IEEE 802.11 Contention-Based Medium Access for Multiple Channels

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Abstract – **The IEEE 802.11™ medium access protocol is based on carrier sensing, and contention, i.e., collision avoidance of frame transmissions from different radio stations. This contention-based protocol is discussed in this paper and extended for the usage in multiple parallel frequency channels, in which a multi-channel station groups channels for increasing its own achievable throughput. We discuss a capture effect that occurs if single-channel and multi-channel stations operate in parallel. Methods to enable multi-channel stations and single-channel stations to coexist by sending out redundant preambles, frame headers, and control frames on each individual frequency channel before the channels are grouped, are studied. Single-channel "legacy" stations operating in one of the grouped channels can then detect that the data frame that follows is not intended for them. We provide a first analytical evaluation for the expected efficiency of the proposed modifications.**

Index Terms **–IEEE 802.11 Wireless Local Area Networks, IEEE 802.11n, Multi-Channel MAC, CSMA/CA**

A. Introduction

The frequency band of radio systems is usually divided into sub-bands, which are here termed as frequency channels. On each frequency channel, or channel, operates either a single communications link or a complete service set of a radio system. The latter is the case with for example IEEE 802.11™ wireless local area networks (WLANs) [1],[2],[11],[12], which we will focus on in the following.

The bandwidth of each of such a channel sets a limit to the maximum data rate, i.e., channel capacity that can be obtained. Often, a data rate higher than what can be obtained on one single channel is required. One possible way of increasing the capacity of a radio system is to enlarge the bandwidth of the frequency channel. With a preset channel definition, as it is the case in IEEE 802.11™, this can be achieved by grouping two or more channels, to obtain one channel of greater bandwidth, which translates into greater capacity. Grouping approaches are known in theory [8]-[10] and have been implemented in certain WLAN systems, in which a high data rate is obtained.

We discuss in the following some modifications of existing medium access control (MAC) protocols in order to provide means for accessing a medium by a multi-channel station. The medium consists of at least two frequency channels on which IEEE 802.11™ control and data frames are transmitted. The frames comprise a preamble and a header plus a succeeding data or control field. The data fields and control field respectively contain either user data (DATA frame), or control information (RTS, CTS, ACK frames) for coordinating the access to the medium.

However, IEEE 802.11™ is the very area in which there are a variety of manufacturers of stations that may employ channel-grouping methods that are not necessarily standardized. Because channel grouping, as a performance feature, entails additional expenditure in development and manufacture, it may also be the case that a manufacturer of stations offers on the one hand stations employing channel grouping and on the other hand stations without this performance feature. This means that legacy single-channel stations and proprietary multi-channel stations should be able to coexist and share common radio resources. Also, older stations that were developed and sold before channel grouping has been introduced are incapable of operating in the multi-channel mode with high data transmission rate. We discuss in the following basic mechanisms and modifications of the popular IEEE 802.11™ MAC protocol, for multi-channel communication. We focus in our discussion on the problem of coexistence between legacy single-channel stations and multi-channel stations.

This paper is outlined as follows. The MAC protocol of IEEE 802.11™ and its basic functionalities are described in the next section. We present new methods to extend this protocol for the multi-channel operation, and analyze the basic concepts in Section C. A preliminary analysis is given in Section D.The paper ends up with a conclusion, and outlook to further studies.

B. Legacy IEEE 802.11™ Medium Access

The basic IEEE 802.11™ MAC protocol is the distributed coordination function (DCF) that operates as a listen-before-talk scheme, also referred to as carrier multiple sense access (CSMA). Having found that no other transmissions are underway on the channel, the stations transmit MAC service data units (MSDUs) of an arbitrary length of up to 2304 bytes per MSDU. If, however, two stations find that a channel is free at the same time, a collision occurs when the data frames containing the MSDUs are transmitted. The IEEE 802.11™ MAC protocol defines a mechanism for collision avoidance (CA) to reduce the probability of collisions of this kind. It is part of the collision avoidance mechanism that, before it starts transmitting, a station performs a waiting or backoff process. The station continues listening out on the channel for an additional, random period of time after it finds that the channel is free. Only if the channel remains free for this additional random length of time, the station is permitted to initiate a transmission. This random waiting time is composed of a constant portion, referred to as DCF interframe space (DIFS), and a random time. The length of this random time is a multiple of the length of a slot time. Each station draws a random value for the number of slot times to be waited, referred to as the contention window (CW). As long as the channel is idle, the value of the CW is decremented after each slot time. A frame

