Submission to

The Third IEEE Workshop on Wireless Local Area Networks

September 27-28, 2001
Boston, Massachusetts, USA

Title: Co-existence and Interworking of IEEE 802.11a and ETSI BRAN HiperLAN/2 in MultiHop Scenarios

Authors: Stefan Mangold[1], Jörg Habetha[2], Sunghyun Choi[3], and Chiu Ngo[3]

Affiliation:

1 ComNets, Chair of Communication Networks
RWTH Aachen University of Technology, Aachen, Germany
E-Mail: stefan.mangold@comnets.rwth-aachen.de

2 Philips Research, Aachen, Germany

3 Philips Research, Briarcliff Manor, NY 10510 USA

PART I: SLIDES
PART II: PAPER
(optimized for printout)

PART I:
SLIDES

Co-existence and Interworking of IEEE 802.11a and ETSI BRAN HiperLAN/2 in MultiHop Scenarios

Stefan Mangold, ComNets Aachen University, Germany
J. Habetha, S. Choi, C. Ngo, Philips Research
stefan.mangold@comnets.rwth-aachen.de

1. Introduction
2. HiperLAN/2 and the new 802.11e
3. Interworking
4. Co-existence of overlapping BSSs
5. Potentials of a Combined Protocol for MultiHop-Scenarios
6. Conclusions

1. Introduction

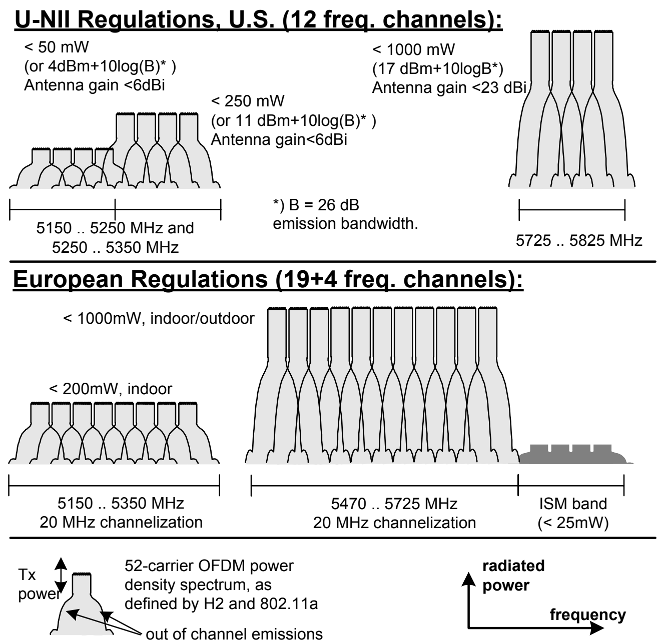
- Co-existence and interworking between two emerging broadband WLAN standards, IEEE 802.11a and ETSI BRAN HiperLAN/2
- Co-existing WLANs operate with the same radio resources at the same time and location, w/o harmful interference
- Fairness concepts and policies are required for co-existence
- Interworking WLANs are able to exchange data, based on a joint coordination function
- Currently, neither co-existence nor interworking is supported

We propose a hybrid of the H2 Central Controller and 802.11a/e Hybrid Coordinator: the CCHC

2. HiperLAN/2 and the new 802.11e (1)

The 5 GHz band and PHY:

- The PHYs are almost identical
- Modulation: OFDM
  - 48 out of 64 carriers used
  - 20 MHz channel grid
- Flexible PHY mode selection
  - BPSK, QPSK, QAM16 and QAM64
  - gross data rate from 6 to 54 Mbit/s



2. HiperLAN/2 and the new 802.11e (2)

Comparison:

- <u>ETSI BRAN HiperLAN/2</u>
  - Centrally Controlled
  - Time-Division Multiple-Access (TDMA-TDD) scheme
  - Broadcast, up-link-, down-link and direct-link channels
  - Dynamic frequency selection, transmit power control
- <u>IEEE 802.11e</u>
  - Enhanced DCF (EDCF)
    - Distributed in contention phase (CSMA/CA with priorities)
    - Enhanced STAs (ESTAs) strictly obey TXOPs, no beacon delays
    - Up to 8 traffic categories
  - Hybrid Coordination Function (HCF)
    - Centrally controlled in contention phase and contention free phase
    - Highest Priority
    - Suffers from overlapping QBSSs
  - Dynamic frequency selection, transmit power control

2. HiperLAN/2 and the new 802.11e (3)

Basic Service Sets:

- Our notation for groups of communicating devices (STAs):

BSS

IBSS — QBSS

802.11a/e DCF (CSMA/CA) | HBSS (HiperLAN/2) | 802.11a/e HCF & EDCF

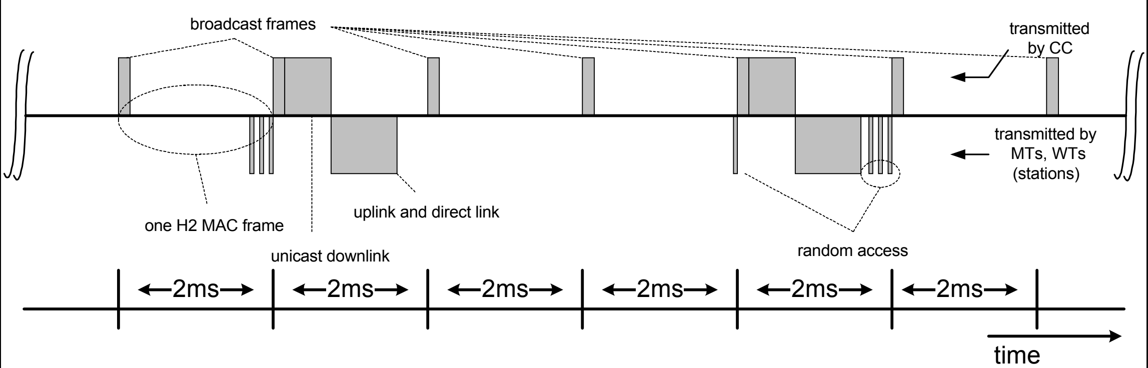
de-central ← | → centralized, QoS support

in case of overlap: OBSS, OQBSS

2. HiperLAN/2 and the new 802.11e (4)

Centralized HiperLAN/2:

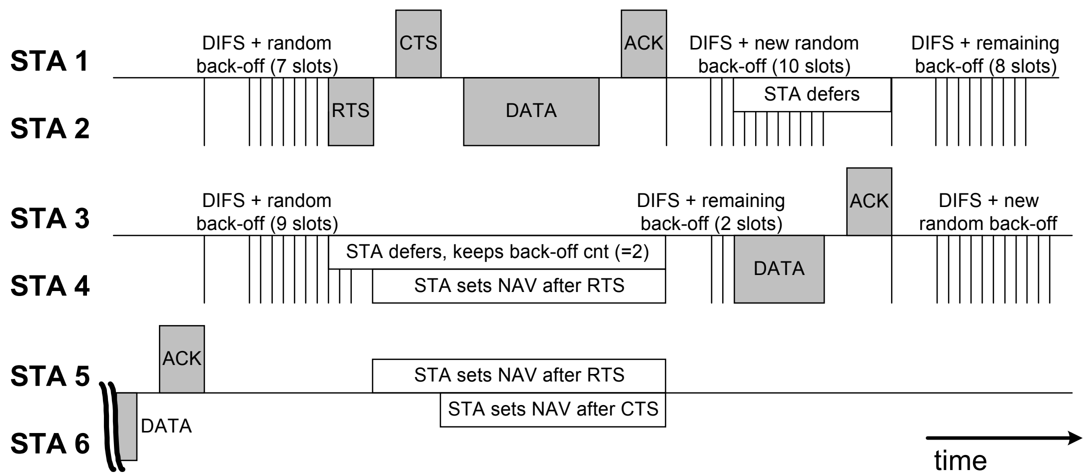
- MAC frame includes broadcast phase, down-, direct- and up-link phase, and random access phase
- MAC frame is repeated every *2 ms*
- Access to the wireless medium is centrally controlled by CC
- HiperLAN/2 requires an exclusive frequency channel



2. HiperLAN/2 and the new 802.11e (5)

802.11-legacy DCF:

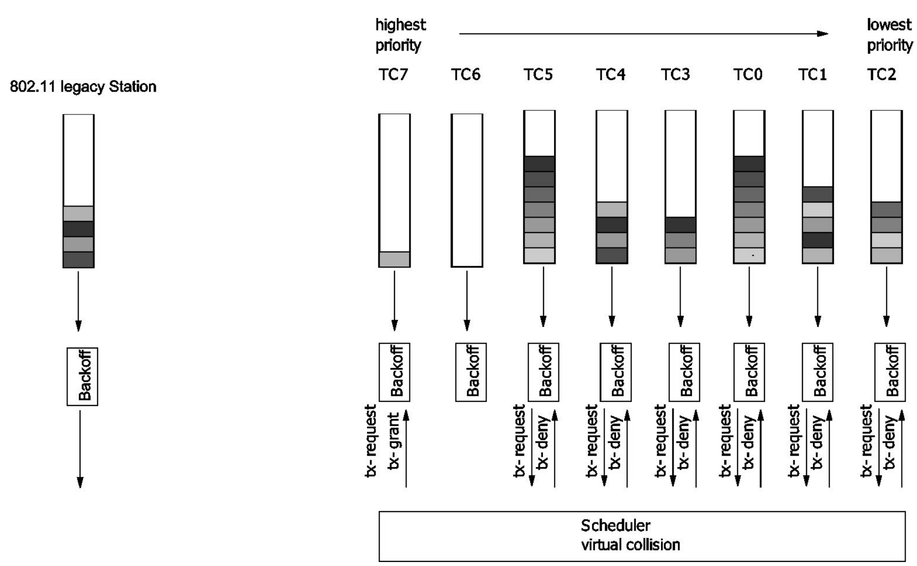
- Distributed Coordination Function w/o QoS support:



2. HiperLAN/2 and the new 802.11e (6)

Enhanced DCF:

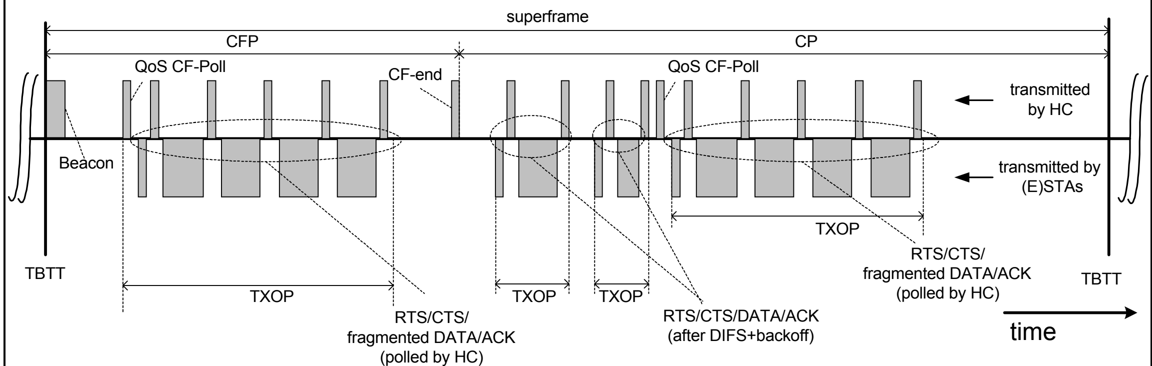
- Up to 8 traffic categories identified by
  - Interframe Space, Contention Window, Persistent Factor



2. HiperLAN/2 and the new 802.11e (7)

Centralized HCF:

- The Hybrid Coordinator allocates TXOPs in CFP and CP
- It has highest priority using QoS CF-Poll
- Needs to know queue status at ESTAs
- Requires an exclusive frequency channel

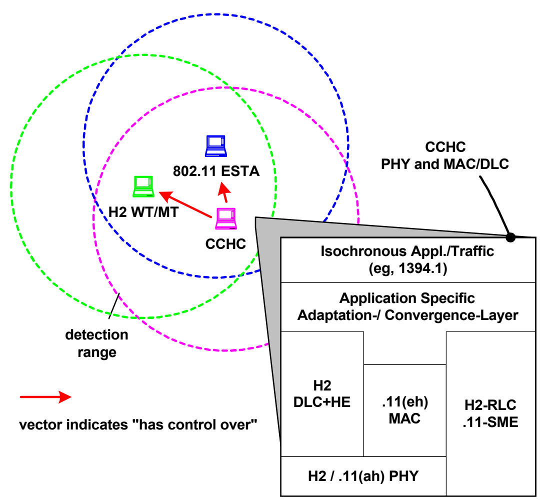


3. Interworking of 802.11a and HiperLAN/2 (1)

The CCHC:

- Approach: A combination of an H2 Centralized Controller (*CC*) and 802.11a/e Hybrid Coordinator (*HC*), the CCHC

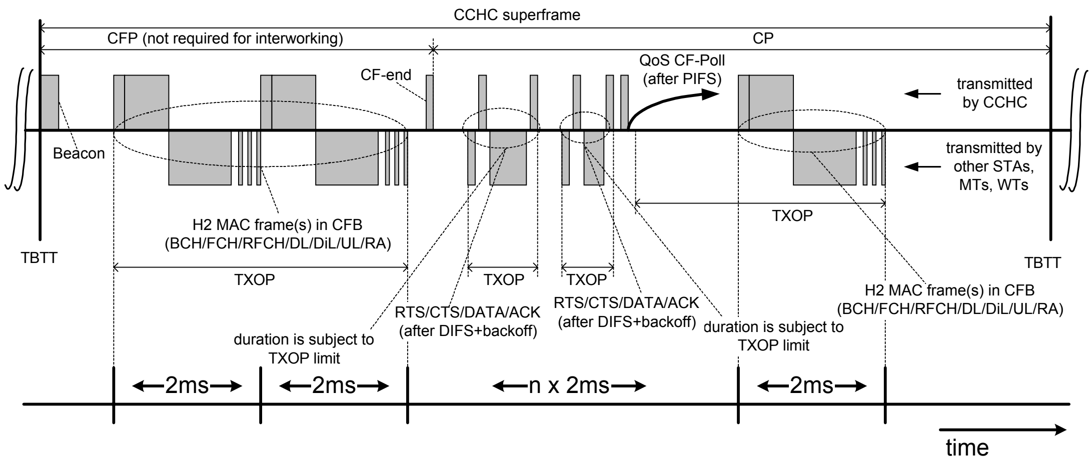
- The CCHC is placed in a device, which has both 802.11a/e MAC/PHY and H2 MAC/PHY implemented
- CCHC works as the HC to 802.11a/e ESTAs and as the CC to H2 MTs/WTs



3. Interworking of 802.11a and HiperLAN/2 (2)

HiperLAN/2 MAC frames in TXOPs:

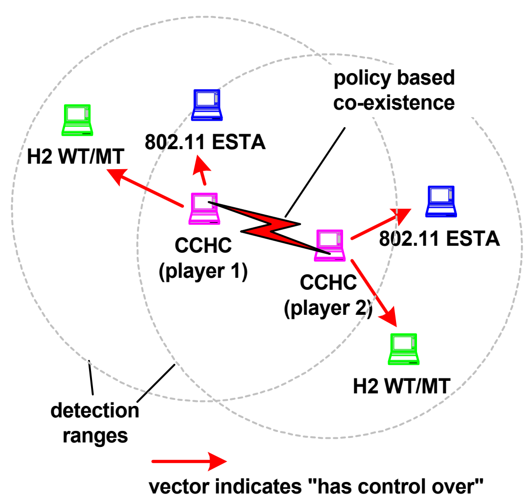
- H2 MAC frames are scheduled within periodically repeated TXOPs.
- No delay (jitter) of the H/2 MAC frames
- As a result, QoS in H/2 can be supported!



4. Co-existence of overlapping BSSs (1)

Competing CCHCs are modeled as players:

- Problem: two or more overlapping QBSSs that employ their own centrally controlled resource coordination
- Until now, this can only be handled by selecting different frequency channels
- It is very desirable that QBSSs can share a single frequency channel w/o QoS compromise
- We look at this coexistence problem with the means of the theory of games

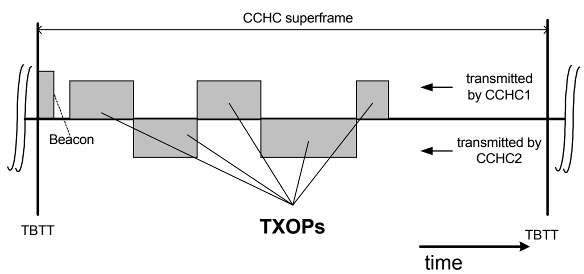


4. Co-existence of overlapping BSSs (2)

The game model:

- The problem is modeled as a strategic game
- Each player has only partial control over the environment
- The payoff of each player depends not only upon its actions but also upon the actions of other players
- One superframe is modeled as single-shot game

$$G = \langle N, \underline{x}, u_i \rangle = \langle N, \underline{x}, \succsim_i \rangle$$

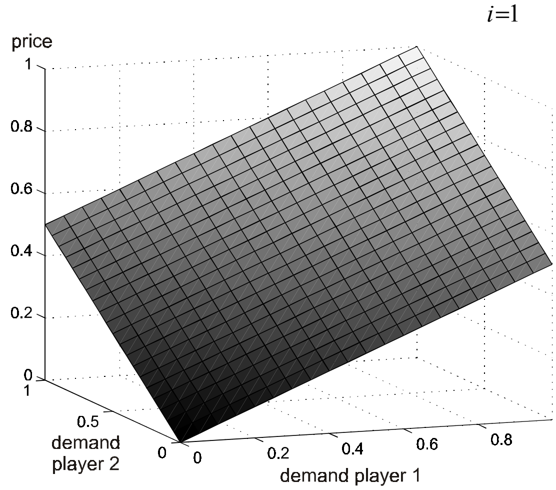


4. Co-existence of overlapping BSSs (3)

Price function:

- We assume common knowledge about an abstract price function of the aggregate demand of all involved players

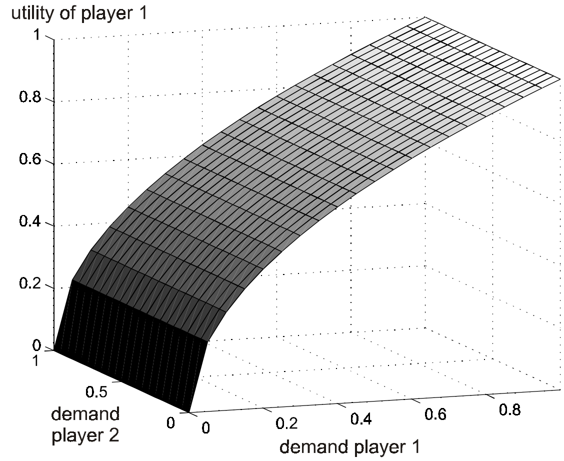
$$p(n) = \Phi(x(n)), \quad with\ x(n) = \sum_{i=1}^{N} x_i(n)$$



4. Co-existence of overlapping BSSs (4)

Utility function:

- The utility function $u_i(\cdot)$ is an abstract representation of QoS
- *It* represents the preference relation $\succsim_i$ of player *i* in the sense that $u_i(a) \geqslant u_i(b)$ whenever $a \succsim_i b,\ a,b \in A_i$.

