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# Spectrum Utilization and Congestion of IEEE 802.11 Networks in the 2.4 GHz ISM Band

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Jan-Willem van Bloem<sup>1</sup>, Roel Schiphorst<sup>1</sup>, Taco Kluwer<sup>2</sup>  
and Cornelis H. Slump<sup>1</sup>

<sup>1</sup>*University of Twente, PO Box 217, 7500 AE Enschede, The Netherlands;  
e-mail: {j.w.h.vanbloem, r.schiphorst, c.h.slump}@ewi.utwente.nl*

<sup>2</sup>*Radiocommunications Agency Netherlands, PO Box 450, 9700 AL Groningen,  
The Netherlands; e-mail: taco.kluwer@agentschaptelecom.nl*

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## Abstract

Wi-Fi technology, plays a major role in society thanks to its widespread availability, ease of use and low cost. To assure its long term viability in terms of capacity and ability to share the spectrum efficiently, it is of paramount to study the spectrum utilization and congestion mechanisms in live environments. In this paper the service level in the 2.4 GHz ISM band is investigated with focus on today's IEEE 802.11 WLAN systems with support for the 802.11e extension. Here service level means the overall Quality of Service (QoS), i.e. can all devices fulfill their communication needs? A cross-layer approach is used, since the service level can be measured at several levels of the protocol stack. The focus is on monitoring at both the Physical (PHY) and the Medium Access Control (MAC) link layer simultaneously by performing respectively power measurements with a spectrum analyzer to assess spectrum utilization and packet sniffing to measure the congestion. Compared to traditional QoS analysis in 802.11 networks, packet sniffing allows to study the occurring congestion mechanisms more thoroughly. The monitoring is applied for the following two cases. First the influence of interference between WLAN networks sharing the same radio channel is

investigated in a controlled environment. It turns out that retry rate, Clear-To-Send (CTS), Request-To-Send (RTS) and (Block) Acknowledgment (ACK) frames can be used to identify congestion, whereas the spectrum analyzer is employed to identify the source of interference. Secondly, live measurements are performed at three locations to identify this type of interference in real-live situations. Results show inefficient use of the wireless medium in certain scenarios, due to a large portion of management and control frames compared to data content frames (i.e. only 21% of the frames is identified as data frames).

**Keywords:** interference, IEEE 802.11e, ISM band, congestion, cross-layer, spectrum sensing.

## 1 Introduction

Commodity wireless broadband, e.g., Wi-Fi technology, plays a major role in society thanks to its widespread availability, ease of use and low cost. Many new applications have emerged for such technologies, intelligent transportation systems (ITS), Dynamic Spectrum Access (DSA) systems and offloading of traffic from cellular networks. Because the role of Wi-Fi technology is becoming increasingly important, its long term viability in terms of capacity and ability to share spectrum efficiently, must be assured. Current practice shows already that Wi-Fi technology is not very efficient and there is a risk of collapse in certain scenarios, like high density video and data off-load from cellular networks.

In this paper we focus on the crowded 2.4 GHz ISM band. The number of wireless devices (smartphones, laptops, sensors) that use this band is rapidly increasing. In many urban areas not only many WLAN networks can be found, also other systems like Bluetooth, Zigbee and wireless A/V transmission systems use this band. On the other hand there is only a limited amount of spectrum available. So it is very likely that interference between systems in this band will occur. Due to the rapid increase of wireless devices, interference is expected to become even more important. In this paper we address this issue by providing a setup to measure the service level - i.e. can all devices fulfill their communication needs - in this band with focus on WLAN standard IEEE 802.11e. The upcoming IEEE 802.11e is an extension of the 802.11 Wireless Local Area Network (WLAN) standard and is developed to enhance Quality of Service (QoS) support. Furthermore, note that IEEE 802.11e has been incorporated into the current published IEEE 802.11

standard to which we refer - with slight abuse of notation - as IEEE 802.11e. On the other hand, we refer to the traditional IEEE 802.11 technology without QoS support as legacy IEEE 802.11 systems.