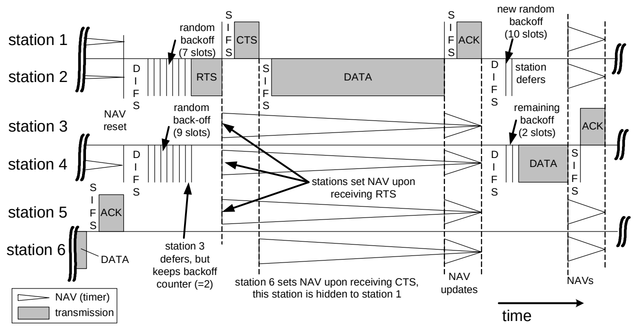

Figure 1: [4] IEEE 802.11™ contention-based medium access. Six stations operating on one single frequency channel have share radio resources. Station 6 is hidden to station 2, but not to station 1, in this example.

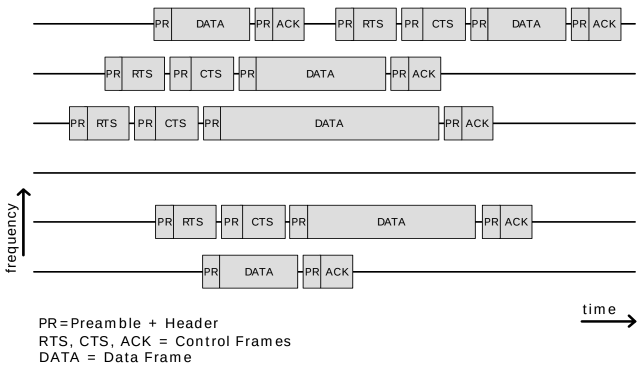

Figure 2: Typical frame exchanges in legacy IEEE 802.11 on six independent frequency channels, without channel grouping.

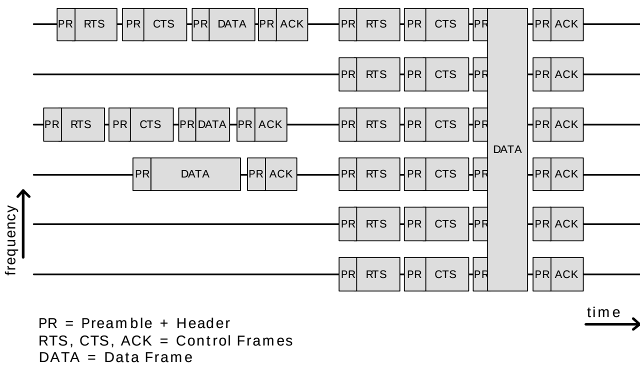

Figure 3: One station groups the six channels to transmit the data frame over all six frequency channels, in a proprietary way. RTS/CTS are still transmitted such that legacy stations can decode them.

transmission is initiated when CW=0.

When a data frame is successfully received, the receiving station sends out an acknowledgement (ACK) frame. After each failed attempt at a transmission, a new medium access is effected after a fresh waiting time, which is usually longer than before, to reduce the likelihood of repeated collisions in the event that a plurality of stations is trying to gain access to the common frequency channel.

Stations that deferred channel access during the time when the channel was busy do not select a new random waiting time but continue the countdown of the time for the deferred medium access on finding that the channel is idle again. In this way, stations that deferred channel access due to their longer random waiting time as compared with other stations are given a higher priority when they resume their efforts to start a transmission.

When CSMA protocols are used for wireless channels, the often discussed hidden station problem may occur. To alleviate it, the protocol defines an optional request-to-send/clear-to-send (RTS/CTS) mechanism. Before data frames are transmitted, it is possible for a system to send a short RTS frame, which is followed by a short CTS frame from the receiving station. The RTS and CTS frames contain information on the length of the transmission time of the next data frame and the corresponding ACK. Other stations near the transmitting station, and hidden stations near the receiving station, do not start a transmission, because they set a counter called network allocation vector (NAV) upon reception of RTS, or CTS, respectively. This helps to protect long data frames against collisions.