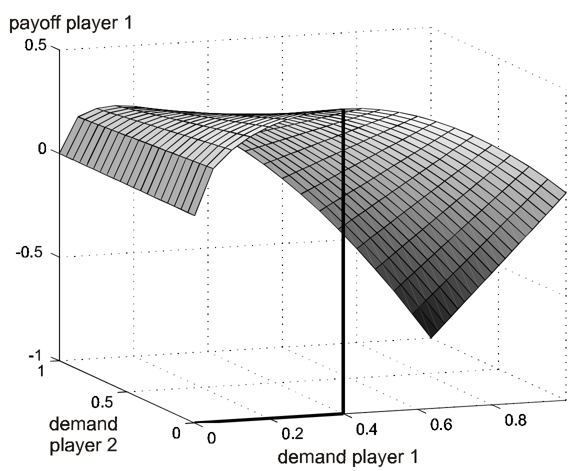


4. Co-existence of overlapping BSSs (5)

Rational behavior:

- Player *i* in a single-stage play of the Cournot competition tries to maximize its payoff $V_i(\underline{x})$

$$V_i(\underline{x}, n) = u_i(x_i(n)) - x_i(n)\Phi(x(n))$$



4. Co-existence of overlapping BSSs (6)

Nash equilibrium:

- A Nash equilibrium is a vector $\underline{x}^* \in A$ of actions with the property that for every player $i \in 1 \ldots N$

$$(x_{-i}^*, x_i^*) \succsim_i (x_{-i}^*, x_i) \quad \forall x_i \in A_i \,.$$

- In NE, no player can profitably deviate from its strategy, given the action of the other players
- No player has reason to change its demand

4. Co-existence of overlapping BSSs (7)

What can we expect from game theory?

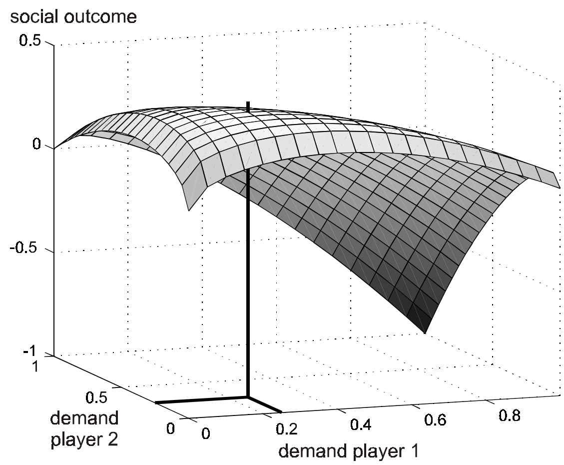
- Game theory helps to answer the questions
  - Does an NE exist?
  - If yes, is it unique?
  - Does the dynamic system converge to this unique NE?
- We face a DILEMMA:

The unique NE in our example is not the optimal outcome for the game

4. Co-existence of overlapping BSSs (8)

Co-operation in repeated games:

- The maximum achievable outcome is not the best response Nash equilibrium
- To converge to this point, rational players need to co-operate.



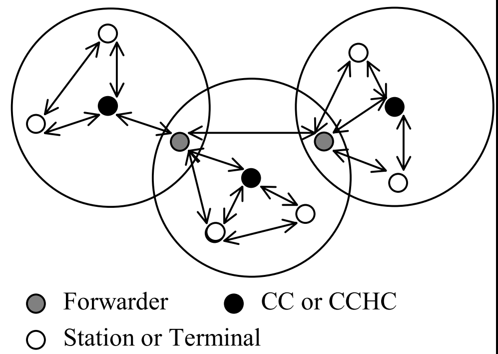
4. Co-existence of overlapping BSSs (9)

An frequency etiquette in repeated games:

- A repeated interaction is a realistic assumption.
- A stable cooperation occurs if all rational players believe that a defection will terminate the cooperation.
- Non-cooperative game theory: the etiquette involves that each player may punish any player who misbehave.
- The termination of cooperation must result in a subsequent loss for the player that gained shortly after defection.
- In a stable repeated game this loss must outweigh the gain.
- Derived from the social science, the strategies that establish cooperation will be the main focus of our future work.

5. Potentials of a Combined Protocol
MultiHop-Scenarios:

- The CCHC organizes the access of all STAs inside one cluster
- Each cluster operates at one frequency
- STAs of different clusters can communicate via forwarders that are able to participate in more than one clusters
- A forwarding Protocol Bridge Terminal (*PBT*) has to switch in-between the two frequencies of the inter-connected clusters
- A PBT selects another 802.11a STA as its Terminal Representative (*TR*) during its absence
- During the absence of the PBT, the TR is responsible for receiving and buffering all data that is bound for the PBT
- When the PBT is back in the original network again, the TR will then forward the data to the PBT



6. Conclusions

- INTERWORKING:
  - The CCHC coordination function renders the time-sharing of the bandwidth between 802.11a/e and H2, w/o sacrificing the QoS support of both systems.
- CO-EXISTENCE:
  - The overlapping BSS problem requires policies to support fair sharing of the resources under QoS constraints.

- Our proposals support isochronous traffic by allowing fair resource sharing between competing individuals.
- The solutions require <u>minor changes</u> of the two standards.
- The CCHC concept has been presented to ETSI BRAN and IEEE 802.11 Working Group.

PART II:
PAPER

Co-existence and Interworking of IEEE 802.11a and ETSI BRAN HiperLAN/2 in MultiHop Scenarios

Stefan Mangold, Jörg Habetha, Sunghyun Choi, Chiu Ngo

***Abstract*— IEEE 802.11a and ETSI BRAN HiperLAN/2 are evolving standards for Wireless Local Area Networks (*WLANs*). Radio systems of these types will operate at the unlicensed 5GHz bands. When these radio systems operate at the same radio channel in the neighborhood, they will mutually interfere with each other. Data throughput, quality of service levels, and availability will be degraded and unpredictable if the different radio systems are not able to coordinate the competing access to radio resources. We discuss a solution for interworking, i.e., communication between 802.11a and HiperLAN/2 and policy-based approaches to achieve fair spectrum sharing. By combining the two protocols of IEEE 802.11a and ETSI BRAN HiperLAN/2 we look at ways to achieve co-existence, interworking, and discuss the potentials of our new hybrid approach for the application of multi-hop networks.**

***Index Terms*— ETSI BRAN HiperLAN/2, IEEE 802.11a, Interworking, Co-existence, MultiHop, Game Theory**

I. Introduction

Co-existence and interworking between the two emerging broadband Wireless Local Area Network (*WLAN*) standards, IEEE 802.11 (*802.11*) and ETSI BRAN HiperLAN/2 (*H2*), are discussed. 802.11a and H2 will operate in the unlicensed bands between *5* and *6 GHz*. Their radio transmission schemes, i.e., Physical Layers (*PHY*), are harmonized and almost identical, but the Medium Access Control (*MAC*) protocols are very different. Neither co-existence nor interworking at the same frequency channel is supported. 802.11 and H2 are candidates for multi-hop systems that flexibly configure and adapt their network settings based on the offered traffic and the radio environment. The WLANs control their access to radio resources individually. Naturally, in such a scenario where multiple WLANs are forced to share radio resources we face complex problems if the WLANs are not coordinated. In this paper we discuss these problems and offer solution concepts for 802.11 and H2.

Interworking WLANs are able to exchange data. This requires the same radio transmission scheme being used by the WLANs. Further, the protocols have to be coordinated. Interworking is often based on a harmonized coordination function available in all protocols.

For interworking, we propose a hybrid of the H2 Central Controller (*CC*) and 802.11a/e Hybrid Coordinator (*HC*)[1]. This new coordination function originally developed for 802.11a/e is placed in a device that is referred to as *CCHC*. This station has both 802.11a/e MAC/PHY and H2 MAC/PHY implemented. See Sect. III for the detailed discussion of the CCHC interworking solution.

WLANs that not necessarily follow the same standard are able to coexist if they can operate with the same radio resources at the same time and location. Then the individual WLANs operate with fewer resources but are still able to control their access to the available resources. Co-existing WLANs operate in the same coverage area without harmful interference. It is not required that a communication between stations adhering to the different standards takes place. Fairness concepts and policies are often discussed in the context of co-existence [7], [1].

For the co-existence of competitive 802.11a and H2 Basic Service Sets (*BSSs*), where a BSS is composed of an Access Point (*AP*) or a CC and a number of wireless stations, a time-sharing of resources must be established. One available frequency channel has to be shared by overlapping and competing WLANs in times of high offered traffic where all other frequency channels are already occupied by co-located WLANs. This overlapping BSS problem exists in pure 802.11 and pure H2 scenarios as well. How those competing WLANs meet their individual Quality of Service (*QoS*) requirements when operating at the same frequency channel is one of the challenges we are facing. It is this single frequency-sharing problem we are focusing on when discussing co-existence in Sect. IV. There, we propose to establish etiquettes derived from non-cooperative game theory for co-existence.