The service level measurements can be split into two parts: utilization and congestion. Utilization or spectrum sensing means how much of the 2.4 GHz ISM band is in use for a certain area. When the utilization has been measured, it is still unknown what the quality is of the wireless connections i.e. degradation cannot be measured; a measure for quality is congestion. Basically it analyzes the frame types transmitted through the wireless medium. Congestion occurs if the retry frame rate or the number of control frames is high. WLAN systems often use these frames to mitigate interference from other WLAN networks. Measuring the service level is an crucial parameter to assess the efficiency of the WLAN networks on other wireless networks and to identify co-existing issues. For the co-existence of competitive 802.11e networks the available resources have to be shared by overlapping and competing WLANs with high offered traffic load. Measuring and assessing the QoS of competing overlapping 802.11e compatible WLANs is the main topic of this paper.

The paper is organized as follows. First in section 2 the related work on monitoring QoS is highlighted. Next, in Section 3 the 802.11(e) co-existence mechanisms are presented. In Section 4 the influence of overlapping 802.11e WLANs on the same radio communication channel is investigated based on measurements set up in a controlled environment. In Section 5 the monitoring results, taken in real environments without control, are presented. Section 6 concludes the paper.

## **2 Related Work on Monitoring QoS**

The OSI protocol stack of the IEEE 802 standard consists of five layers where the lower two layers involve the wireless aspects of communication, i.e. the Physical (PHY) layer and the Medium Access Control (MAC) link layer. To assess the overall Wi-Fi QoS the monitoring must take place at these lower two layers. At the PHY layer this entails a threshold-based approach to determine spectrum occupation. This value can be used to assess utilization of the band. On the other hand, at the MAC link layer the total frame rate and retry frame rate have been found to be good parameters for quantifying the level of utilization and network degradation [37]. In addition, monitoring of the proportions of the different MAC link frame types can be used to assess the overhead in a Wi-Fi network, i.e., data, management and control (e.g.

Clear-to-Send(CTS), Request-to-Send (RTS), and (Block) Acknowledgment (ACK) frames. Much of the papers discuss the QoS on the MAC link layer only, i.e. in [18, 19] the performance evaluation of 802.11 WLAN systems is provided and in [7, 25, 27, 28] the 802.11e MAC link layer QoS. The advantage herein lies in the broad range of MAC link layer specific aspects and protocols which can be modeled and compared. Notice that in this paper we use both RF spectrum and MAC link layer monitoring in order to address the overall QoS.

Not much related literature has been found on overall QoS. First, a description of the overall Wi-Fi QoS monitoring is provided in *Estimating the Utilization of Key License-Exempt Spectrum Bands*, Final report, issue 3, April 2009 by Mass Consultants Limited commissioned by the British regulator Ofcom [37]; here monitoring takes place at various locations in the UK and live readings are obtained. In the latter report the QoS is assessed at the MAC link layer level but is only monitored at the highest abstraction level, i.e., whether the type of frame is data, management or control; this means that no deep packet inspection is carried out (e.g. ACK, RTS, CTS, etc) so that a description of the occurring mechanisms cannot be provided thoroughly. Furthermore, in [34] the total QoS is assessed of WLAN systems in live environments using a cognitive radio approach. Regarding monitoring QoS, the impact of overlapping WLAN interference is not addressed in the above-provided papers.

## **2.1 QoS: Overlapping WLANs**

The problem of overlapping WLANs is for legacy 802.11 systems mainly focused on co-channel interference. Note that in this paper we do not cover adjacent channel interference (e.g. see [26, 36]) for the sake of brevity. Elaborating on co-channel interference simulation based studies – using game theory models – are provided e.g. in [18, 23], and experimental studies in [4, 12, 13]. This entails MAC link layer performance models for assessing QoS; mainly the 802.11 interference impact on concurrent data throughput is investigated. For instance, it is shown in [4] that the throughput remained nearly constant irrespective of the distance between the 802.11 Access Points (APs), indicating that distance does not have an effect on the throughput as long as the APs are in the carrier sensing range. In addition, in [13] the performance of a particular AP in a highly congested environment is evaluated, i.e. many concurrent WLAN networks. Here the live recordings show that in case of bad link quality the AP becomes inactive for a while,

i.e. the AP operates in cycles of respectively activity and inactivity. Furthermore, the related problem of 802.11 hidden node issues and the impact of the RTS/CTS mechanism are addressed in [14]. However, a drawback of the above-mentioned studies is that 802.11e is not taken into account.

