sent (It is not necessary that the candidate successfully receives the packet.) On the other hand if no such increase in signal strength is observable, the other candidates conclude that the highest prioritized candidate did miss the data packet. In that case, the second highest prioritized candidate starts to transmit its ACK prematurely. The radio switches from receive to transmit within delay *RX/TX*, so the ACK is sent *SIFS* after the expected ACK and *2*SIFS* after the data packet was received. Up from this point the acknowledgement process is continued like in the no-error case, except that all subsequent events happen earlier. The previously described scenario is illustrated in Figure 3c. However, it is also possible that the two highest prioritized candidates miss the data packet (Figure 3d). Finally, for a candidate set size of less than six the medium is idle for not longer than *DIFS*.

4. Simulation

We implemented a prototype of MCExOR using the JiST/SWANS [11] wireless network simulator. The following sections cover implementation details and results. Our outcomes show that MCExOR outperforms traditional protocols like AODV by the simultaneous use of multiple RF channels. In conjunction with realistic radio propagation models a further increase in the throughput is observed due to the opportunistic feature of MCExOR. With increasing number of channels the observed overall throughput superproportionally increases.

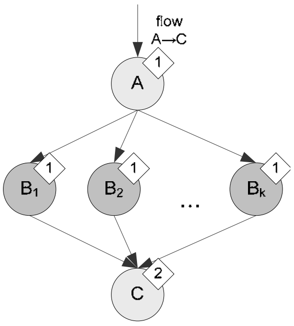


Figure 4: Network with one packet flow from node A to C demonstrates the influence of the candidate set size on the overall throughput.

4.1 Implementation Details

JiST/SWANS offers two radio propagation models: free space and two-ray ground. Both models are based on the assumption that the received signal power is a deterministic function of the node's distance. Therefore nodes within the communication range of a transmitting node always receive the packet. A more realistic propagation model is shadowing [13]. The received signal power is modeled as log-normal distributed random variable. Furthermore, JiST/SWANS does not support multiple RF channels. 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, so the node is deaf.

4.2 Methodology

The simulation scenario consists of a grid of nodes. Within a field with a fixed dimension the nodes were regularly placed using a fixed density. In case of MCExOR the radio 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. We used constant bit-rate UDP traffic with packet sizes of 1400 bytes.

4.3 Results and Discussion

Multi-channel protocols known so far benefit from the multi-channel advantage at the expense of highly increased complexity. Because an adequate implementation was not available we focused on the comparison with well-known protocols like AODV and ExOR.

In the following sections we show how MCExOR handles deafness, we compare MCExOR with AODV to show the multi-channel advantage. Finally, MCExOR outperforms AODV by utilizing its opportunistic and multi-channel advantage. Route discovery was not necessary because the whole topology and all link qualities were known in advance. A detailed analysis on route discovery can be obtained from [14].

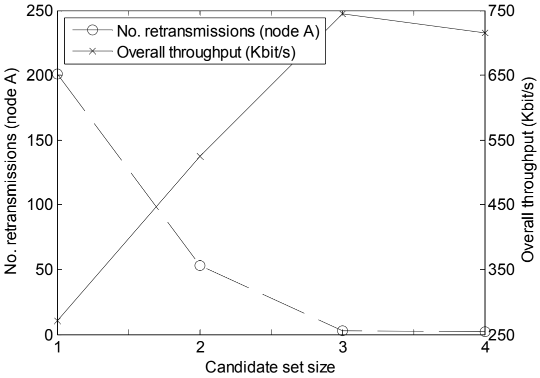


Figure 5: The diagram shows the impact of the candidate set size on the throughput of the packet flow of the network in Figure 4.

4.3.1 Deafness

As mentioned before MCExOR computes a set of forwarding nodes that use 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 (→'deafness'). This problem is handled by MCExOR in the following way. Instead of choosing only one next forwarder, MCExOR selects a set of potential forwarding candidates to reduce 'deafness'. This means that the use of multiple candidates does not only increase the single channel performance (the *opportunistic advantage*) but also is used to overcome the deafness problem.

Consider the example from Figure 4. 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 5. 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.

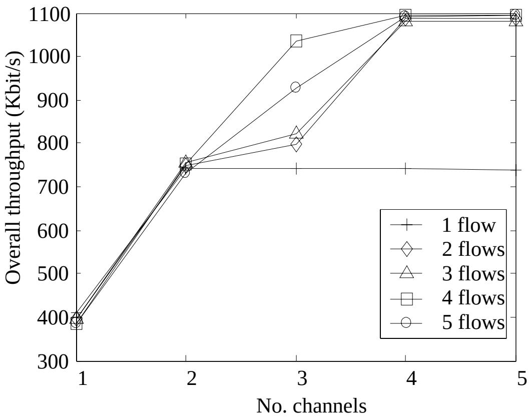
Finally, we investigated the impact of the channel switching delay on the throughput. An increased channel switching delay (> 80 µs) does not significantly reduce the observed throughput.

4.3.2 AODV vs. MCExOR using Free Space

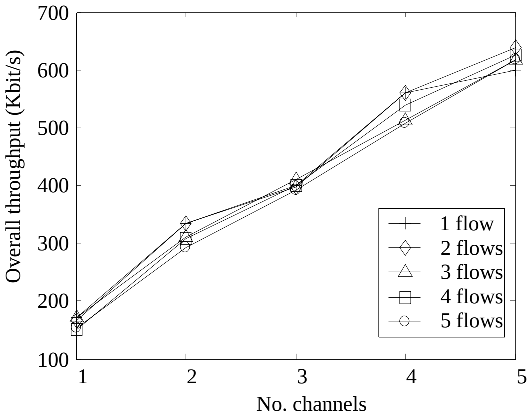
In this section we compare AODV with MCExOR. In order to show the *multi-channel advantage* introduced by MCExOR we use the free space radio propagation model. With this radio model the advantage of being opportunistic only plays an inferior role. In the next section we will compare AODV with MCExOR under more realistic conditions to show the opportunistic feature of MCExOR.

