Design and Performance of an Enhanced IEEE802.11 MAC Protocol for Multi–hop Coverage Extension

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Abstract

Ad hoc communication is gaining popularity in recent times, not only for pure ad hoc communication networks but also as a viable solution for coverage extension in wireless networks. Especially for upcoming WLAN hotspots this is an interesting option to decrease installation costs. In this paper we introduce a new MAC protocol that needs only marginal changes to the standard and enables efficient multi–hop networking. We advocate the use of multiple IEEE802.11 channels, where one channel is reserved as a common signaling channel for the task of assigning the others ("data channels") among wireless terminals. The proposed MAC protocol is based on a four way handshake over the common signaling channel, while data transmission occurs on a dedicated channel. We propose a further optimization applying multiple wireless network interface cards. This improvement in performance comes at the price of a slightly more complex hardware. Two different simulation models are implemented to investigate our approach. The first model investigates the MAC protocol and its improvements while the second model analyzes the multi–hop performance in terms of delivery ratio and transmission delay. By means of numerous simulations we present the performance of our MAC approach in comparison with two standard approaches in terms of bandwidth, packet delivery, and transmission delay. For our performance evaluation we apply the IEEE802.11a technology, but we note that our approach can also be used for IEEE802.11b.

Keywords

IEEE802.11, MAC protocol design, ad hoc, cellular coverage extension, connectivity, multi–hop, throughput

I. Introduction and motivation

The exploding success of Wireless Local Area Networks (WLANs), especially of products based on the IEEE 802.11 standard, has led to a massive presence on the market of wireless networked devices at relatively low prices. While this can be seen a a threat to the success of the evolved cellular systems, many view an opportunity for inter–working between WLANs and third generation systems. In a context in which effective access to data networks and the Internet is a primary need for many people, the use of ad hoc and multi–hop[1] communications is becoming of interest for coverage extension of cellular systems, beyond classic ad hoc applications (such as military, disaster relief and temporary installments). Due to the high installation costs or the impossibility to install further wired access points (missing building license), wireless nodes may be used to extend the coverage by multi–hop capabilities. The multi–hop capabilities can be applied to wireless nodes such as communication end–systems (PDA, laptop, phone) or intermediate communication bridges (virtual access points). In contrast to pure ad hoc networks, we are focusing more on networks such as given in Figure 1: One access server is connected to the Internet. Access points can be wired to the access server if an infrastructure exists. Wireless terminals (WT) and virtual access points (VAP) in the coverage of the wired access point use their air interface to connect. Other WTs or VAPs, which are not within the coverage of the access point have to use the multi–hop capability of other entities to reach the access points. Security for multi–hop networks is out of the scope of this paper, but is addressed in [1].

Unfortunately omnipresent WLAN systems based on the IEEE802.11 standard lead to poor performance for such multi–hop networks. Researchers identified the standard IEEE MAC protocol as the reason for the poor performance, due do its "unfriendliness" with multi–hop operation. It therefore makes sense to look for more efficient MAC schemes, which make it possible to operate these devices in multi–hop mode without excessive performance degradation. On the other hand, the IEEE 802.11 standard is so established by now that any completely new MAC will find it very hard to succeed commercially. Our approach in this paper is therefore to look for small variations to the current standard in order to solve the major performance problems without requiring major hardware modifications.

The solution we propose leverages on the fact that multiple channels are available in the ISM band used for wireless LANs, so that the handshake used for contention and channel allocation can be segregated from the actual user traffic. This makes it possible to run multiple channels in parallel, thereby increasing the achievable throughput. On the other hand, dynamic allocation of channels on demand can be used in order to provide good connectivity properties. In fact, besides throughput, connectivity is another major concern in these systems, and is to be carefully evaluated as well.

In this paper, we describe the proposed solution in the context of the IEEE 802.11a WLAN standard. In Section II, we give a brief outline of the standard itself, pointing out its limitations in the present context. In Section III we give a description of the protocol, while in Section IV we provide simulation results to support our claim that the modified protocol leads to significantly improved performance. Conclusions and outlook close the paper.

II. IEEE802.11 Overview

For a better understanding of the proposed MAC protocol we give a short introduction to the IEEE WLAN technology. We refer the interested reader to [2] for a more detailed description. IEEE802.11 focuses on the design of the MAC and the PHY layer for wireless communication. While the PHY layer differs in IEEE802.11 (Release99), IEEE802.11a, IEEE802.11b, and IEEE802.11g, the access mechanism (MAC) remains the same. The basic access mechanism, called Distributed Coordination Function (DCF), is based on CSMA/CA. In Figure 2 the MAC structure for the DCF is given. A wireless terminal willing to transmit a data packet senses the current channel state. If the channel has been detected as idle, the station waits a DIFS time interval. If no other transmission takes place during the DIFS period, the station starts its packet transfer immediately after the DIFS has elapsed.

If the terminal detects a busy channel, the station selects a slot out of its initial Congestion Window (CW). After the current transmission has been completed, the station waits for a DIFS period. When the DIFS has expired, the sender reduces its congestion window unless another station starts its transmission or the CW value reaches zero. In the latter case the sender itself starts the transmission of an RTS (Ready To Send) packet towards the receiver. In order to avoid the hidden terminal problem an optional RTS/CTS phase may be inserted before the data transmission. The RTS packet is used to inform the senders' neighbors to set the *NAV(RTS)* (Network Allocation Vector) properly. The NAV is used to determine how long the medium will be busy in the future. After a SIFS (Short Inter Frame Space) the receiver conveys a CTS (Clear To Send) packet towards the sender and informs its own neighbors about the correct value of the *NAV(CTS)* vector. The SIFS value is shorter than the DIFS value so that other stations will not collide with the ongoing transmission. The RTS/CTS mechanism is used to avoid the hidden terminal problem. After the CTS the sender waits a SIFS and starts the transmission of the data packet, which will be acknowledged by the receiver after another SIFS period. The end of the ACK transmission leads to the restart of the MAC procedure.