Between each successive pair of frames in the sequence RTS frame, CTS frame, data frame and ACK frame, there is a short interframe space (SIFS). Figure 1 is illustrates the protocol. As SIFS is shorter than DIFS, hence CTS and ACK frames always have the highest priority for medium access. In the diagram for the six stations shown in Figure 1, although station 6 cannot detect the RTS frame of the station 2 that is transmitting, it can detect the CTS frame of station 1: Station 6 is hidden to station 2, but not to station 1.

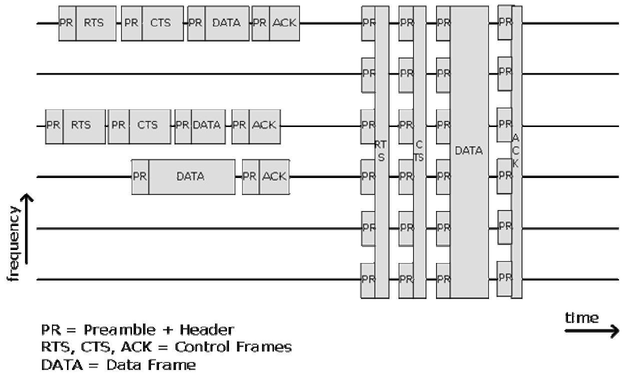

Figure 4: Channel grouping with proprietary control frames RTS/CTS, and proprietary data frames. Preambles are not modified to enable legacy stations detecting the channel as busy with the typically used preamble based clear channel assessment (CCA).

C. Multi-Channel Medium Access

Let us now introduce multi-channel medium access methods for a transmission system having at least two channels. The figures in this paper illustrate the case of six parallel frequency channels, but the methods discussed here are applicable for any number of channels. The multi-channel medium access as it is discussed in the following will make it possible multi-channel stations to coexist with legacy single-channel stations.

Figure 2 illustrates the plain legacy medium access on six independent frequency channels. No station groups neighboring channels to increase its own throughput: Legacy stations operate on one frequency channel only. Note that the medium access and backoff processes on the different channels are not coordinated with each other, and the frame transmissions are not synchronized.

Figure 3 illustrates a simple method for a proprietary multi-channel medium access: Stations exchange redundant legacy RTS/CTS frames on all channels in parallel, and then transmit parallel preambles, before the proprietary data frame is transmitted in multi-channel mode on the grouped channel. Because of the higher channel capacity provided by the grouped channel, the duration of the data frame transmission is now significantly shorter compared to a single-channel transmission, which of course depends on the number of channels that are grouped together. This method appears to introduce unreasonable overhead, but shows some interesting advantages: Legacy single-channel stations will understand the RTS/CTS frames transmitted before the multi-channel phase, and hence the legacy stations will set their NAVs accordingly. They will therefore remain silent during the proprietary multi-channel phase. The preambles that are transmitted in parallel will allow legacy stations that use a specific type of carrier sensing, the so-called preamble-based clear channel assessment (CCA), to actually detect the ongoing transmission of the data frame. Note that in today's implementations of 802.11, many stations operate with this type of carrier sensing.

In Figure 4 we extend the so-far discussed proprietary multi-channel communication by allowing RTS and CTS control frames to be transmitted in multi-channel mode, but as before all preambles are still transmitted in legacy mode on each of the channels. This allows legacy single-channel stations to

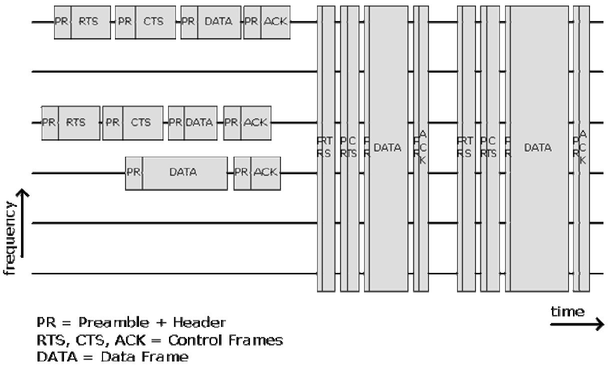

Figure 5: Completely proprietary multi-channel communication.