Potentials of our CCHC approach for multi-hop scenarios are discussed in Sect. V. The next section briefly outlines the relevant parts of the two standards.

II. HiperLAN/2 and the new IEEE 802.11e

A. Harmonized physical layer, 5GHz unlicensed band

The 802.11a and H2 Physical Layers (*PHY*) are almost identical. They apply a 52-carrier Orthogonal Frequency

E-Mails stefan.mangold@comnets.rwth-aachen.de, joerg.habetha@philips.com, sunghyun.choi@philips.com, and chiu.ngo@philips.com. Stefan Mangold is with ComNets, Aachen University of Technology, D-52074 Aachen, Germany. Jörg Habetha is with Philips Research, D-52066 Aachen, Germany. Dr. Sunghyun Choi and Dr. Chiu Ngo are with Philips Research, Briarcliff Manor, New York 10510 USA.

[1] IEEE 802.11e is a new extension to the 802.11 MAC being developed currently to support QoS. More details about 802.11e are found below.

Division Multiplex (*OFDM*) with convolution coding and linear modulation schemes that can be adaptively chosen based on QoS requirements and radio channel conditions. 48 carriers out of 52 are used for data transport [9], [10]. The remaining 4 sub-carriers of the OFDM symbols are used for pilots. The 802.11a Task Group at the 802.11 Working Group accepted the same OFDM transmission scheme as H2, which facilitates the development of the coexistence and interworking of both systems. Note that the IEEE 802.11 standard specifies a MAC protocol without the definition of the PHY for 5 GHz. 802.11a as a supplement of 802.11 specifies the PHY for the 5GHz OFDM transmission.

The *5 GHz unlicensed* band comprises frequency bands between *5.15* and *5.825 GHz*. Fig. 1 illustrates this spectrum as it is defined for the U.S. and Europe. A spectrum of *300 MHz* has been released in the U.S. for the Unlicensed National Information Infrastructure (*U-NII*). *455 MHz* of spectrum are available in Europe, there called a *license exempt* band because of historical reasons. In a license exempt band, regulators permit the operation of any radio communication systems, in contrast to an allocation of spectrum on a licensed base. The restrictions that regulators put on the candidate systems are radio parameters such as limits of the radiated power, out of band emissions, antenna characteristics and the communication services that are supported.

The U-NII bands in the U.S. are for example reserved for communication services for the information infrastructure, an initiative to extend wired Internet services by means of wireless systems.

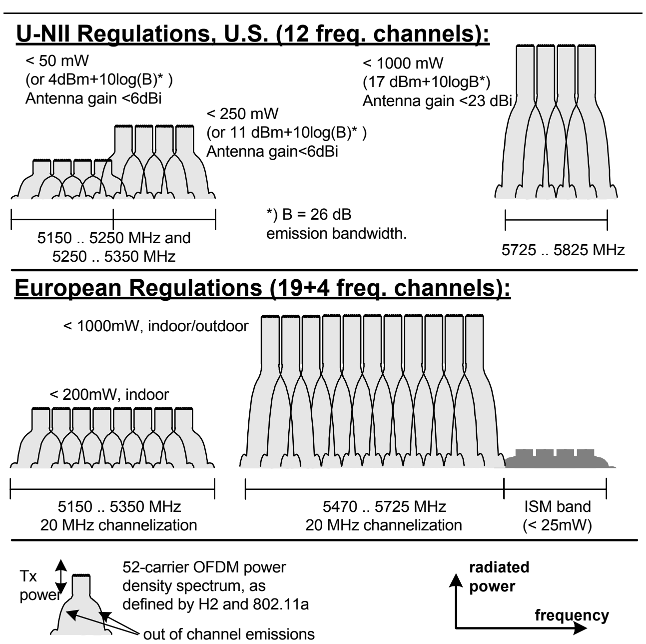


Fig. 1: The 5 GHz band for WLANs in the U.S. and Europe. The 20 MHz channelization is not mandatory in the U.S.; further, higher antenna gains are permitted with corresponding reduction of transmitter power. In Europe, WLANs must use full spectrum range in order to share the spectrum with radar systems, based on dynamic frequency selection and transmitter power control.

B. Centralized H2

H2 is centrally controlled where one station, usually the AP, announces every *2 ms* the timing of the Medium Access Control frame (*MAC frame*) that follows this announcement. This station is the CC and has the full control over the frequency channel it is operating at. To support this exclusive control, Dynamic Frequency Selection (*DFS*) is part of the H2 standard. With DFS, H2 systems can avoid that co-located CCs operate at the same frequency channel.

The H2 MAC frame comprises four generic phases, all controlled by the CC. Order and duration of the phases are determined by the CC and may change from MAC frame to MAC frame depending on the capacity requirements. After the announcement sent to the associated Mobile and Wireless Terminals (*MTs/WTs,* here referred to as stations, or *STAs*, in this paper), the unicast data from the CC to the STAs follow in downlink, before the STAs are scheduled to send their data in uplink. A direct link phase, when data is transmitted directly from STA to STA is optionally allowed. During the random access phase STAs may send short control frames in contention to require capacity in the subsequent MAC frame. After this random access phase the next MAC frame starts with the broadcast frame.

We call a group of H2 STAs including CC with its associated MTs and WTs an *HBSS*, in this paper see section II.D. Fig. 2 illustrates the operation of H2. The CC keeps transmitting the broadcast frame at the beginning of the periodic MAC frames even in times when there is no data to be transmitted.

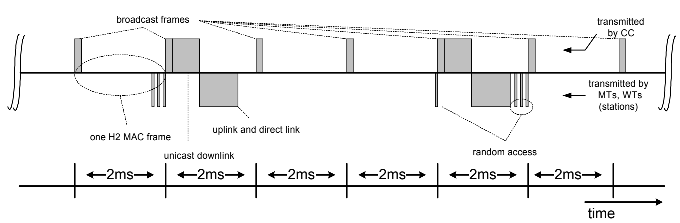


Fig. 2: H2 timing. The MAC frame comprising broadcast phase, down-, direct- and up-link phase, and random access phase, is repeated every *2 ms*. The access to the wireless medium is centrally controlled by one station, the CC. H2 requires an exclusive frequency channel.

C. 802.11 and its new concepts for QoS support

The basic 802.11 MAC protocol is the Distributed Coordination Function (*DCF*) that works as listen-before-talk scheme, the Carrier Sense Multiple Access (*CSMA*). STAs transmit data packets after detecting that there is no other transmission in progress. However, if two STAs detect the channel as free at the same time, collisions occur. To reduce the probability of a collision, 802.11 defines a Collision Avoidance (*CA*) mechanism. As part of CA, before starting the transmission a STA has to perform a back-off mechanism. It has to keep sensing the channel for an additional random time after detecting the channel as being idle. Only if the channel remains idle for this additional time, the STA is allowed to initiate the transmission. The duration of this random time is counted as a multiple of a slot time (*9 µs* in 802.11a). Each STA maintains a so-called Contention Window (*CW*), which is used to calculate the number of slot times a STA has to wait before transmission. The CW size increases when a collision occurrs, i.e. transmitted data frames have not been acknowledged. This reduces the collision probability in case there is more than one STA trying to access the channel.

STAs that deferred from channel access because their random back-off time was larger than the back-off time of other STAs are given a higher priority when they try again to transmit. After sensing a channel as being idle again the STAs that deferred from channel access do not select a new random back-off time but continue to count down the time of the deferred back-off in progress. This results in a higher priority to a STA that deferred before. There is one situation when a STA is not required to perform the CA mechanism. A frame arriving at the STA may be transmitted immediately after detecting the channel as being idle for at least a fixed short time called DCF Interframe Space, *DIFS*, which is *34 µs* for 802.11a, if it is the first frame arriving at an empty transmission queue.

To reduce the hidden station problem inherent in CSMA, 802.11 defines a Request-to-Send/Clear-to-Send (*RTS/CTS*) mechanism. Before transmitting a long MAC frame that may collide and thus may waste a lot of capacity, it has the option to send a short RTS frame, followed by the CTS transmission by the addressed STA. The frames RTS and CTS include the information of how long it does take to transmit both the following data frame and the corresponding Acknowledge (*ACK*) response. Thus, other STAs close to the sender and the transmitter will not start any transmissions (a timer called Network Allocation Vector, *NAV,* is set). See Fig. 3 for an example of the DCF.

To support QoS, there are priority schemes currently under discussion. Task Group E (*TGe*) of the IEEE 802.11 defines enhancements to the above-described 802.11 MAC, called 802.11e, which defines Enhanced DCF (*EDCF*) and Hybrid Coordination Function (*HCF*). STAs, which operate under 802.11e, are called Enhanced STAs (*ESTAs*), and an ESTA, which works as the centralized controller for all other ESTAs within the same QBSS,[2] is called the Hybrid Coordinator (*HC*).