The PHY layer is realized for two ISM frequency bands. IEEE802.11R99/b/g uses the 2.4GHz frequency band

[1] The terms multi–hop and ad hoc are used interchangeably throughout this paper.

achieving 1/2/11/54 Mbit/s respectively. The frequency band is the same world-wide. While IEEE802.11R99/b are based on direct sequence, frequency hopping, and infra red, IEEE802.11g uses OFDM technology. IEEE802.11a [7] wireless LAN technologies work in the 5 GHz ISM frequency band. In North America the FCC reserved 300 MHz for the ISM band. This band is divided into three sub–bands of 100 MHz each. Each sub–band is subdivided into four data channels of 20 MHz bandwidth and guard bands for a total of 20 MHz. Thus, a total number of 12 channels are available in the 5 GHz bandwidth in the US. 455 MHz are reserved in Europe, which leads to an even larger number of available channels. In Japan only 100 MHz are reserved leading to four parallel channels. Because of the power transmission levels allowed in the US the lower and medium band containing eight channels will be used for indoor communication, while the upper band will be used for outdoor (bridging) communication. IEEE802.11a uses an OFDM scheme. Each channel has 52 sub–carriers, where four sub–carriers are used for pilot signals while the others convey data. IEEE802.11a uses multiple modulation schemes in combination with different coding rates. For modulation, BPSK, QPSK, 16-QAM and 64-QAM are used. Coding rates are 1/2, 9/16, and 3/4. The combination of coding rates and modulation leads to multiple data rates starting at 6 Mbit/s up to 54 Mbit/s (see also [8]).

In Figure 1 the possible data rates between wireless terminals are given for one specific scenario. The concentric circles represent the possible data rates achievable for each terminal (generated using the ViTAN tool [9]).

The question to answer is how multi–hop networks can be realized. Multi–hop networks based on IEEE802.11 MAC [2] do not perform well as discussed in [3], [4], [5]. The reason is that the RTS/CTS exchange will block all wireless terminals in the neighborhood. In [3] the authors examine the capacity of multi–hop networks based on the IEEE802.11b technology [6]. As an example they have shown that the capacity of a chain network is only 14% of the raw channel bandwidth. Investigating the performance of TCP, the authors of [4] claim that the IEEE802.11 standard is not suitable for ad hoc networks. The upcoming IEEE802.11a technology features larger bandwidth and multiple parallel channels. Even if higher data rates are offered, the RTS/CTS problem remains, therefore our approach aims at exploiting the availability of multiple channels in an efficient way. In our following consideration we are changing the standard MAC protocol and present the performance for IEEE802.11a, but the solution found could be applied to IEEE802.11b as well.

III. The Proposed MAC Protocol

To introduce our approach and for the following considerations, we assume J wireless nodes distributed randomly in a rectangular area. A connection between two WTs can be established by using one of the F available channels. We assume that each WT is able to hop among channels in a timely fashion. Later in this paper we relax this assumption by introducing multiple network interface cards (NICs). In general, a node may have N such NICs, with $N \leq F$. In the following text we refer to three different approaches using F IEEE802.11 channels: i.) *static choice* All wireless terminals communicate over one single channel. ii.) *random choice* Each wireless terminal chooses randomly one out of the F channels. iii.) *dynamic choice* Channels are assigned dynamically to the wireless terminals on demand. The first approach uses only one out of F channels and $(F-1)/F$ of the bandwidth is not used at all, which seems to be very inefficient at first glance. But there are three advantages of this approach in contrast to the second approach: a.) the distances between neighboring terminals are smaller and for IEEE802.11a this leads to higher bandwidth values b.) connectivity might be higher and c.) routing is much easier as all wireless terminals use the same channel. In case different channels are used randomly, a multi–hop enabled wireless terminal does not know in advance on which channel the next terminal can be reached and a more distant terminal (with lower achievable data rate due to link adaptation) might have to be chosen. To overcome this waste of resources, we propose the third approach, where the channels are assigned dynamically. To overcome the drawback of the *random choice* approach, we advocate the usage of a common signaling channel, where the distribution of the channels takes place. A sub–set of the total amount of channels F_{CC} are used as *common channels* referred to as CC. The CC channels are **only** for signaling traffic. More specifically, only RTS/CTS packets (but not the acknowledgment packet) are sent over the common channels. The remaining channels are called *dedicated channels* DC_x (the index x is used to distinguish among dedicated channels) and used for data exchange including the acknowledgment packet. The number of dedicated channels equals $F_{DC} = F - F_{CC}$. In this paper we use only one channel as the common signaling channel ($F_{CC} = 1$) and a maximum of seven dedicated channels ($F_{DC} = 7$) as default settings. These numbers are motivated by the reasoning given in Section II regarding the frequencies reserved per region. The overall number of eight channels can be achieved in Europe and the US. In Japan only four channels are available. The concept of a common signaling channel for network administration is not new, and in the considered environment has the potential to provide an effective solution to the problems related to RTS/CTS in a multi–hop scenario, thereby assuring efficient routing and resource control. In the following section we give a more detailed description of our approach.

A. Basic Handshake Proposal

In this section, we explain the *basic* handshake approach for our new MAC protocol. For the proper functionality of our protocol we have chosen five control packets as given in Figure 3. The first RTS/CTS handshake is used to contact the appropriate communication partner, while the probing packet is used to test the actual channel conditions on the dedicated channel. The last RTS/CTS exchange is necessary to set the transmission parameters properly and to inform the neighborhood about the upcoming communication. All five control packets are sent at maximum transmit power and at minimum rate in the default scenario. Each control packet, the data packet, and acknowledgment packet are sent with a time–interval of length $SIFS$ as given in Figure 3. While the SIFS times between RTS_1 and CTS_1 as well as CTS_2 and RTS_2 are no problem, the SIFS times before and after the probing packet might be too small to change channel in time under such tight constraints. Nevertheless, because of the lack of realistic timer values for this case, we assume a SIFS here as well. Larger inter frame times might lead to a slightly lower performance. Later in this paper we introduce multiple wireless network interface cards, where the channel changes are no longer a problem. A full description of the control packets and their functionality is given in the following:

RTS_1 ***@ CC (sender → receiver)*** In case a WT has data to transmit, it starts with the transmission of an RTS_1 packet if the common channel is idle. The RTS_1 packet is used to ask the receiver if it is ready to receive a packet. The RTS_1 packet contains a list of the channels that are not occupied by others terminals to the knowledge of the sender. From the RTS_1 packet the sender's neighbors are informed that the common channel CC might be busy for $5 - 1 = 4$ additional control packets. Note that no information about the setting of network allocation vector (NAV) for dedicated channels is given up to now, because sender and receiver have not yet decided the common transmission rate, which is a feature of the link adaptation mechanism.

CTS_1 ***@ CC (receiver → sender)*** When the receiver gets the RTS_1 packet, it chooses the dedicated channel by taking into account the following information: i.) list of occupied channels at sender–side and ii.) its own list of occupied channels. After choosing a dedicated channel that is free for both, the sender and receiver, a CTS_1 packet is sent towards the sender. The CTS_1 packet is used to inform the sender about the dedicated channel that will be used, or possibly that there is no channel which can be used for transmission. In the latter case, the handshake stops. In the former case, we consider that the chosen channel is DC_x. Moreover, it informs its neighbors that the common channel CC is busy for $5-2 = 3$ control packets (two are already sent). Note that still no information about the settings of NAV for dedicated channel is given up to now, because sender and receiver have not yet decided the common transmission rate.