Regarding 802.11e, stochastic simulations on overlapping 802.11e WLANs are provided in [21, 22, 24, 25]. This entails a 802.11e MAC link layer investigation using respectively the aggregate data throughput and data packet delay as performance metrics. Another simulation study on the related problem of hidden node terminals in the vicinity of 802.11e WLAN is given in [16]. Note that the advantage of [16,21,22,24,25] lies in the thorough theoretical research of overlapping 802.11e networks. However, the experimental work and the overall QoS are beyond the scope of their work.

## **2.2 Contributions**

To assess the overall QoS for 802.11 systems – in highly congested environments with overlapping WLANs – an experimental validation is required. In line with this, the main contributions of this paper are:

- A measurement setup to measure the congestion in the 2.4 GHz ISM band. The setup is able to analyze three WLAN channels in parallel. In addition, the setup allows to identify which frame types (and sub fields) are transmitted, useful to identifying congestion (This setup is an extension of the work by Mass Consultants [37]).
- Reporting the results of measurements in a controlled environment where the interference of a second WLAN network is measured. From these results one can conclude that the RTS/CTS mechanism found in the WLAN standard (used for the hidden node problem) is one of the main sources of congestion. WLAN networks often identify interference as a hidden node.
- Reporting the experimental results of devices that use the new 802.11e extension.
- Reporting the results of measurements in a live environment (college room, office room, city center). The results reveal that for a college room only 21% are actual data type frames. Almost 70% are control frames.

## **3 IEEE 802.11 Co-existence Mechanisms**

In this section a short overview of legacy 802.11 mechanisms is provided to access the shared medium; subsequently the mechanisms of its enhanced

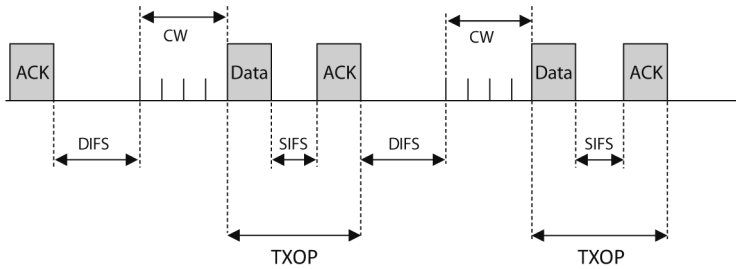


Figure 1 The 802.11 DCF protocol timeline. For each data frame transmission a back-off period precedes. The bounded time interval reserved for transmission is denoted as Transmission Opportunity (TXOP) using the 802.11e terminology.

version 802.11e are highlighted. It is important to know these co-existence mechanisms to analyze the experimental results.

### 3.1 Legacy IEEE 802.11

The legacy 802.11 WLAN technology is characterized by its best-effort service (no guarantee of any service level to users/applications). In legacy 802.11 WLAN the PHY layer comprises 11 channels in the 2.4 GHz ISM band where each channel has a bandwidth of 20 MHz.

On the other hand, legacy 802.11 MAC link layer defines two procedures for 802.11 stations to share a common radio channel [3], i.e., Distributed Coordination Function (DCF) and Point Coordination Function (PCF). Here the mandatory DCF is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and operates in a listen before talk fashion; DCF is designed for time-bounded services. Compared to DCF, the optional PCF is a contention-free scheme using a central controller to schedule channel access [5]. Note, in the sequel only DCF is highlighted as most of the current 802.11 technologies operate in DCF mode only. The timing of the DCF scheme is depicted in Figure 1. Essential for DCF is the so-called Contention Window (CW) which is maintained at each station. Based on the size of the CW a Back-off Counter (BC) is determined as a random integer drawn from an uniform distribution over the interval  $[0, CW]$ . Note, a station is allowed to transmit a frame if the channel stays idle during the so-called DCF Interframe Space (DIFS) time interval and if it subsequently remains idle during the followed-up back-off process. In addition, for each successful frame reception the receiving station immediately sends ACK frame. Note that the ACK frame is transmitted after a Short IFS (SIFS), which is shorter