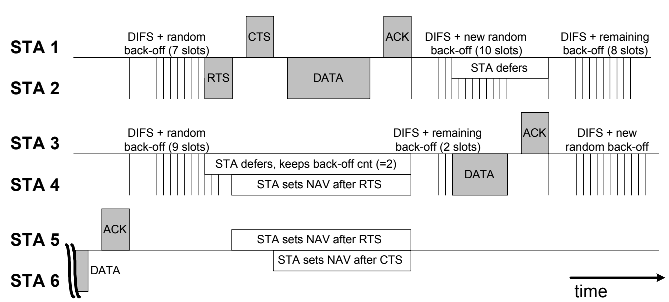


Fig. 3: Timing of the DCF in 802.11. STA 6 cannot detect the RTS frame of STA 2, but the CTS frame of STA 1.

[2] A BSS, which include of 802.11e-compliant HC and ESTAs.

The EDCF in 802.11e is the basis for the HCF. QoS is realized with the introduction of Traffic Categories (*TCs*). A single ESTA may implement up to eight TCs realized as virtual STAs inside an ESTA, with a parameter set that affects its behavior under EDCF rules.

With 802.11(e), there are two phases of operation, the Contention Period (*CP*) and the Contention Free Period (*CFP*), which alternate over time continuously. A CFP and the following CP comprise a *superframe* of 802.11. The EDCF is used in the CP, and the HCF is used in both phases, which makes this new coordination function hybrid.

One crucial feature of 802.11e MAC is the Transmission Opportunity (*TXOP*). A TXOP is defined as an interval of time when an ESTA has the right to initiate transmissions, defined by a starting time and a maximum duration. TXOPs are allocated in either CP or CFP. In the CP each TC within the ESTAs contends for a TXOP and starts an individual back-off after detecting the channel being idle for an Arbitrary Interframe Space (*AIFS*); the AIFS is at least DIFS, but can be enlarged individually for each TC. After waiting for AIFS each back-off sets a counter to a random number from the CW. The minimum size of the CW is another parameter dependent on the TC value. The back-off reduces the counter by one for every slot time, the medium is sensed idle after AIFS; when the counter reaches zero, the contention is won. When the medium is sensed busy before the counter reaches zero, the back-off must wait for the medium being idle for AIFS again, before continuing to reduce the counter. After any unsuccessful transmission attempt the next back-off is performed with a larger minimum size of the CW, increased by a Persistence factor (*PF*), to reduce the probability of a new collision on the medium. If the counters of two or more TCs in a single ESTA reach zero at the same time the *virtual collision* is avoided by a scheduler in the ESTA, that gives the TXOP to the highest TC. With these parameters per TC, i.e., AIFS, minimum CW size and the PF, a prioritized channel access can be achieved.

The HCF extends the EDCF access rules. At regular intervals the HC sends the beacon frame that includes information for synchronization of the QBSS, the QoS parameter sets for the TCs, and may start a CFP. The HC may allocate TXOPs to itself to initiate frame exchanges whenever it wants, however, only after detecting the channel as being idle for Point Coordination Function Interframe Space (*PIFS*), which is shorter than DIFS.

During CP, each TXOP begins either when the medium is determined to be available under the (E)DCF rules, i.e. after AIFS plus back-off time, or when the ESTA receives a special poll frame, the *QoS CF-Poll*, from the HC. The QoS CF-Poll from the HC can be sent without any back off. Thus the HC can place polled TXOPs in the CP using his prioritized medium access.

During the CFP, the starting time and maximum duration of each TXOP is specified by the HC, again using the QoS CF-Poll frames.

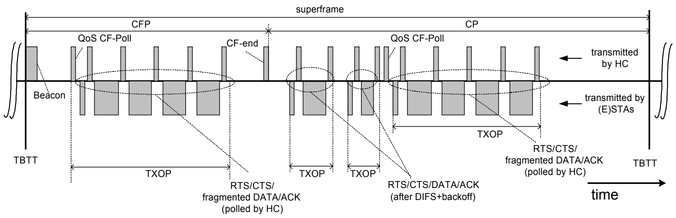


Fig. 4: The 802.11e MAC protocol. The concept heavily relies on transmission opportunities (TXOPs) allocated by the HC or grabbed via contention. Data frames can be transmitted via multiple fragments.

ESTAs will not attempt to get medium access on its own during the CFP, so only the HC may place TXOPs by sending QoS CF-Poll frames. The CFP ends after the time announced in the beacon or by a CF-End frame from the HC.

D. Basic Service Sets

There are various possible configurations of a BSS as illustrated in Fig. 5. A BSS may be an Independent BSS (*IBSS*) of 802.11 that by definition operates without an AP applying a de-centralized MAC protocol, i.e., the DCF. An IBSS does not support QoS. A BSS may be further a QoS-supporting BSS (*QBSS*) of 802.11a/e, coordinated by an HC. The EDCF with its limited QoS support is defined as part of the HCF.

The H2 standard does not define an equivalent name for a BSS; therefore we define another acronym, the H2-BSS (*HBSS*), for a set of H2 stations. The acronym HBSS reflects that we understand an H2-cell as a BSS. As H2 defines a centrally controlled MAC protocol, it supports QoS and is therefore another type of QBSS.

The acronym OBSS stands for Overlapping BSS, i.e. an interfering BSS. In the worst-case scenario the OBSS is a QBSS or HBSS; then it is called an *OQBSS*. The diagram in Fig. 5 shows the acronyms, which will be used in the following discussion.

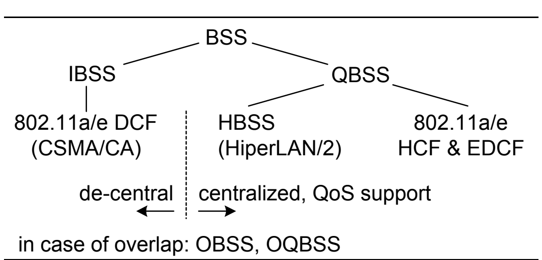


Fig. 5: Different types of BSSs, notation. The EDCF falls under the HCF as part of the QoS MAC enhancement.

III. Interworking

Interworking means the communication between 802.11a and H2 STAs in an integrated protocol where a centrally coordinating device, called CCHC, is capable of operating in both 802.11a and H2 modes. It requires a dual protocol inside this coordinator.

Our interworking proposal relies on the fact that the 802.11e MAC will have enhanced functionalities for QoS as proposed in 802.11e. Specifically, our solution is realized by applying the HCF 802.11e QoS-enabled MAC as found in the current draft of IEEE 802.11e [16].

A. The CCHC hybrid protocol

The CCHC is placed in a station, which has both 802.11a/e MAC/PHY and H2 MAC/PHY implemented. Basically, the CCHC works as the HC to 802.11a/e ESTAs and as the CC to H2 STAs (WTs/MTs). Within the limit of each TXOP, decisions regarding what to transmit are made locally by the MAC entity at the ESTA. It is natural to extend this concept for allocating H2 MAC frames to provide an uncomplicated interworking solution.

The CCHC, controls both 802.11a/e and H2 networks/systems, i.e. an HBSS and an 802.11a-QBSS. The CCHC must understand both systems/protocols completely. Fig. 6 shows the CCHC scenario. By allocating TXOPs to ESTAs and to H2 STAs the CCHC will have the full control over the frequency channel. As the H2 standard defines periodic transmission of frame synchronizations every *2 ms*, the H2 MAC frames have to be periodically allocated with a period of *n* 2 ms,* where *n* is an integer. As in the HCF and H2, all STAs have to be in the reception range of the beacon for understanding the management frames sent by the CCHC.

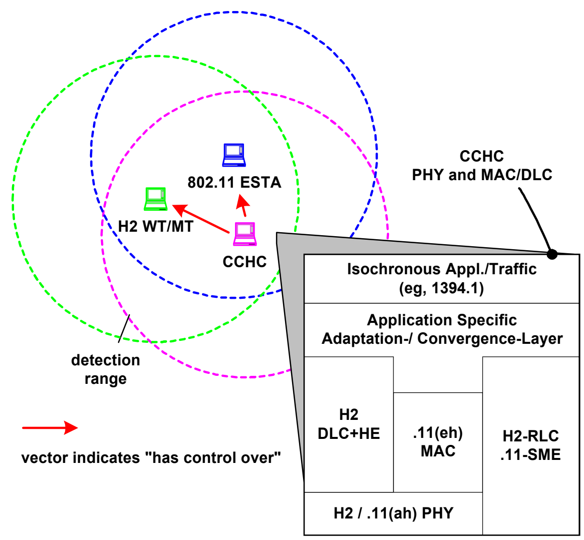


Fig. 6: CCHC coordinating H2 STAs (WTs/MTs) and 802.11a ESTAs. The figure indicates that all (E)STAs are in the range of CCHC, which is required for QoS support. Note that this requirement is present for all standard QBSS.

B. Frame structure of the CCHC

Fig. 7 shows the CCHC frame structure. It can be seen that within the CCHC superframe with an optional CFP, the CCHC allocates TXOPs in order to allow periodically scheduled H2 MAC frames. For a resource sharing, the H2 terminals experience the periodic *AP-Absence* announcement by CCHC, a concept in H2 that allows the H2-AP or CC to stop transmitting the periodic broadcast frames. Originally, AP-Absence was defined so as to let the AP/CC perform channel measurements. Here we use it for periodically switching between the twoMAC protocols. QoS CF-Poll is used by the CCHC to allocate TXOPs within the CP with high priority, i.e. after PIFS. In Fig. 7, four TXOPs are illustrated. The beacon defines the superframe structure and the TXOP limit broadcasted by CCHC via beacon frames. The first TXOP is allocated by CCHC. Because of this reason it is not restricted to TXOP limit in duration, but has to be finished before the end of CFP. However, the length of CFP is under control of the CCHC as well.