Probe @ DC_x (sender → receiver) If the sender has received the CTS_1 packet properly, the dedicated channel chosen is known to both terminals. At this time instant both sender and receiver switch to the agreed dedicated channel and the sender transmits a probing packet. A probing packet is simply an enhanced RTS packet, used by the receiver to decide the modulation/coding scheme (specifying the data rate). After sending/receiving the probing packet, the terminals switch back to the common channel. Note that the probing packet is necessary as the fading characteristics on the signaling and the dedicated channels may be different in general.

CTS_2 ***@ CC (receiver → sender)*** Evaluating the probing packet, the CTS_2 packet is used to inform the sender about the chosen modulation/coding scheme, and to let the receiver's neighbors set their NAV on DC_x properly. It is important to note that each terminal maintains a NAV for each channel [2].

RTS_2 ***@ CC (sender → receiver)*** The RTS_2 packet is used to confirm the parameters chosen by the receiver. Moreover, it is used to inform the sender's neighbors to set their NAV on DC_x properly.

B. Redesign of the MAC Control Packets

For the proposed four way handshake the standard RTS and CTS packets given in [2] have to be extended to include the information introduced in Section III-A. Without any optimization, the size for the RTS packet of originally 20 bytes will only increase up to 24 and 23 bytes for the RTS_1 and RTS_2 packet, respectively. For the CTS packet a total amount of 15 and 17 bytes is needed for CTS_1 and CTS_2, respectively. For the probing packet we use our extended RTS packet. A full description of the packet structure is given in [10].

C. Discussion on the MAC Efficiency

Collisions may occur on the dedicated channel because the knowledge of used dedicated channels at some WTs is not correct. The terminals transmitting or receiving over dedicated channels do not receive control packets if they are equipped with only one wireless NIC, and therefore they cannot set their NAV properly for the dedicated channels. As a result, these WTs could end up sending a probe packet on one of the occupied dedicated channel leading to a collision. As an example, consider the situation depicted in Figure 4: At time t_1, wireless terminal B is sending a data packet

[2]Thus, all wireless terminals following the communication on the signaling channel are aware of which channels are busy (and for how long), as well as of the activities of the other terminals within range.

over dedicated channel DC_j to WT A. At time t_2, D starts a handshake with C. C chooses the dedicated channel DC_k. B does not receive CTS_1 nor CTS_2 sent by C for channel k since it is transmitting, so it cannot set the NAV properly. At time t_3, D starts its dedicated transmission. After that, B finishes its transmission on channel DC_j. Now, it may happen that B wants to transmit another packet to A or to some other terminal (which is not aware of the ongoing transmission on DC_k) on the dedicated channel DC_k. In this case the ongoing transmission from D to C and from B to its transmission partner will collide at time t_4. One simple solution to this problem is to set a timer with a proper value, in order to be sure that a successive transmission of B will start only after the end of any other transmission in the neighborhood, i.e., after being on a dedicated channel the involved stations have to wait a period equal to the longest possible transmission on a dedicated channel. This obviously degrades the overall performance. Another solution is the usage of a second wireless NIC monitoring the common channel as given in the next section.

D. Improvements of the Basic Approach

The *basic* handshake approach can be improved. The first improvement focuses on the size of the back–off window. Since we reserve one channel only for signaling, the back–off scheme shall be modified with respect to the standard protocol. More in detail, when no CTS_1 is received by the sender, we will not increase the contention window (CW), for the following reason. CTS_1 was lost for a collision (either of RTS_1 or CTS_1). Even though there was a collision, the common channel is used only for signaling, so it makes no sense to double CW since there is no evidence of congestion on the dedicated channels. When the receiver sends CTS_1 in which it refuses the transmission because all the channels are busy (either for the transmitter or for the receiver), CW should be doubled because the system is congested. So, we can consider the following situations: i.) in case the transmitter does not receive the CTS_1 or CTS_2, CW is **not** doubled. ii.) otherwise, if the sender receives CTS_1 refusing the transmission, CW is doubled. iii.) CW is also doubled if the transmitter does not receive the ACK packet. If the transmitter receives the ACK, the CW is set equal to CW_{MIN}. Further improvements are: i.) the use of rate adaptation for the common channel: In case rate adaptation can be used even for the handshake phase (note that so far we only used 6Mbit/s on the signaling channel), we could use higher rates for the probing packet and the second CTS/RTS exchange. This would help reduce the load on the signaling channel. A problem that might occur is that neighboring nodes might not be informed because of the chosen data rate. ii.) leaving out the probing packet: In case the modulation can be derived without any probing packet, the second CTS is no longer necessary. This is only possible if the channel conditions on the signaling channel are similar to those of the dedicated channels. By reducing the time on the signaling channel for the handshake phase, more dedicated channels can be loaded. iii.) the use of multiple wireless network interface cards: Multiple NICs would allow to monitor the common channel all the time, which would in turn reduce the collisions. The price for such an approach is a slightly more complex hardware.

IV. Simulation Results

In this section we present some simulation results which show that our scheme makes effective use of the available radio resources while providing high level of connectivity and network throughput. The purpose of our scheme is to allow effective multi–hop operation in an ad hoc network. As a first step, we consider a scenario in which all nodes can hear each other, and study the throughput and delay performance in order to evaluate the effectiveness of the proposed MAC scheme. Once this has been done, we address the performance of the scheme in a multi–hop setting. Considering the two scenarios separately makes it possible to more clearly understand the various effects involved.

A. MAC Performance

In our first simulation mode we focus on the performance of the MAC protocol without routing. We choose the following scenario: Up to 80 wireless nodes are distributed over a small area. The locations of the wireless nodes are chosen randomly. Each wireless node has always a packet in the queue to transmit (high load). Packets are sent randomly to one of the neighboring nodes. The packet length is set to 4 kbytes. Packet sizes larger than reported in the standard are motivated by the work of Gruteser et.al. in [11]. In this work packet trains are introduced, which allow the transmission of multiple packets in a row. In our case longer packet lengths (or packet trains) may be seen as a longer reservation phase of a dedicated channel. Because of the limited area, all nodes can hear each other, which avoids the hidden terminal problem. This condition will be relaxed later. Each of the nodes may serve as the bridge to the Internet. Only one wireless NIC is used per terminal and we assume one channel for signaling and seven channels for data transmission as default values. All simulations have a confidence interval of 95% for a relative error of 5%.