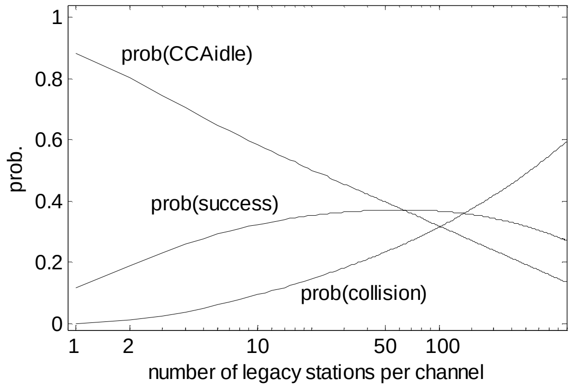

Figure 6: Probabilities that a single-channel station sees the channel as idle, and probabilities of successful transmissions, or collisions.

detect frame transmissions with their preamble based CCA. However, the actual frames cannot be decoded, and the NAV would not be set accordingly.

For higher channel usage efficiency, and in cases where coexistence with legacy stations has not be considered, the multi-channel mode can be further extended as it is illustrated in Figure 5. Here, even the preambles are optimized for the multi-channel communication. Such a method should only be used if legacy single-channel frame exchanges occur occasionally from time to time, because as long as legacy stations would operate with the preamble based CCA, they would not detect any proprietary frame transmission, and initiate their own frame exchanges independently.

D. Analysis

The previously discussed methods for multi-channel communication suffer from a capture effect that occurs when channels are used independently, and a multi-channel station is waiting for all channels to be idle, in order to initiate a frame exchange [3],[4].

Legacy single-channel stations usually operate without mutually interfering each other, as long as they use different frequency channels and the used channels are orthogonal, i.e. as long as frequency channels do not overlap in the frequency domain. This is the case for IEEE 802.11a™. However, when some stations attempt to use multiple channels in parallel for their proprietary data frames, a resource capture may occur. For example, let us assume that legacy single-channel stations operating at a channel 1, and other legacy single-channel stations operating at a channel 2 can initiate frame exchanges without mutually interfering with each other. The operation on the two channels are independent, the channels are orthogonal, activities on the channels are not synchronized. However, it is obvious that a multi-channel station that attempts to operate on both channels, i.e., channel 1 and channel 2, will have difficulties to identify an idle time which allows it to initiate its own frame exchange. One channel may be idle for some slot times, but the other channel is likely not to be idle on the same time. This is more significant if the single-channel stations operate in saturation and therefore would transmit many frames. Further, the problem is expected to become even more dramatic in case the number of channels that are grouped increases, for example from two as in the example, to six as in the illustrations in this paper.

In the following, we analyze this problem and offer two modifications of the proposed multi-channel communications to reduce the discussed effects.

For the contention of legacy 802.11 backoff entities, [7] gives an analytical approximation that allows the analysis of the saturation throughput of a single channel. A finite number of N contending stations is considered to approximate the probability τ of a transmission attempt of one station at a generic slot. If more than one station transmit, frames collide. If there is an ongoing transmission, regardless if it collided or not, the medium is busy, and CCA will detect the medium as busy *(CCAbusy)*. Equivalently, without ongoing transmission, the medium is idle *(CCAidle)*. The probability $P_{CCAbusy}$ that there is a transmission of at least one station in a generic slot time, and the probability $P_{CCAidle} = 1 - P_{CCAbusy}$ that there is no transmission, as well as the probability $P_{success}$ that the transmission attempt leads to a successful frame exchange (conditioned by the probability of transmission, $P_{CCAbusy}$), are obtained to

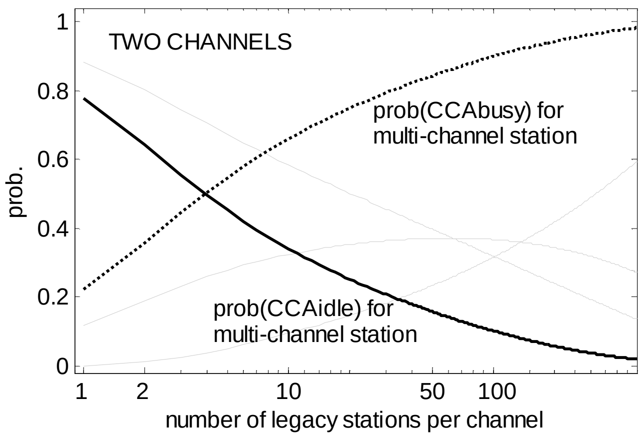

Figure 7: Probability that a multi-channel station sees the group of two channels as idle (CCAidle) or busy (CCAbusy).