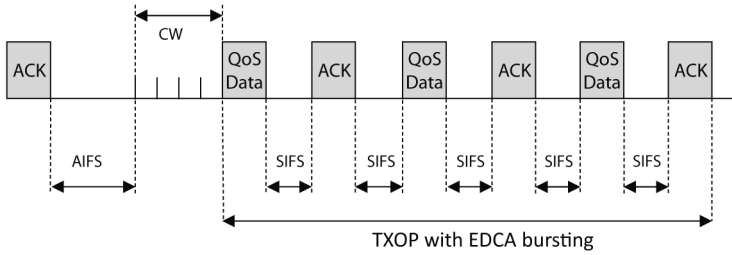


Figure 2 The 802.11e EDCA timeline. Using the 802.11e terminology, the MAC data units are denoted as QoS data frames.

than the DIFS, i.e.  $DIFS = SIFS + 2 * Slottime$ . To mitigate congestion the following mechanisms occur as part of DCF: a transmission failure causes the CW to increase in an exponential fashion; the other way around, the CW is decremented linearly in case of successful transmission (i.e. ACK reception).

### 3.2 IEEE 802.11e

#### Occurring 802.11e Mechanisms without Communication Errors

To support QoS the IEEE 802.11 Task Group E has defined 802.11e [2, 30] as an enhancement to the above-described legacy 802.11 technology. At the PHY layer the 802.11e standards allows 20/40 MHz mode protection. This entails automatic channel switching possibilities in order to be compliant with legacy 802.11 systems [6]. However, a maximum bandwidth width of respectively 22 and 42 MHz is tolerated due to the extra 1MHz on each end that the channel is allowed to attenuate. At the 802.11e MAC link layer the Enhanced Distributed Channel Access (EDCA) protocol is defined to provide priority-based distributed channel access [6]. The EDCA is controlled by the HC (Hybrid Coordinator) – resided in the AP – and is developed to be compatible with the legacy 802.11 MAC protocol. Note, in literature [7] EDCA is also referred to as Enhanced (DCF), i.e. EDCF; moreover, according to the 802.11e terminology a data packet needs to be denoted as *QoS Data*. Under the EDCA, each channel access does not result necessarily in a single data frame transmission but more data frames are allowed in burst transmissions [31]. This means that a particular station – with gained channel access – has the right to initiate transmissions during the granted Transmission Opportunity (TXOP) time interval [8, 15, 20, 33]. In addition, another 802.11e parameter is defined: Arbitration Interframe Space (AIFS). Here AIFS is the legacy 802.11 DIFS equivalent, but its size depends on the frames/packet

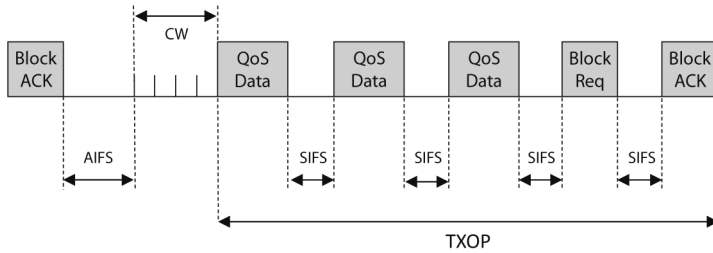


Figure 3 The IEEE 802.11e Wireless LAN with Block Acknowledgments. After a burst of consecutive data frames a Block Request frame is sent by the transmitter which in turn is acknowledged with a Block ACK frame by the receiver.

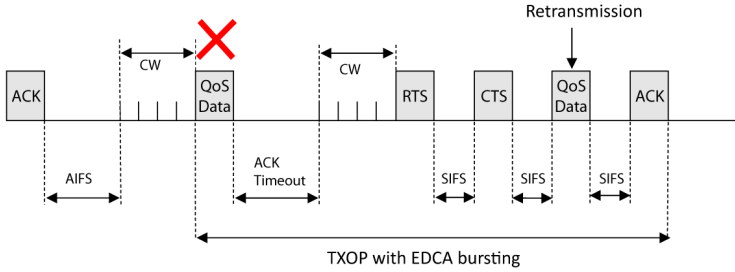
priority (note that AIFS is at least DIFS). Furthermore, in EDCA-TXOP mode the CW size is made significantly smaller than that for 802.11 DCF. The timeline of 802.11e communication in EDCA-TXOP mode is depicted in Figure 2. As a consequence, the higher throughput of EDCA-TXOP can cause jamming interference to other systems operating in the 2.4 GHz ISM band [35].