Another three TXOPs, which fall in the CP, are illustrated in Fig. 7. The first two are allocated by ESTAs after contention. These TXOPs are used for the normal operation of 802.11 (E)DCF. In order to allow periodically scheduled H2 MAC frames, the CCHC needs to grab the channel at the right moments. This may seem challenging during the CP. However, thanks to the HCF, the CCHC can use various techniques to grab the channel in CP. One way is to use its high priority over the EDCF channel access and transmit the QoS CF-Poll frame addressed to itself in advance right after the end of a TXOP. Thus, after the TXOP it waits for the duration of PIFS in order to transmit QoS CF-Poll for scheduling the next H2 MAC frames, now within CP. In this case since there is no ESTA being polled, the QoS CF-Poll is addressed to itself, i.e., CCHC. By transmitting the QoS CF-Poll, the CCHC can suppress all the ESTA within the QBSS during the period it wants to use for the H2 MAC frames. There are two more different ways for the CCHC to grab the channel. One is to transmit some downlink (i.e., CCHC to 802.11a ESTA) frames, and the other is to send QoS CF-Poll to grant TXOP to ESTA(s). Note that once the CCHC grabs the channel, it can continue to grab the channel by not allowing more than a specific time between two channel grabbing methods.

Clearly, the CCHC interworking solution does provide a simple technique for the combination of the two different protocols. In the next section we provide methods to establish the co-existence of QBSSs assuming that no co-ordination of medium access by one central STA, i.e., interworking, takes place.

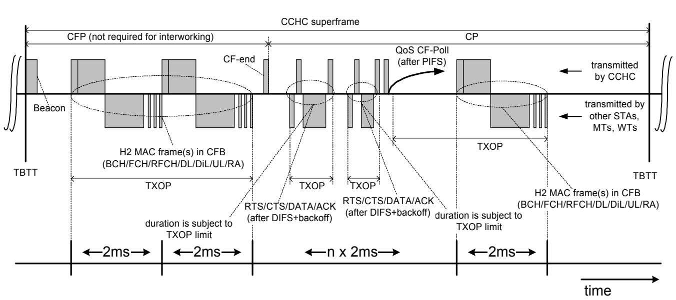


Fig. 7: The structure of the CCHC superframe. One superframe between two TBTTs is illustrated. H2 MAC frames are scheduled within periodically repeated TXOPs.

IV. CO-EXISTENCE OF OVERLAPPING BSSS

We now address the question of co-existence of overlapping QBSSs. We argue that establishing policies, i.e., the etiquettes that describe the behavior of competing CCHCs, can solve this complex problem.

A. Overlapping BSSs competing for radio resources

There are various types of BSSs, which may overlap with each other (*OBSSs*). One scenario is the overlapping IBSS, which is the simplest form of an 802.11 BSS. IBSSs operate in DCF only, performing CSMA/CA. Because an IBSS follows the coordination of an HC even if this HC is placed in a co-located OQBSS, this co-located OQBSS is always able to handle the overlapping IBSS without any QoS compromise. This is also the case if one of two co-located OQBSSs operates in EDCF only. Note that the HCF always has priority over EDCF. This coordination of the HCF requires that all STAs are in the range of the HC, i.e., the IBSS and the OQBSS do not partially overlap. The OQBSS problem gets worse in case overlapping QBSSs employ their own centrally controlled resource coordination, for example two CCHCs, or two H2-APs, or a scenario where one OQBSS is coordinated by an HC and another OQBSS is coordinated by a CCHC. Until now, this can only be handled by selecting different frequency channels upon detecting an overlapping QBSS, using DFS. As described earlier, DFS is available for HBSSs as part of H2 and is available for 802.11a as part of the 802.11h supplementary standard.[3] Some radio resource management schemes such as the reduction of transmitter powers and the selection of robust PHY modes will help to further reduce the problem of OQBSSs. However, in times of high offered traffic and a large number of QBSSs it is very desirable that QBSSs can share a single frequency channel and at the same time support the same level of QoS as if they do not have to share a frequency channel with a competing QBSS. It is natural to tackle this coexistence problem using game theory.

In the following, we assume a scenario of two fully overlapped QBSSs coordinated by the HCF, see Fig. 8.

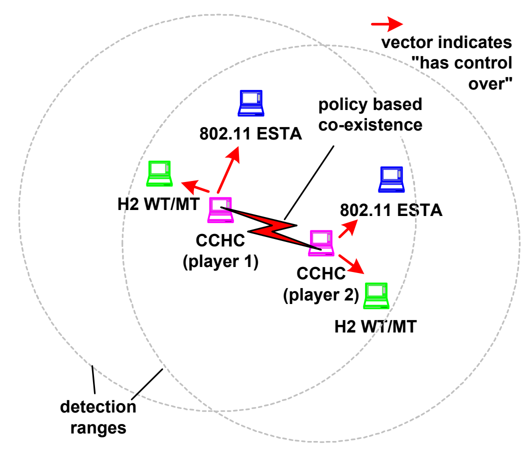


Fig. 8: Two BSSs sharing one frequency channel. Dynamic and fair resource allocation based on the demands is the objective of policies.

[3] IEEE 802.11h is an extension to the IEEE 802.11 MAC and 802.11a PHY being developed currently to define Dynamic Frequency Selection (*DFS*) and Transmit Power Control (*TPC*).

There is no hidden STA, which would be the case if the BSSs would only partially overlap. We further assume that the two QBSSs cannot find any other free frequency channel, and hence have to share resources by applying policy-based sharing rules.

B. The game model

We take the Cournot competition game-theoretic approach to study the coexistence between overlapping QBSSs coordinated by CCHCs [12]…[14].

The problem is modeled as a strategic game. A Cournot game in a strategic form consists of a finite set of players, the strategy profile for each player, a price function that is common knowledge between the players, and payoff functions that give utilities for each profile, i.e., set of actions. In the following we do not consider mixed strategies and allow only deterministic pure strategies. In our model of Cournot competition, an action taken as part of a strategy corresponds to the choice of resource utilization when knowing the demand of all players and thus knowing the price to be paid.

Competing CCHCs are modeled as rational players attempting to maximize their payoffs within a simple pricing scheme. Here, a payoff is a measurable quantity related to QoS (for example throughput, delay, jitter) a player receives after playing the game once. Rationality of players requires that players act as best response to the anticipated actions of its opponents.

Fig. 9 illustrates the strategic game for two players. Suppose that the beacon is successfully sent periodically by one of the two CCHCs. In case the two CCHC cooperate, they request alternating TXOPs. Success of allocation, number and duration of the TXOPs represent the level of cooperation. The demand of resources per CCHC (per player) defines the number, size and times of the TXOPs. If throughput is the only QoS parameter involved, the demand assigns a numerical value of *0…1* for a capacity demand of *0…100%* per superframe. Within this abstract model, we look at the TXOPs directly allocated by a CCHC. We do not take into account that there are other TXOPs allocated under the rules of (E)DCF.

Let N be the number of players, in our case, $N=2$. The periodic superframes define discrete time stages numbered by n. In each superframe, i.e., time stage, a player allocates a quantity of capacity $x_i(n)$.

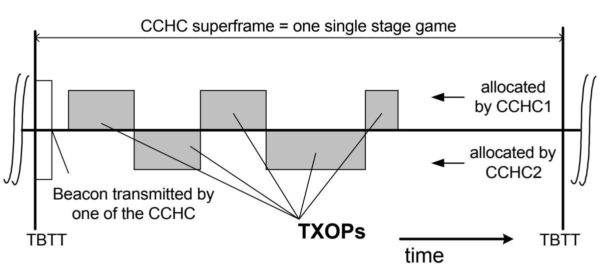


Fig. 9: One superframe is modeled as single-shot (i.e., single stage) strategic game of two players. In case the two CCHCs cooperate, they request alternating TXOPs.

Allocating or demanding capacity is an action of a player i, where $x_i(n) \in A_i$, the set of feasible actions of player i. Suppose that there is a common knowledge about an abstract price function. The unit price of capacity in a time instance $p(n)$ is a function of the aggregate demand $x(n)$ at time n of all N involved players

$$p(n) = \Phi(x(n)), \quad \text{with } x(n) = \sum_{i=1}^{N} x_i(n), \tag{4.1}$$

where $\Phi(\cdot)$, the corresponding price function is increasing and differentiable, see Fig. 10 for an example. The term price suggests a monetary transaction, but it does not involve real money. The following figure shows a linear price function as a function of the demand of two players.

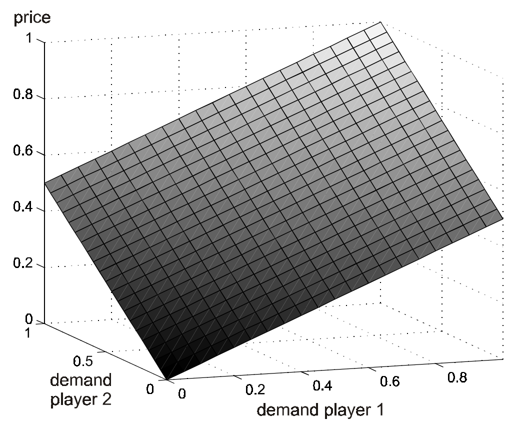


Fig. 10: The normalized price vs. demand in a two-player Cournot competition game. The price function is common knowledge as part of the game model.