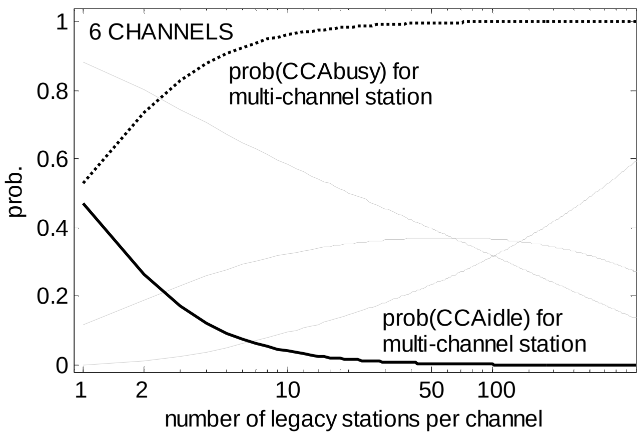

Figure 8: Probability that a multi-channel station sees the group of six channels as idle (CCAidle) or busy (CCAbusy).

$$P_{CCAidle} = (1-\tau)^N ,$$

$$P_{CCAbusy} = 1 - P_{CCAidle} = 1-(1-\tau)^N ,$$

$$P_{success} = \begin{cases} 0, & P_{CCAbusy} = 0, \\ \dfrac{1}{P_{CCAbusy}} \cdot N \cdot \tau \cdot (1-\tau)^{N-1}, & else. \end{cases}$$

The collision probability P_{coll} is given by $P_{coll} = 1 - P_{success}$. In each generic slot, the system is in one of the three states, no transmission *(CCAidle)*, successful transmission *(success)*, or collision *(coll)*. The carrier sense indicates *CCAbusy* during transmission and during collision. The state durations $T_{CCAidle}$, $T_{success}$, T_{coll} of the three respective states depend on many PHY and MAC parameters. The state duration $T_{CCAidle}$ is given by a slot duration *aSlotTime*, which is defined in the IEEE 802.11™ protocol. The state durations $T_{success}$ and T_{coll} depend on the duration of a transmission. The state durations are given by

$$T_{success} = \underbrace{T_{RTS} + T_{SIFS} + T_{CTS} + T_{SIFS}}_{only\ with\ RTS/CTS} + T_{MSDU} + T_{SIFS} + T_{ACK} + T_{DIFS} ,$$

$$T_{coll} = \underbrace{T_{RTS} + T_{DIFS}}_{only\ with\ RTS/CTS} \ or\ \underbrace{T_{PPDU} + T_{DIFS}}_{without\ RTS/CTS} ,$$

$$T_{CCAidle} = aSlotTime.$$

The normalized system saturation throughput is finally given as

$$Thrp_{sat} = \frac{time\ used\ for\ successful\ transm.}{E\left[length\ of\ renewal\ interval\right]} =$$

$$= \frac{P_{CCAbusy} \cdot P_{success} \cdot FrameBody[\,Mbyte\,]}{P_{success} \cdot T_{success}[s] + P_{CCAbusy} \cdot \left(P_{coll} \cdot T_{coll}[s] + P_{CCAidle} \cdot T_{CCAidle}[s]\right)} \cdot {}^{1}\!/_{Mbyte/s} .$$