In highly congested wireless environments the 802.11e devices are allowed to switch transmission mode in order to increase throughput and reduce overhead, but this is not obligatory [11, 17, 29]. This is achieved by acknowledging several consecutive data frames with one response, i.e. a block ACK. The decision on the mode of transmission is made by the AP, and this can be set up within an ongoing TXOP transmission. The 802.11e block ACK feature is explained in Figure 3.

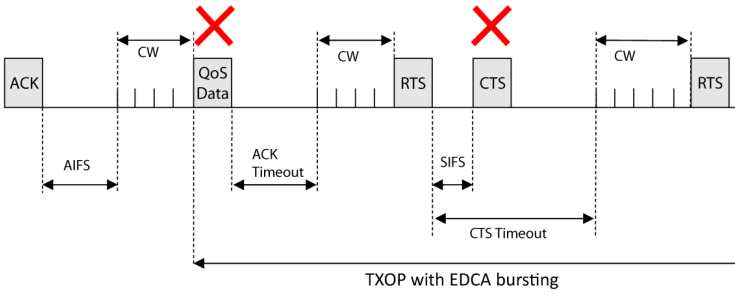
### Occurring 802.11e Mechanisms with Communication Errors

The operation of 802.11e – with RTS/CTS protection enabled – in response to channel errors is the following. First the data frame losses are discussed which is depicted in Figure 4(a). A possible failed data transmission is detected by the sender due to the ACK timeout which in turn triggers a new back-off period. If the channel is sensed idle a RTS/CTS exchange is initiated which is followed up by the actual data retransmission. However, in a highly congested environment a subsequent RTS packet collision loss is not unlikely. The sender detects this by means of the CTS timeout mechanism so that another RTS packet can be queued for transmission. This in turn can lead to a (large) number of consecutive RTS frames transmitted over the channel as illustrated in Figure 4(b).





(a) The data frame loss, detected by the ACK timeout at the transmitter.



(b) The RTS packet loss, detected by the CTS timeout mechanism. In a highly congested environment this can lead to a large number of consecutive RTS frames.

Figure 4 The 802.11e features in conjunction with RTS/CTS to cope with channel errors.

## 4 Interference Mechanisms

The interference between 802.11e WLANs sharing the same radio channel is highlighted in this section. This is important before measurements in a live environment can be made in order to identify the interference mechanisms better from the live recordings. Interference mechanisms are investigated by performing measurements in a controlled environment. In order to determine the mechanisms that lay behind this type of interference a cross-layer approach is introduced comprising monitoring at both the PHY and MAC link layer.

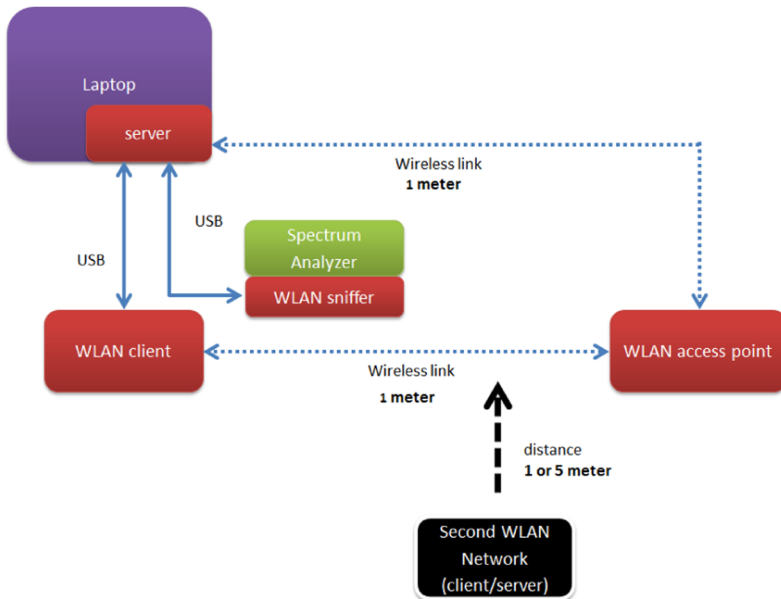


Figure 5 Measurement setup to assess the influence of an interfering network in a controlled environment.