In Figure 5 a comparison between IEEE802.11b, IEEE802.11a using one channel (*static choice* approach), and IEEE802.11a using multiple channels (*dynamic choice* approach) is given. First of all, IEEE802.11a has a much higher throughput than the IEEE802.11b system. While IEEE802.11b achieves throughput values only around 7 Mbit/s, IEEE802.11a achieves values around 22 Mbit/s for our chosen scenario. The throughput for both mechanisms is stable over the range of 10 up to 80 users. Our proposed scheme using 8 channels (one only for signaling) achieves even higher values. Up to 50 Mbit/s can be achieved if more than 50 wireless terminals are in the cell. With an increasing number of users the throughput increases. Note that none of the curves is decreasing with larger number of users. This is due to the chosen scenario, where all stations can hear each other and therefore the hidden terminal problem does not occur. Note that the presented comparison is not unfair even though we have used only one channel for the *static choice* approach and eight channels for the *dynamic choice* approach. If the *static choice* approach had been used with eight channels there would two major drawbacks: i.) the connectivity level would decrease from 100% down to 12.5% and ii.) the mean distance between wireless terminals increases and therefore the achievable bandwidth between terminals decreases due to the channel adaptation used by IEEE802.11a. We will come back to this discussion in Section IV-C.

To investigate the impact of the number of dedicated channels for our proposed scheme we keep one channel for signaling and vary the number of dedicated channels. In Figure 6 the throughput versus the number of terminals with a changing number of dedicated channels is given. The mean throughput increases considerably if more channels are used, and this improvement is especially significant when going from three to four data channels. This behavior is caused by the fact that collisions occur less frequently if a larger number of channels is available. In case of a small number of dedicated channels, ongoing transmissions will be corrupted by new transmissions that choose the same channel. With a relatively large number of channels (more than four) the performance gain is smaller with each additional dedicated channel, because the common channel becomes the bottleneck of the system. Furthermore with a small number of dedicated channels the receiver might inform the sender about the fact that no more channels are available. In this condition the congestion window of the sender increases. We also noted from the simulation results that the throughput performance with few channels tends to be very dependent on the specific network topology, which makes the scheme not very robust if not enough bandwidth is available.

In the following we highlight some possible improvements for our scheme as explained in Section III-D. In Figure 7 the throughput for each improvement is depicted. The rate-controlled handshake achieves only a slight improvement. Furthermore, we note that this is only an upper bound result, as we assumed that all neighboring stations received the information on the signaling channel properly. The improved calculation of the congestion window is more promising. This approach leads to a throughput increase of about 5 Mbit/s compared to the basic handshake, while being easy to implement. In case of heavy load conditions the throughput values decrease due to collisions on the signaling channel. The highest throughput values are achievable if the handshake is shortened by not sending the probing at all. On the other hand, this can only work in case the fading on the various frequency channels is very correlated so that its estimation on the common signaling channel holds for the dedicated channels as well.

B. Multiple Wireless Network Interface Cards

If the terminal has more than one wireless NIC, the performance of the system can be improved by using one NIC for common channel monitoring only. In this section we will focus on terminals with multiple wireless NICs. The performance evaluation is done using the same simulation model and assumptions as in the previous section without any of the improvements introduced in Section IV-A. In Figure 8 the throughput versus the number of wireless terminals for two wireless NICs in dependency of the total number of dedicated channels is depicted. For a given number of dedicated channels the throughput achieved with two NICs is always higher than with only one NIC as given in Figure 6. While one wireless NIC achieves reasonable results with more than three dedicated channels, the approach with two wireless NICs needs only more than one dedicated channel. In contrast to the case with one wireless NIC, collisions will never occur on the dedicated channel. The gain between one and two wireless NICs is larger with a lower number of dedicated channels. The highest gain is achieved if three dedicated channels are used. From the results, we can conclude that one NIC may be sufficient if enough dedicated channels (at least four) can be provided. On the other hand, in the presence of severe bandwidth limitation (e.g., in Japan), two NICs may greatly outperform the single-NIC case, not only in terms of throughput but also in terms on robustness with respect to the network topology. The reason for this behavior is that the probability of collision is reduced due to channel diversity, i.e., WTs that are not aware of occupied dedicated channels will collide with a lower probability in case of a higher number of channels. Note that even a scenario with heterogenous wireless terminals is possible, where a subset of nodes use multiple wireless NICs and the rest only use one wireless NIC. One might call this scenario unfair, because high cost terminals take care of the low cost terminals. But remembering the scenario described at the beginning of this paper, where we introduced the virtual access points, these entities might be the right choice for multiple W–NICs (higher costs may be acceptable and power is not crucial due to a fixed power supply).

C. Multi–hop Communication

In the multi–hop scenario each wireless terminal generates packets of 4 kbytes according to a Poisson process with 3 packets per second. Each WT selects a communication partner randomly using only one IEEE 802.11a wireless NIC. Different topologies were under investigation. In case a direct transmission between sender and receiver is not possible, multi–hop enabled nodes are used to forward packets to the destination applying shortest path routing, which is reasonable as we want to investigate the performance of our scheme in comparison with other MAC strategies. More advanced routing schemes are not taken into consideration in this preliminary evaluation, but will be part of our future work. Furthermore, mobility of the wireless nodes is not considered. For the investigated scenario a total number of 64 wireless terminals are randomly spread over a two dimensional area with variable size. Because the number of WTs is kept constant, small sized areas are referred to as *high density networks*, while larger areas are referred to as *low density networks*.

Figure 9 shows the performance for the *static*, the *random*, and the *dynamic choice* approaches in terms of packet delivery for a multi–hop scenario. Packet delivery is defined as the ratio of successfully delivered packets to the overall number of packets generated. Unsuccessful packet delivery may happen for two reasons: i.) there is no route at all to convey data from the sender to the receiver. ii.) the maximum number of retransmissions for a single link is reached and the packet is discarded. In Figure 10 the transmission delay versus the area size is depicted for all three approaches. The transmission delay is the time needed to transmit a packet from the sender to the receiver including the multi–hop transmissions and all retransmissions. The transmission delay is only defined for packets that arrive successfully at their destination.

The proposed *dynamic choice* approach outperforms the other two approaches almost in all scenarios in terms of packet delivery. For areas smaller then 400 $m \times 400$ m the performance of the *dynamic* approach is significantly higher than the other approaches. The packet delivery values shrink with larger surface areas, which is caused by the physical restriction of the topology, i.e. no multi–hop route can be found to convey data between terminals.