Based on its individual QoS demand, player i obtains a utility function $u_i(x_i(n))$ for time instance n. The utility function is an abstract representation of the QoS parameters, associated with the services the players are carrying. An example is shown in Fig. 11. The utility function $u_i(\cdot)$ is increasing, strictly concave[4], and differentiable. The utility function $u_i(\cdot)$ represents the preference relation $\succsim_i$ of player i in the sense that $u_i(a) \geqslant u_i(b)$ whenever $a \succsim_i b,\ a,b \in A_i$.

Player i in a single-stage play of the Cournot competition tries to maximize its payoff $V_i(\underline{x})$:

$$V_i(\underline{x}, n) = u_i(x_i(n)) - x_i(n)\Phi(x(n)). \tag{4.2}$$

Here, $\underline{x}=(x_1, \dots x_N)$ is a vector of demands. As we model the single stage game, we neglect the index n in the following without loss of generality. With the payoff function we have a complete description of a game G among players where $V_i(\underline{x})$ denotes the single-stage payoff to the player i as function of the actions of all players:

$$G = \langle N, \underline{x}, u_i \rangle = \langle N, \underline{x}, \succsim_i \rangle.$$

[4] A function f:ℝ→ℝ (equivalently, a set valued function f:X→X) is strictly concave if f(ax+(1-a)x') > af(x)+(1-a)f(x') for all x, x'∈ℝ (respectively, for all x, x'∈X), and all a∈[0,1].

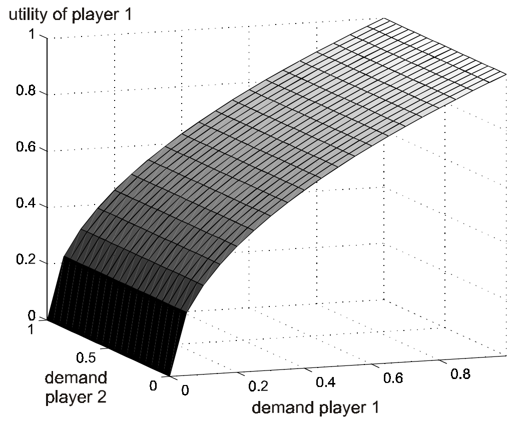


Fig. 11: Utility of player 1 vs. demand in our model of two players.

In contrast to decision problems, in a game each player has only partial control over the environment. The payoff of each player depends not only upon its actions but also upon the actions of other players. Fig. 12 shows the payoff $V_1(\underline{x})$ of player 1 in our two-player example for the price and utility functions presented above.

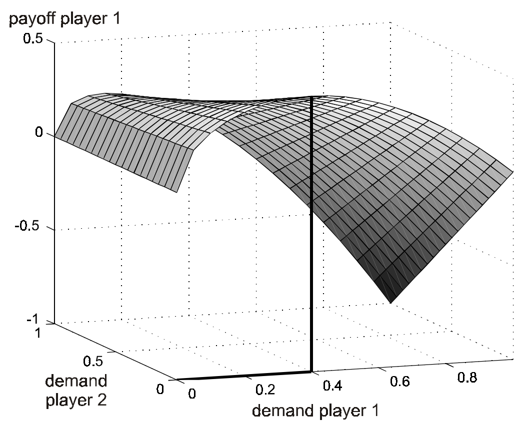


Fig. 12: Single-stage payoff to player 1 vs. demand in our model of two players. Indicated is the individual maximum payoff. If the aggregate demand of the two players exceeds 1, i.e., 100% capacity) the payoff falls to values of less than 0.

A commonly used solution concept for a single stage game is the Nash equilibrium (*NE*) [12]. The notion of a NE captures a vector of demands $\underline{x}^*$ of the players of our game in which the players act rationally by responding to the correct expectation about their opponent players behavior. A Nash Equilibrium of a strategic game $G=\langle N,\underline{x},u_i\rangle$ is a vector $\underline{x}^*\in A$ of actions with the property that for every player $i \in 1...N$

$$(x_{-i}^*, x_i^*) \succsim_i (x_{-i}^*, x_i) \quad \forall x_i \in A_i . \tag{4.3}$$

Here, x^*_{-i} denotes x^*_j, $j\neq i$. The set

$$A = \times_{i\in N} A_i , \tag{4.4}$$

which is the Cartesian product of all N sets of pure strategy.

In NE, no player can profitably deviate from its strategy, given the action of the other players; no player has reason to change its demand. The NE is characterized by the fact that for each player x^*_i maximizes $V_i(\underline{x})=V_i(x_i, x_{-i})$ over $x\in A_i$. A necessary condition for $\underline{x}$ to be an NE is that

$$0=\frac{d}{dx_i}V_i(\underline{x}) \quad \forall i=1...N,$$

that means

$$0=\frac{d}{dx_i}u_i(x_i)-\Phi(x)-x_i\frac{d}{dx_i}\Phi(x) \;\; \forall i=1...N. \tag{4.5}$$

Differentiability is given in our example but cannot be assumed in general. In Fig. 12 the payoff $V_1(\underline{x})$ is concave in x_1. Thus (4.5) is a sufficient condition for NE [12].

When viewing our co-existence scenario as a game of active players, several questions can be answered by applying the theory of games, such as whether there exists an NE, whether this NE is unique, and whether the dynamic system actually converges to this unique NE. The unique NE in our example is $\underline{x}^*=(x_1^*=0.303, x_2^*=0,303)$, which is not the optimal outcome for the game. When played once, the rationally achieved $\underline{x}^*$, to which our single-stage game converges to, does not reflect the co-operative optimum for all players. The co-operative optimum is referred to as social optimum and illustrated in Fig. 13.

At high level of co-operation, a CCHC seeks to establish the ability to guarantee -or at least to support- the allocation of resources for contracted QoS levels of services within its BSS. It generally attempts to reach a guaranteed (supported) continuous or periodic availability of resources in time division based sharing and coexistence with OQBSSs. Specifically for the H2 mode of operation, the CCHC must support that always the periodic idle duration between H2 intervals is clearly defined, i.e., the CCHC must guarantee that there is no unpredictable long delay of H2 MAC frames. If that is achieved through co-operation, QoS in H2 can be supported.

Cooperation between competing players evolves only in case individuals repeatedly interact with each other [15].

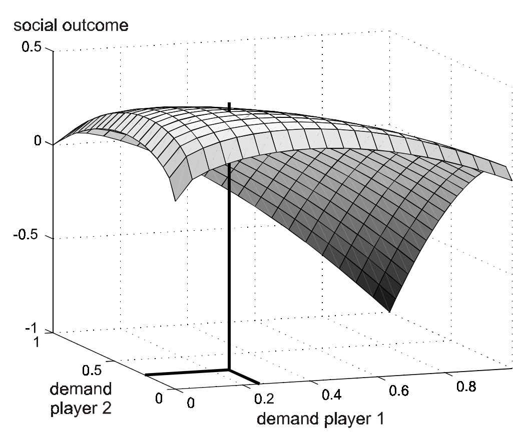


Fig. 13: Social optimum surface vs. demand of the two players. The figure shows the accumulated payoff of all players. The maximum achievable outcome is not the best response equilibrium. To converge to this point, rational players need to co-operate.

A repeated interaction is a realistic assumption specifically for the co-existence scenarios, which we are discussing here. Overlapping BSSs typically do not share resources only once, i.e., during one superframe. Rather they have to take into account the actions of the other BSS for a very large number of superframes. Thus, our single-shot game model must be extended by the theory of repeated games. The idea behind the model of a repeated game is that if the game is played repeatedly then a stable cooperation occurs if all rational players believe that a defection will terminate the cooperation.

Non-cooperative game theory indicates that the etiquette involves that each player may punish any player who misbehave. The termination of cooperation must result in a subsequent loss for the player that gained shortly after defection. In a stable repeated game this loss must outweigh the gain. Derived from the social science, the strategies that establish cooperation will be the main focus of our future work.

V. POTENTIALS OF A COMBINED PROTOCOL FOR MULTIHOP

The interworking solution described in Sect. III is only feasible in a one-hop scenario, in which a central station like the CCHC can organize the access of all stations in a BSS. In a multi-hop scenario however, there is no unit that has a centralized control of the complete network, i.e. multiple *cells* or *clusters* of BSSs.

In the ad hoc multi-hop mode of operation of the 802.11a system, the access to the wireless medium is based on the (E)DCF, i.e. a decentralized CSMA/CA protocol.

The H2 standard does currently not define any multi-hop mode of operation. However, we have presented how several H2 cells or clusters of stations could be inter-connected to build a multi-hop network [4], [5]. The concept is illustrated in Fig. 14.

In each cluster, one station, i.e., the CC, organizes the access of all stations (terminals) inside the cluster. Terminals of two different clusters can communicate via terminals that are able to participate in both clusters. A terminal can only participate in clusters, if it is in the transmission range of the CCs in the respective clusters. The traffic can then be forwarded from one cluster to another by the forwarding terminal in the overlap zone of the clusters, see Fig. 14.