#### 4.1 Setup

The measurement setup consists of two 802.11e WLANs with network load, respectively denoted as the main network (first network) and the interfering network (second network). The measurements are set up in a controlled environment, i.e. a quiet environment without any nearby devices active in the 2.4 GHz ISM band.

To assess the interference influence of the second network on the main network RF monitoring and MAC link layer packet capturing take place simultaneously (see Figure 5). In this setup we use passive methods for monitoring, i.e. the measurement setup only receives signals. The two networks are characterized in general terms as follows:

1. Main 802.11e WLAN: a client streaming data from a server system at a fixed rate via the AP of network 1.
2. Interfering 802.11e WLAN network: positioned in range of the main network; data transmission takes place between a client at server through the AP of network 2 on the same WLAN channel as the main network.

The measurement equipment is located in the main network close the client/server devices, since the influence of the interfering network on the main network needs to be assessed. The measurement equipment consists of:

- Packet sniffer: to capture raw packets on MAC link layer level.
- RF monitoring equipment: spectrum analyzer tuned to the 2.4 GHz ISM band.

Furthermore, to assess the level of interference certain performance metrics are required to determine service level degradation. At the MAC link layer level the following metrics are used: packet frame rate, retry rate (only defined for data and management frames), and subfields (e.g. RTS/CTS/ACK, etc.).

In addition the measurement parameters associated to the setup are listed below:

- In the WLAN network the client, AP and server are within a radius of 1 meter.
- The AP operates at a maximum rate of 300 MBits/sec (IEEE 802.11e mode) with 20/40 MHz protection mode enabled.
- The WLAN channel is set to channel 11: 2451–2473 MHz.
- Spectrum Analyzer: CRFS RFeye equipment [1].
- The field strengths are measured and depicted in dBm. The spectrum analyzer measures the spectrum every 200 ms at a frequency resolution of 4 kHz. For each frequency bin the instantaneous peak power is recorded.
- The packet sniffing software is custom-made, tailored to the specific monitoring needs.
- The sniffer application filters the frames by (destination) MAC address. So it allows to measure both the frames transmitted by the client and server.
- Data is transferred using the Unix network tool Iperf, and a session is set up between server and client devices.

Note that in this setup both server and client are connected to one Laptop using virtualization software. In Iperf the UDP (User Datagram Protocol) mode has been selected instead of TCP, because it allows to study the WLAN interference better. The reason for this is that TCP is supplemented with control algorithms that set back the frame rate to a lower level when the packet loss increases. This is not the case regarding the UDP mode – which

is connectionless – and therefore gives a better understanding of the involved interference mechanisms.

## 4.2 Experiments

Using the measurement setup of Figure 5 two experiments are carried out. The conducted experiments are set up in order to investigate the impact of distance between two overlapping WLANs w.r.t. the service level. Here, in both 802.11e WLANs the QoS data rate between server and client is fixed to 170 frames/sec.

- Experiment 1: the interferer 802.11e WLAN at 1 m distance.
- Experiment 2: the interferer 802.11e WLAN at 5 m distance.

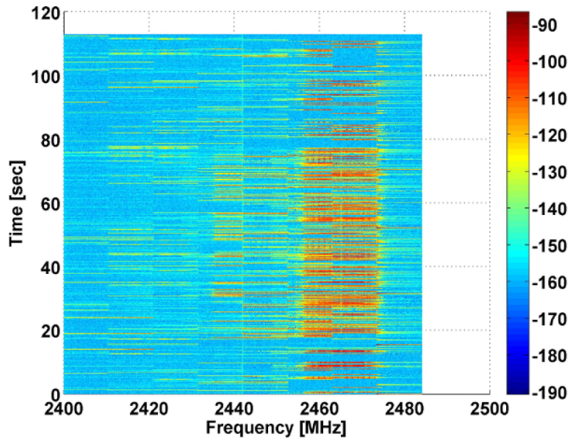
For both experiments the interferer traffic load is high, i.e. 424 frames/sec. In perspective, the maximum packet rate for IEEE 802.11g is around 2200 frames/sec.