While the *random choice* approach yields acceptable packet delivery values for very small areas, the performance decreases dramatically for larger areas. This is due to the fact that in the random approach a sender will only choose receivers using the same channel and the distance between two WTs using the same channel becomes large and in turn the link quality decreases. For the transmission delay the *random choice* approach yields better results because of the lower number of hops in case a route can be found.

The *static choice* has the lowest performance in terms of packet delivery for small areas. The reason is that the overall bandwidth is only partially used. The *static choice* outperforms the *random choice* if the area becomes larger. In these situations the *static choice* gains because of the smaller distance between WTs. For very large areas the performance of the *dynamic choice* and *static choice* converge, and the *static choice* may even provide a slightly higher performance. This is due to longer hand-shake phase in the *dynamic choice* approach. The large values for the transmission delay of the *static choice* with 10 sec for *high density networks* is caused by the limited resources used and resulting congestion.

To sum up we can conclude that, among the schemes considered in this paper, our proposed MAC protocol (i.e., the *dynamic choice* approach) is the best choice for ad hoc networking, especially for dense networks. The performance can be improved by using multiple wireless NICs as previously discussed.

V. Conclusion

We have explored the viability of a new MAC protocol for multi–hop networking based on IEEE802.11 technology. The approach is suitable for pure ad hoc networks as well as for coverage extension of existing wireless networks. The approach is based on the separation of the signaling part and the data transmission using multiple channels. For signaling, a four way hand shake in combination with a probing sequence is used to determine the most efficient distribution of the channels among wireless terminals. By means of simulation we have shown the behavior of this new MAC protocol and its behavior within a multi–hop network. Only few changes are necessary within the standard to implement our approach. We have investigated the performance of our approach for an IEEE802.11a network and we have shown that it outperforms the existing IEEE802.11 MAC protocol. Furthermore the impact of the number of available data channels was investigated. For one signaling channel four data channels lead to high data rates and high efficiency. Using a multi–hop scenario with shortest path routing our proposed MAC scheme lead to large packet delivery ratio (more than 90% for a 200×200 m^2 area) and small transmission delays (around 10 ms for a 200×200 m^2 area) compared to two other schemes (achieving 35%/65% with a delay of 10 ms/10 sec respectively). We advocate the application of a second network interface card to improve the system performance in case a low number of dedicated channels is available.

VI. Outlook

In our future work we will continue to improve the performance of the MAC protocol. Preliminary simulations have shown that the common channel becomes the bottleneck in some situations such as with high number of dedicated channels or small packet size. In case two wireless NICs are available, we might extend the capacity of the common channel by applying two channels for signaling separating the four way handshake. Routing schemes such as AODV, DSR, and OLSR will be introduced in our future work. We have shown for the MAC investigations that the performance of networks with a small number of dedicated channels can be improved significantly with a second wireless NIC. Therefore we will investigate the impact of two wireless NICs even for multi–hop scenarios.

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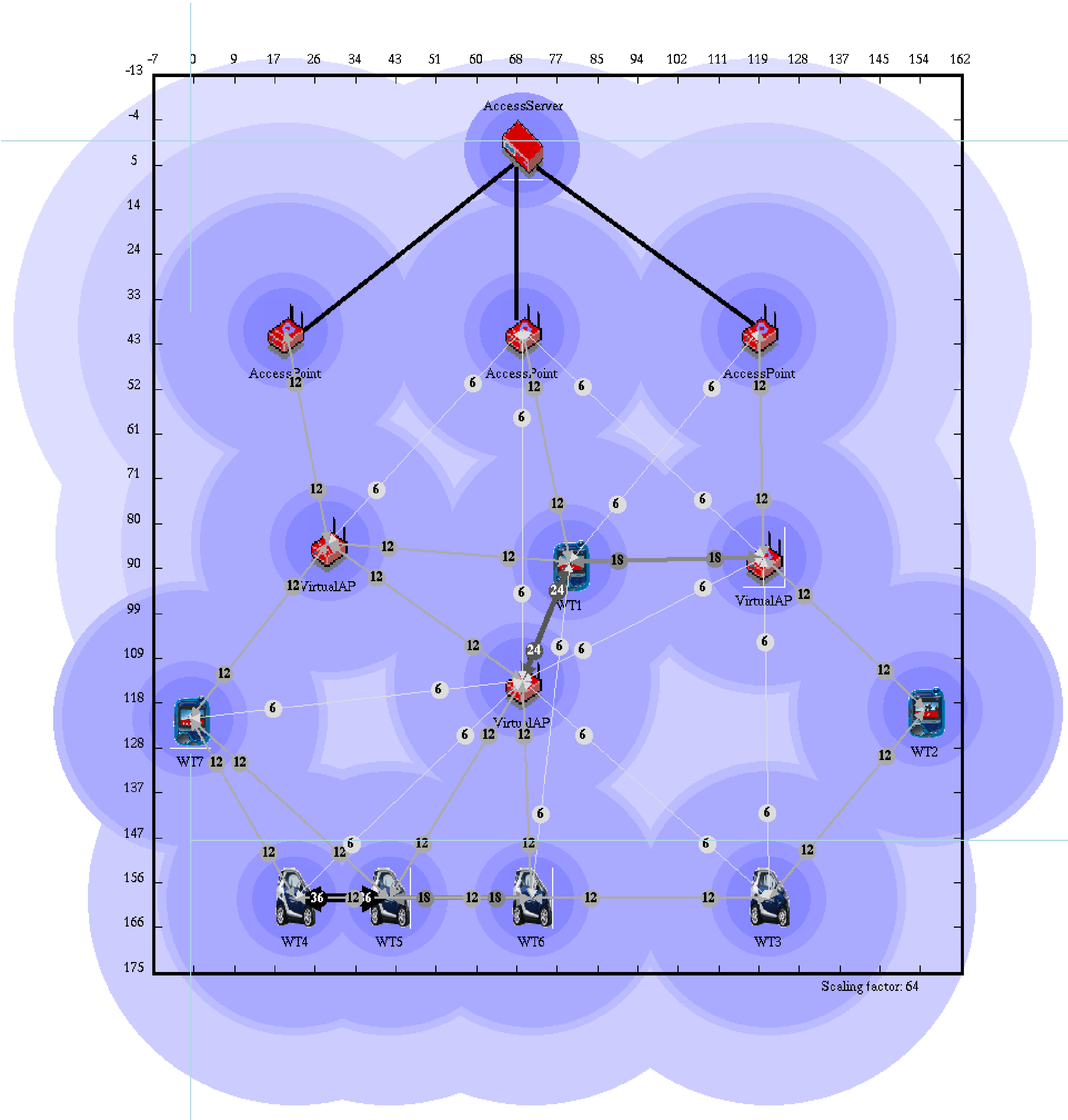

Fig. 1
MULTI–HOP NETWORK USING IEEE802.11A TECHNOLOGY.