The results of our simulations are displayed in Figure 6. We selected the horizontal field size in a way that AODV has to make 2 and 5 hops on the average respectively. The resulting sizes are 900m and 2100m, respectively, with a vertical dimension of 500m. Furthermore, we varied the number of simultaneous horizontal traffic flows from 1 to 5. The AODV protocol uses only one channel, whereas the MCExOR protocol varies the number of channels from 2 to 5. Furthermore the influence of the number of flows on the overall throughput was measured.

In the smallest network (Figure 6a) MCExOR scales with the number of channels and flows. Using more than 2 channels in the case of only one flow does not lead to an increase in the throughput. This is clear, because the packet route has an average length of 2 hops. In the larger network (Figure 6b) all 5 available channels could be simultaneously used by one flow. Again, in the smallest network one flow cannot benefit from a further increase in the number of channels above 2. However, by increasing the number of simultaneous flows the load imbalance among all available channels is reduced. In contrast to other approaches MCExOR assigns channels to nodes and not to flows. So also a single flow (Figure 6b) can benefit from the existence of multiple channels (here 5).



(a) field size 900x500

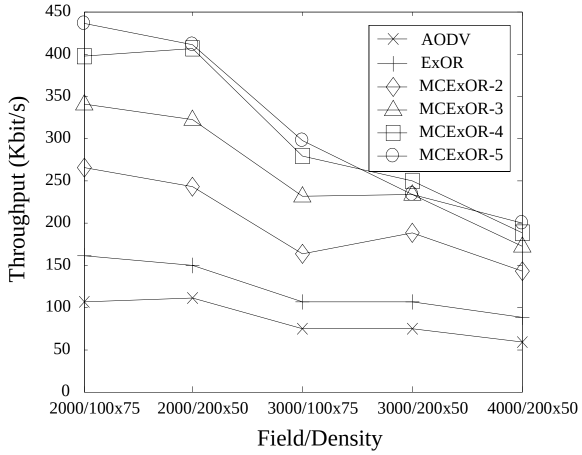


(b) field size 2100x500

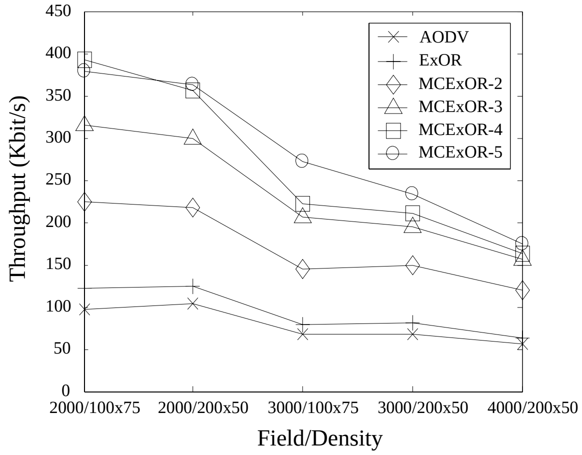
Figure 6: AODV (No. channels = 1) vs. MCExOR (No. channels = 2-5) with free space radio propagation model with field size of (a) 900x500 and (b) 2100x500.

4.3.3 AODV, ExOR, and MCExOR using Shadowing

The results of the measurements using AODV, ExOR, and MCExOR and the shadowing model are displayed in Figure 7. 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. In order to show the combined advantage introduced by MCExOR – the opportunistic behavior as well as the multi-channel support – we used the more realistic shadowing radio propagation model. Furthermore we measured up to 4 simultaneous horizontal traffic flows. Figure 7a 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. Furthermore, from the practical point of view the case with 3 channels is of interest since IEEE 802.11b 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 7: AODV, ExOR and 4 versions of MCExOR with 2, 3, 4 and 5 RF channels with shadowing model and (a) 1 flow and (b) 4 flows.

5. Additional Observations

The (MC-)ExOR packet forwarding relies on link qualities. It is crucial that the measurement of link delivery probabilities produces accurate and dependable data. So there is a tradeoff between link probing overhead and convergence time of link qualities: if the probing interval is small, than changes in link quality are propagated quickly, but the overhead is high. In addition there is a problem with link probing based on packet counts. The moment that a node switches from a channel to another, it will miss link probe counts and so the computation of the metric is inaccurate. One feasible solution is considering only the time spent on the home channel. Further details about an accurate measurement of link quality are discussed in [15]. The problem of an initial assignment of home channels is not considered in this paper and left out for future work. Another task is the implementation of MCExOR on real hardware and measurements whether performance can be reproduced in a real world deployment [7].

6. Conclusions

In this paper we have introduced the multi channel opportunistic routing protocol MCExOR which enables devices with only one transceiver to operate on multiple channels. In a wireless multi-hop mesh network MCExOR minimizes the number of data transmissions and reduces interference to avoid packet collisions. This leads to an increase of the network's capacity as well as to a reduction of latency.

The simulation results presented in this paper show that MCExOR outperforms traditional protocols like AODV by the simultaneous use of multiple RF channels. In conjunction with realistic radio propagation models (shadowing) a further increase in the throughput is observed due to the opportunistic feature of MCExOR. With the increasing number of channels the observed overall throughput superproportionally increases. Furthermore MCExOR is more robust than AODV since it offers a higher end-to-end packet delivery. In contrast to other approaches MCExOR assigns channels to nodes and not to flows. So also a single flow can benefit from the existence of multiple channels.

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