## 4.3 Results

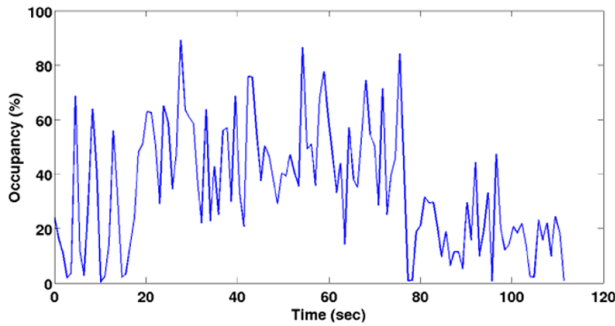
### 4.3.1 Experiment 1: WLAN Interferer Network at 1 m

Regarding PHY layer, the monitoring the results are depicted in Figure 6(a) (RF spectrum) and Figure 6(b) (RF occupancy). On the other hand, the MAC link layer monitoring results are shown in respectively Figure 7(a) (transmitted frames with destination client), Figure 7(b) (transmitted frames with destination server), and Figure 7(c) (transmitted frames from the interfering 802.11e WLAN). During the experiments no parameters have been changed, so the figures show behavior in time. Note that the that the occupancy has been determined by placing the threshold several dBs above the noise floor at  $-155$  dBm.

- 0–20 seconds: the server data rate is at a normal level, i.e. 170 frames/sec. This also holds for the client with a similar ACK frame rate. The retry rate is nearly zero. The amount of QoS data load in the interferer network is very low.
- 20–80 seconds: period of congestion. The QoS data rate at the server drops gradually from 170 frames/sec to 50 frames/sec. The RF activity increases to occupancy values above 50%. In addition, there is an increase in the number of retry frames in conjunction with a very strong drop of detected ACK frames to nearly zero. Besides, no RTS/CTS frames have been injected in the wireless medium by the server of the



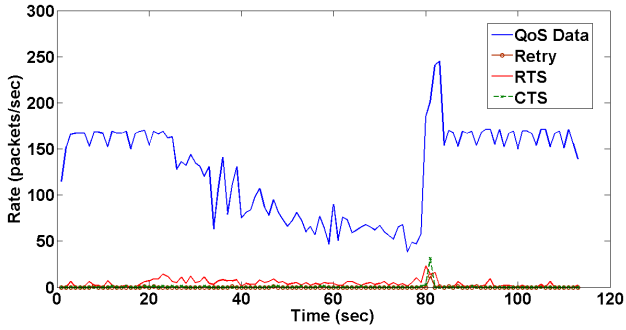
(a) Spectrum analyzer RF recordings (field strength values are in dBm)



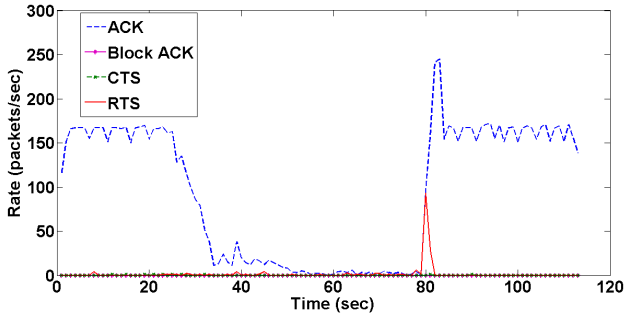
(b) The occupancy of WLAN channel 11

Figure 6 The RF spectrum monitoring results for experiment 1 with nearby interfering 802.11e WLAN at 1 m. A rise in RF field strengths is visible during the period of high interferer activity, i.e. 20–80 seconds. Moreover, the extra bandwidth channel is visible in the spectrogram due to the 20/40 MHz protection mechanism.