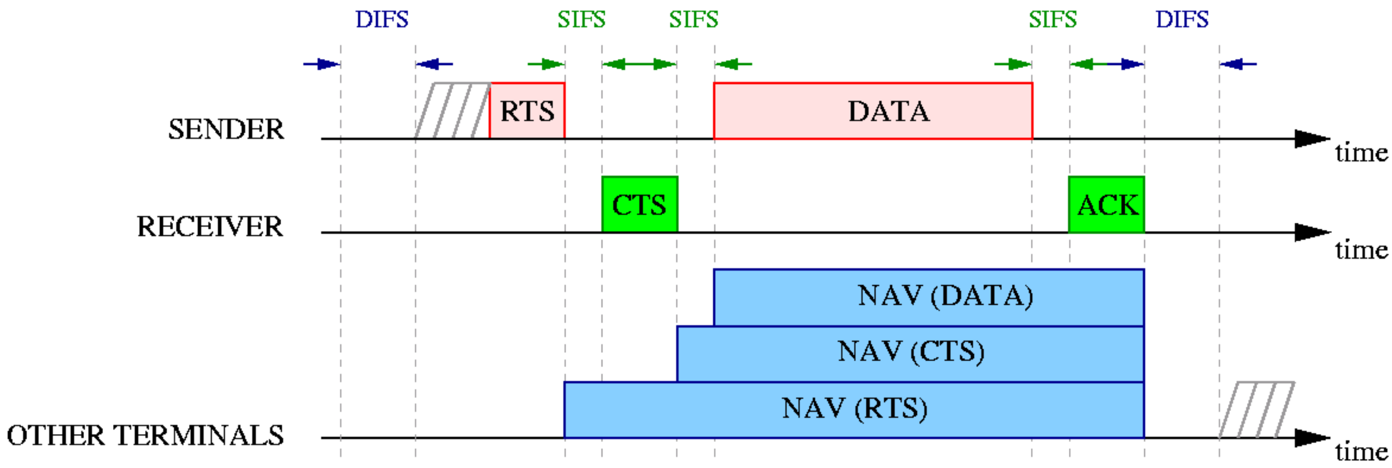

Fig. 2
MAC Structure of the Distributed Coordination Function.

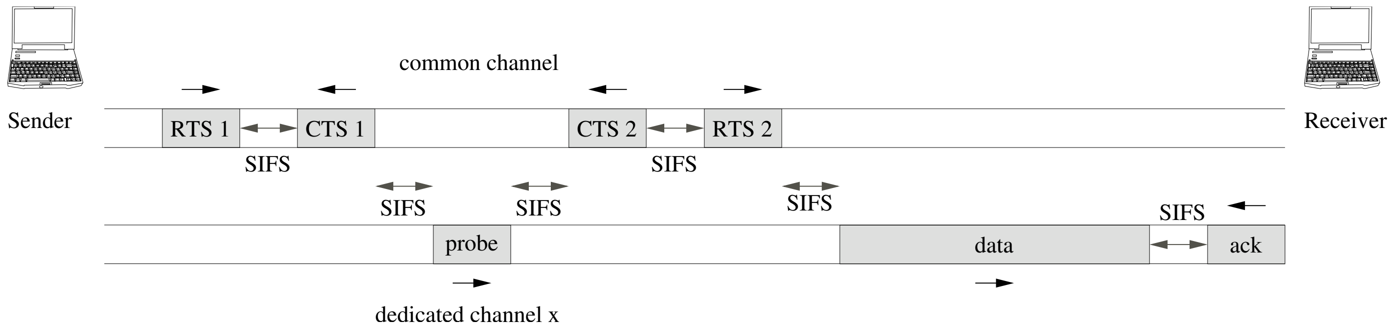

Fig. 3
THE HANDSHAKE PROPOSAL ON THE COMMON CHANNEL CC AND ONE DEDICATED CHANNEL DC_x.

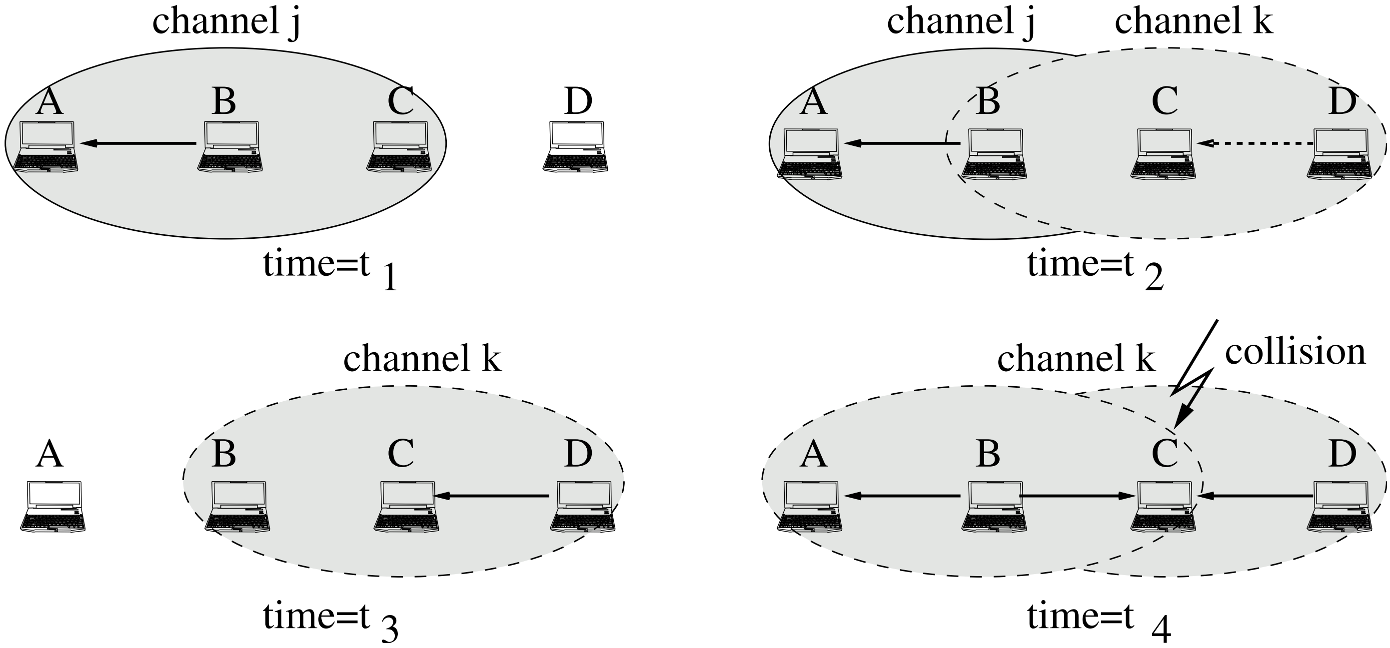

Fig. 4

Explanation of the possible collisions using one wireless NIC.