It is uncomplicated to analyze the probability for a multi-channel station to experience an idle or busy group of channels, if we assume that the legacy single-channel stations are not affected by the multi-channel stations. In this case, the probability $P^{MC}_{CCAidle}$ that a multi-channel station sees an idle slot is given by

$$P^{MC}_{CCAidle} = \prod_{c=1}^{\#CHAN} P_{CCAidle} .$$

Since without loss of generality we can assume the same load per channel (here: saturation), this equation reduces to

$$P^{MC}_{CCAidle} = P_{CCAidle}{}^{\#CHAN} ,$$

where "#CHAN" indicates the number of grouped channels. Figure 6 illustrates the typical results from [7] for the probability that a slot is idle, and the probabilities that a frame exchange was successful or not. The shown results indicate the dependencies on the number of contending stations, and depend quantitatively on the data frame sizes. Here we assumed an error-free channel, the usage of RTS/CTS all the time, and a maximum data frame size of 2312 byte including encryption overhead (2304 byte without encryption). Now, Figure 7 and Figure 8 illustrate how the probability of a group of channels being idle reduces for two and six channels, respectively. It is clearly visible that a contending station will have difficulties to find an idle channel in scenarios where the individual channels are used independently by legacy single-channel stations. This is referred to as resource capture: Legacy single-channel stations capture the radio resources.

The figures indicate that the problem is more severe when six channels are used instead of two, or one: the more channels are grouped, the more likely it is that a multi-channel station will not find an idle channel. In order to mitigate this effect, the multi-channel MAC protocol has to be modified towards a more asynchronous medium access: the individual frequency channels must be accessed as independent as possible: If one channel becomes free, this individual channel has to be allocated regardless what the status on the other channel would be.

Figure 9 and Figure 10 illustrate two modifications of the proposed methods for multi-channel communication that would reduce the discussed capture problem, and improve efficiency of spectrum usage. Both modifications are based on asynchronously transmitted RTS/CTS frames: The multi-channel station transmits its RTS frames on each channel independently as soon as the respective channels are idle. Whereas in Figure 9, the NAV is used to reserve the channel for some default time such that legacy stations would not attempt to access the medium after CTS, in the modification illustrated in Figure 10, the transmitting multi-channel station would use all channels immediately for data frame exchanges.

E. Conclusion

New protocols and emerging standards such as the IEEE 802.11n™ extension will use not only the existing channelization of legacy protocols, but introduce methods for grouping channels with broader channel bandwidths. We discussed initial MAC protocol modifications to support high throughput communication as well as to mitigate undesirable resource capture effects that occur in coexistence scenarios of legacy and proprietary radio stations. Our analysis shows the severity of this problem. Further, two modifications are proposed that will hopefully reduce the unwanted loss in efficiency when multi-channel and single-channel stations share radio resources.

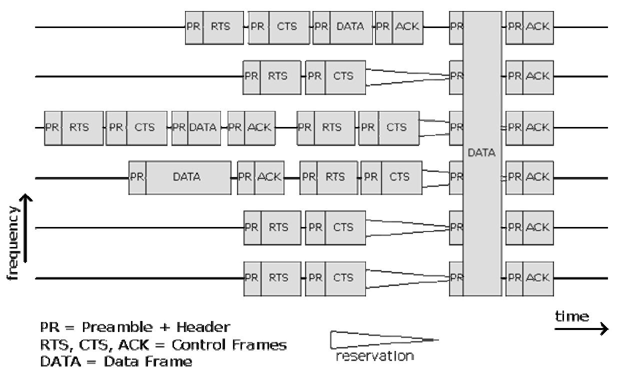

Figure 9: Multi-channel communication with asynchronous RTS/CTS frames and NAV protection of waiting times after the CTS frames.

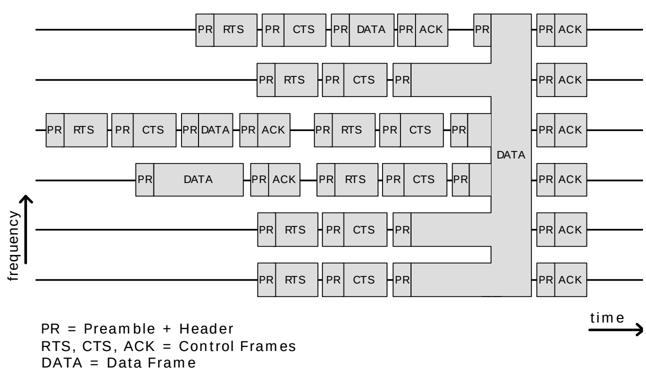

Figure 10: Multi-channel communication with asynchronous RTS/CTS frames and immediate data transmission after the CTS frames.

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