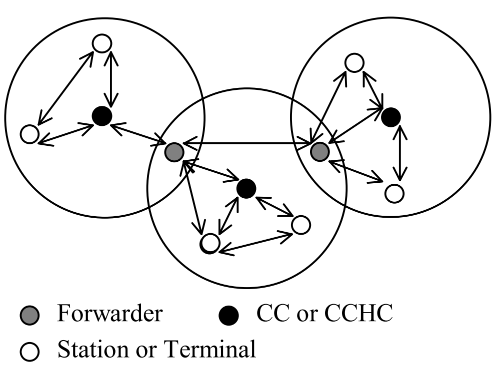


Fig. 14: Cluster-based Multi-hop concept

Each cluster operates on a different frequency. A forwarding terminal therefore has to switch in-between the two frequencies of the inter-connected clusters or has to be equipped with two transceivers.

We propose to use a similar approach for the interworking of 802.11a and H2 in a multi-hop environment. An 802.11a and a H2 multi-hop network should operate on different frequencies. Note that the 802.11a system in (E)DCF mode operates on a single frequency, whereas the multi-cluster CCHC network would occupy several frequency channels.

Terminals, which support both MAC protocols, should switch between the two frequencies of the 802.11a multi-hop network and the CCHC cluster to which the terminal is associated. These terminals would serve as protocol bridges between the two networks and will be called Protocol Bridge Terminal (*PBT*) in the following.

It has to be considered what happens if the PBT is absent from one of the two systems to participate in the other system. In case of the H2 multi-hop network, the same problem arises in case that a forwarding terminal inter-connects two H2 clusters. It is solved in the way that the CC is informed about the absence of the forwarding terminal a priori. Therefore the CC will not grant any resources for transmissions to the forwarding terminal, respectively PBT, during its absence.

Considering the 802.11a (E)DCF, the absence of a terminal is somewhat more critical, because there is no central entity that could withhold any transmissions to the absent station. To cope with this problem we propose the concept of a Terminal Representative (*TR*): Each PBT chooses another 802.11a terminal as its TR during its absence. The TR is informed about its role by a message handshake with the PBT. During the absence of the PBT, the TR is responsible for receiving and buffering all data that is bound for the PBT. When the PBT is back in the 802.11a network again, the TR will then forward the data to the PBT. However, all STA can buffer the frames to be sent to the PBT while the PBT is absent from the current channel as long as they are informed, i.e., as long as they are in the range of the PBT. If a CCHC should be active in the 802.11a network, we propose that this CCHC should always be chosen as TR by any PBT in its range. Note that the absence times of a PBT should be in the order of several milliseconds.

A possible solution for the PBT to operate without a TR has been proposed in the framework of the inter-connection of two H2 clusters [5] but could as well be used for the interworking of 802.11a and H2 multi-hop networks. The idea is to equip a forwarder, respectively a PBT in the interworking case, with two transceivers. The PBT could then operate in both systems at the same time and no TR would be required. Finally, it should be stressed that the proposed concept of PBTs and TRs can not only be used to inter-connect an 802.11a and a H2 multi-hop network, but would also be solve the problem how to operate an 802.11a (E)DCF system on several frequency channels. In the latter case a PBT would have a TR on each of the 802.11a frequency channels it is connecting.

VI. CONCLUSIONS AND OUTLOOK

This contribution gives an in-depth analysis of new approaches for co-existence and interworking, and looks on the overlapping BSS problem where policies are required to support a fair sharing of the resources under QoS constraints. Our solutions to provide interworking and co-existence between 802.11a and H2 require only minor changes of the two standards. The interworking concept has been presented by the authors to the two standardization bodies, i.e., ETSI BRAN and IEEE 802.11 Working Group.

It is important to note that all interworking and coexistence proposals discussed here intend to support isochronous traffic by allowing fair resource sharing between competing individuals. The CCHC coordination function will render the time-sharing of the bandwidth between 802.11a/e and H2 without sacrificing the QoS support of both systems. If a full interworking is required, our approach based on the new HCF enables QoS support for both system types.

Future work will include the extension of the game model. Using the abstract pricing model described above as the game that is repeatedly played, we will be able to define strategies that support mutual cooperation and thus maximize the desirable outcome based on the individual demands. We will look at the *structure of behavior* of players that may be interpreted as social norm or *etiquette*. It is this etiquette for WLANs we are looking for.

LIST OF ABBREVIATIONS AND REFERENCES

802.11	IEEE 802.11
ACK	Acknowledgement
AIFS	Arbitration Interframe Space
AP	Access Point
BRAN	Broadband Radio Access Networks
BSS	Basic Service Set
CA	Collision Avoidance
CC	Central Controller
CF	Coordination Function
CFP	Contention Free Period
CP	Contention Period
CSMA	Carrier Sense Multiple Access
CA	Collision Avoidance
CTS	Clear-to-Send
CW	Contention Window
DCF	Distributed Coordination Function
DFS	Dynamic Frequency Selection
DIFS	DCF Interframe Space, *34 μs* in 802.11a
EDCF	Enhanced DCF
ESTA	Enhanced STA
ETSI	European Telecommunications Standards Institute
H2	HiperLAN/2
HBSS	H2-BSS
HC	Hybrid Coordinator
HCF	Hybrid Coordination Function
HiperLAN	High Performance Local Area Network
IBSS	Independent BSS
IFS	Interframe Space
MAC	Medium Access Control
MT/WT	Mobile Terminal/Wireless Terminal
NAV	Network Allocation Vector
NE	Nash Equilibrium
OBSS	Overlapping BSS
OFDM	Orthogonal Frequency Division Multiplex
PIFS	Point Coordination Function IFS, *25 μs* in 802.11a
PBT	Protocol Bridge Terminal
PF	Persistence Factor
PHY	Physical Layer
QBSS	QoS-supporting BSS
QoS	Quality of Service
RTS	Request-to-Send
SIFS	Short IFS, *16 μs* in 802.11a
STA	Station
TBTT	Target Beacon Transmission Time
TC	Traffic Category
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TGe	Task Group E
TPC	Transmit Power Control
TXOP	Transmission Opportunity
U-NII	Unlicensed Network Information Infrastructure
WLAN	Wireless Local Area Network
WM	Wireless Medium

[1] Mangold, S. and Hmaimou, M. and Wijaya, H., "Coexistence of IEEE 802.11a and ETSI BRAN HiperLAN/2: The Problem of Fair Resource Sharing in the License Exempt Band at 5GHz," in *Proc. IEEE Int. Conf. on Third Generation Wireless Communications*, pp. 530-536, June 2000.

[2] Mangold, S., "Game Theoretical Approaches for Spectrum Sharing in Wireless Communication," in *Proc. 7th Viennese Workshop on Optimal Control, Dynamic Games and Nonlinear Dynamics*, May 2000.

[3] Habetha, J. and Mangold, S. and Wiegert, J., "802.11 versus HiperLAN/2 - a comparison of decentralized and centralized MAC protocols for multihop ad hoc radio networks," in *Proc. 5th World Multiconference on Systemics, Cybernetics and Informatics (SCI)*, Orlando, July 2001.

[4] Habetha, J. and Nadler, M., "Concept of a wireless centralised multihop ad hoc network," in *Proc European Wireless*, Dresden, Sep 2000.

[5] Habetha, J. and Wiegert, J., "A comparison of new single- and multiple-transceiver data forwarding mechanisms for multihop ad hoc wireless networks," in *Proc Symposium on Performance Evaluation of Computer and Telecommunication Systems (SPECTS),* Orlando, July 2001.

[6] Walke, B. and Esseling, N. and Habetha, J. and Hettich, A. and Kadelka, A. and Mangold, S. and Peetz, J., "IP over Wireless Mobile ATM - Guaranteed Wireless QoS by HiperLAN/2, " *Proc. IEEE*, vol. 89, pp. 21-40, Jan 2001.

[7] Walke, B., *Mobile Radio Networks*, Chichester, Sussex, U.K.: *Wiley & Sons Ltd.*, 2nd ed., 2001.

[8] Qijao, D. and Choi, S., "Goodput enhancement of IEEE 802.11a wireless LAN via link adaptation," in *Proc. IEEE ICC'2001,* Helsinki, Finland, June 2001.

[9] Mangold, S. and Choi, S. and Esseling, N., "An Error Model for Radio Transmissions of Wireless LANs at 5GHz," in *Proc. Aachen Symposium 2001*, Aachen, Germany, Sept. 2001.

[10] Khun-Jush, J. and Schramm, P. and Wachsmann, U. and Wenger, F., "Structure and performance of the HIPERLAN/2 physical layer," in *Proc IEEE VTC Fall-1999*, Amsterdam, The Netherlands, pp. 2667-2671, Sep 1999.

[11] Li, H. and Malmgren, G. and Pauli, M., "Performance comparison of the radio link protocols of IEEE 802.11a and HIPERLAN/2," in *IEEE Proc VTC Fall-2000*, Boston, USA, Sep 2000.

[12] Fudenberg, D. and Tirole, J., *Game Theory. MIT Press*, 1998.

[13] Osborne, M. J. and Rubinstein, A., *A Course in Game Theory*, *MIT Press*, 1997.

[14] Ganesh, A. and Laevens, K. and Steinberg, R., "Dynamics of congestion pricing," Technical Report, Microsoft Research, June 2000.

[15] Axelrod, R., *The Evolution of Cooperation,* New York: *Basic Books*, Inc., 1984.

[16] IEEE 802.11 WG, *Draft Supplement to STANDARD FOR Telecommunications and Information Exchange Between Systems - LAN/MAN Specific Requirements - Part 11: Wireless Medium Access Control (MAC) and physical layer (PHY) specifications: Medium Access Control (MAC) Enhancements for Quality of Service (QoS)*, IEEE 802.11e/D1.2, March 2001.