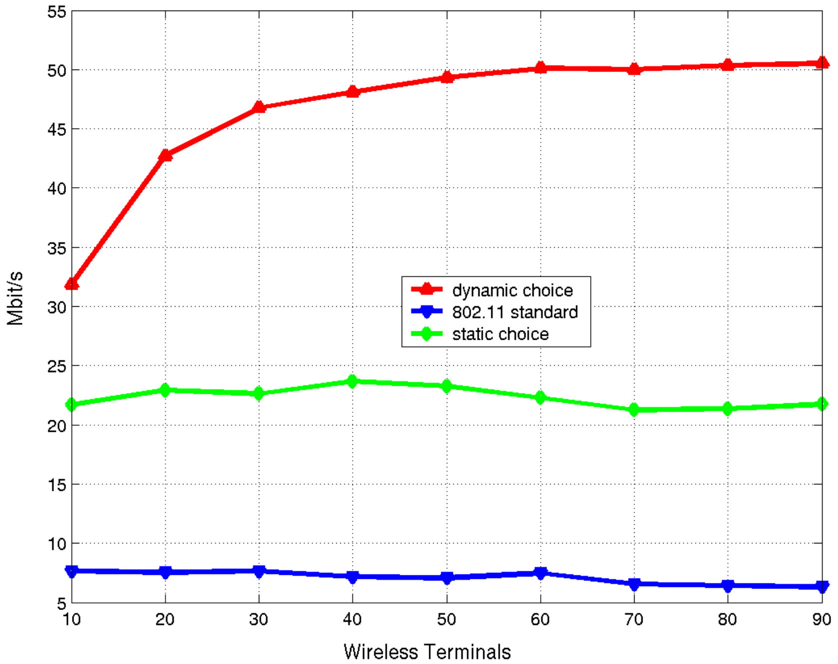

Fig. 5

Comparison between IEEE802.11b standard, IEEE802.11a with static choice, and IEEE802.11a using dynamic choice.

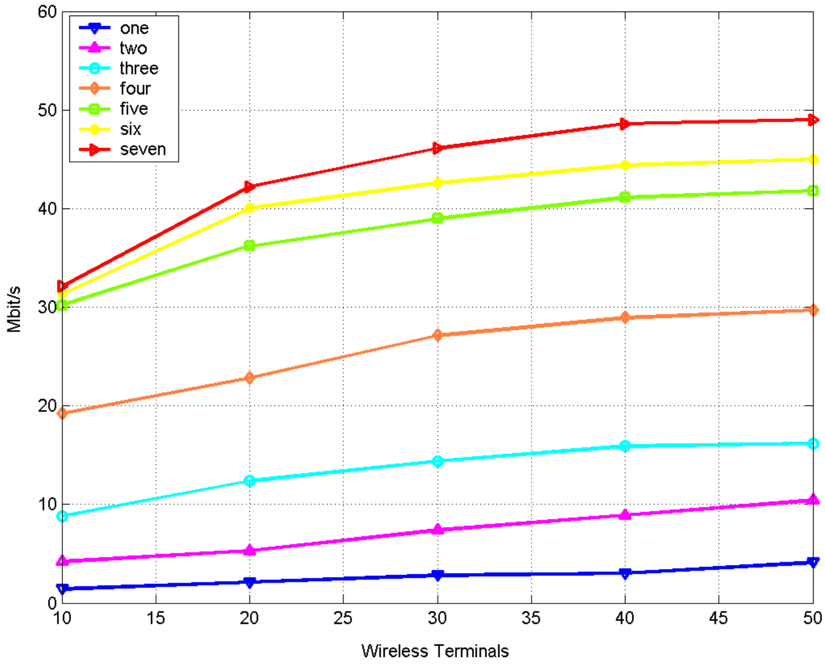

Fig. 6

Throughput versus number of wireless terminals in dependency of the total number of dedicated channels for one wireless NIC.

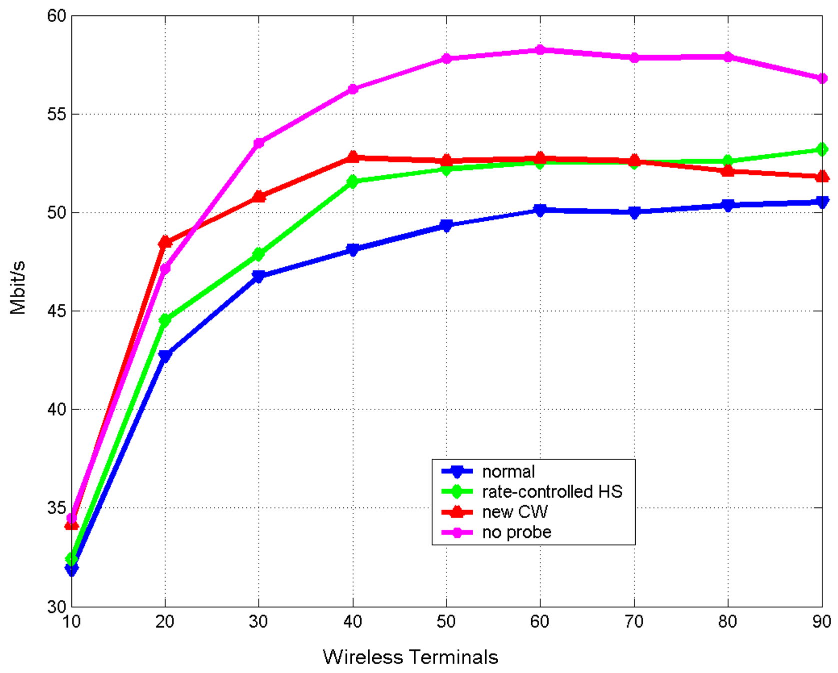

Fig. 7
Improvements for the Dynamic Choice Approach.

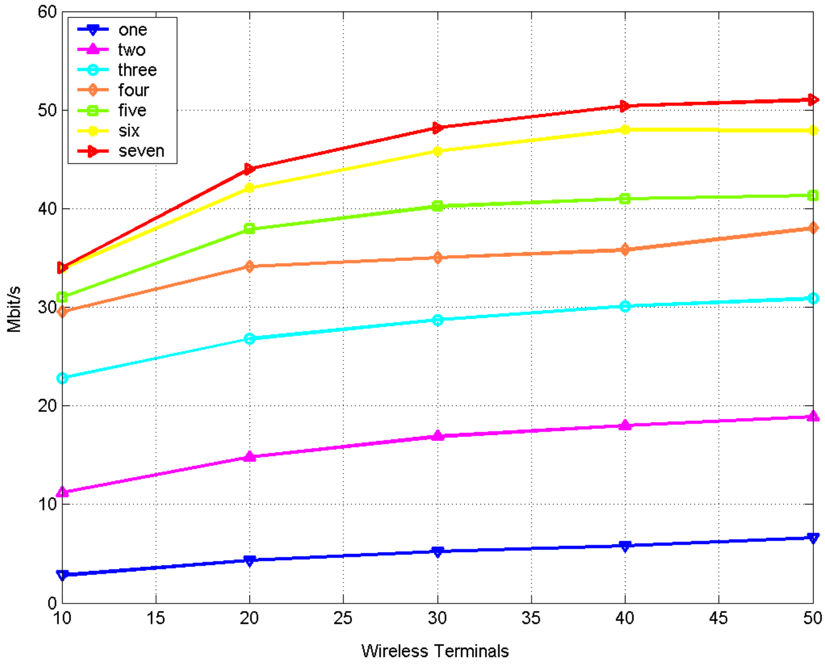

Fig. 8

THROUGHPUT VERSUS NUMBER OF WIRELESS TERMINALS IN DEPENDENCY OF THE TOTAL NUMBER OF DEDICATED CHANNELS FOR TWO WIRELESS NICS.

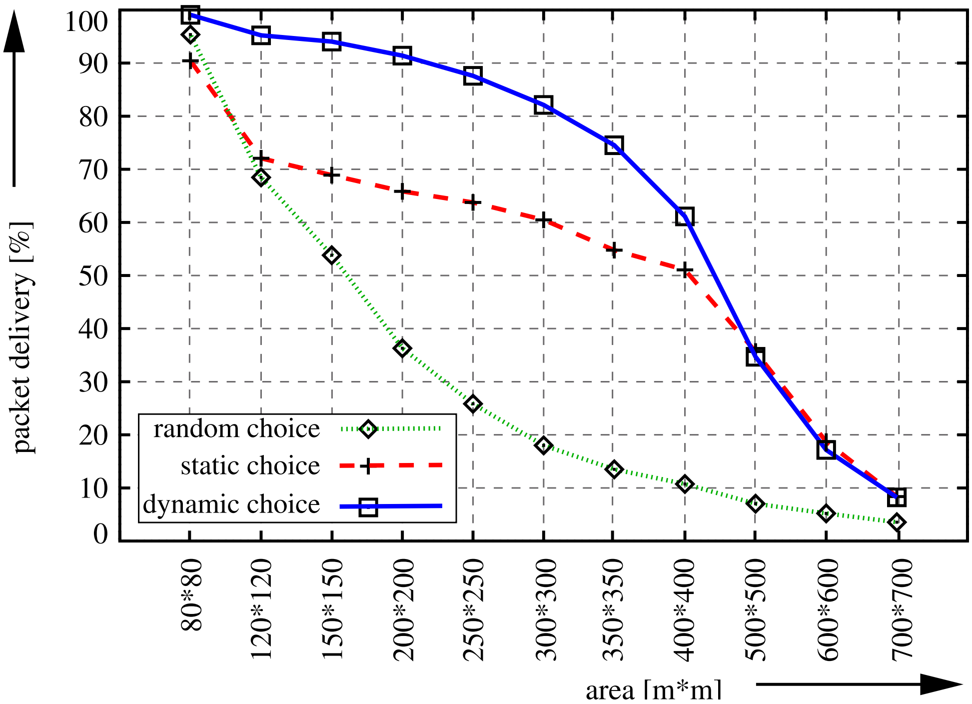

Fig. 9
MULTI–HOP PERFORMANCE IN TERMS OF PACKET DELIVERY VERSUS AREA SIZE FOR THE *random*, *static*, AND *dynamic* APPROACH.

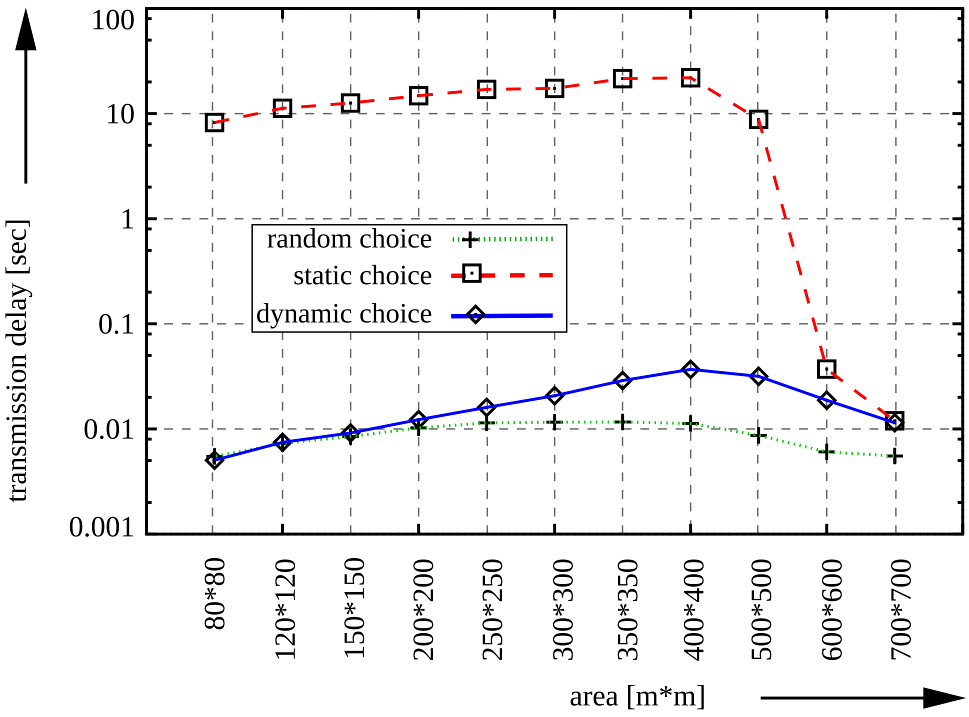

Fig. 10

Multi–hop performance in terms of transmission delay versus area size for the *random*, *static*, and *dynamic* approach.