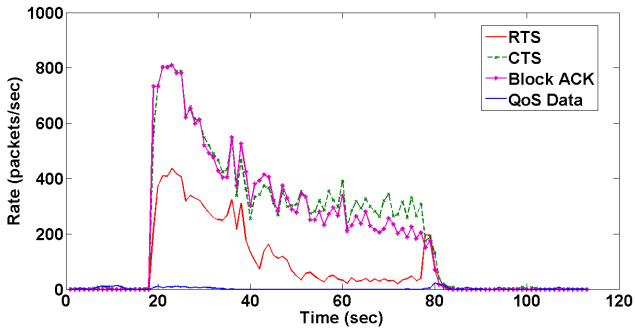
main network. However, a rise of RTS/CTS activity is measured coming from the interferer network (see Figure 7(c)). Thus it is likely that the interferer AP has initiated the RTS/CTS mechanism in order to mitigate interference; this according to the described 802.11 co-existence mechanisms in section 3, i.e. the main 802.11e WLAN network has been identified as hidden node. In a similar fashion an increase of (duplicate)



(a) Packets with destination client.



(b) Packets with destination server.



(c) Packets with a destination in the interferer network.

Figure 7 The MAC link layer monitoring results from experiment 1 with the interfering 802.11e WLAN at 1 m. The impact of the interference network is visible mainly in the period of 20–80 seconds. Here the CTS and Block ACK frames in the interferer network are counted twice by the sniffer application because these frames are retransmitted by the AP and are not filtered as such.

802.11e Block ACK frames is measured. However, the amount of QoS data load in the interferer 802.11e WLAN remains nearly zero.

- 80–110 seconds: this period starts with a short peak (at 80 seconds) of QoS data in the main 802.11e WLAN which sets back to a rate of 170 frames/sec subsequently. In addition, the retry rate falls back to a minimum together with a low RF activity level of around 35%. The QoS data rate of the interferer WLAN remains very low.

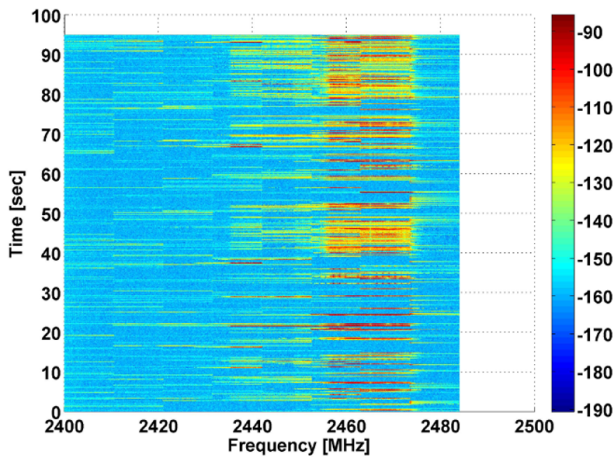
From the above-presented figures it can be concluded that the co-channel interference of a nearby second 802.11e WLAN network (at 1 m) occurs in cycles of respectively activity and inactivity. This is in accordance with the experimental live results in [13] where the impact of overlapping WLANs on the aggregate AP throughput is recorded. During the active period this entails an initial strong increase of RTS/CTS frames. Next, the number of RTS/CTS frames falls back exponentially during this interval. This can be explained by the high number of occurring collisions with frames coming from the main network which in turn triggers the CSMA/CA mechanism of the interferer network to back off. However, the amount of traffic load from the 802.11e interferer 802.11e WLAN is very high and has a jamming character which can be explained by the shorter CW interval due to the EDCA-TXOP transmission mode of 802.11e [2]. This is in line with the observations in [35] where the jamming impact of 802.11e is observed.

During this period of congestion a strong increase of RF occupancy is observed in the spectrum occupancy plot in Figure 6(b) in conjunction with the use of an extra channel which leads to a total bandwidth of 40 MHz; this in contrast to the single 20 MHz channel mode employed in the cycle of interferer inactivity. However, according to [6] the 20/40 MHz protection mechanism has been developed to operate differently, i.e. switch to single channel 20 MHz mode in case of detected interference. In addition, there seems to be a second mechanism active, i.e. in the main network the retry rate increases due to the high load of RTS, CTS and Block ACK frames coming from the interfering network. This in turn triggers the the CSMA/CA mechanism to back off which leads to a decline of QoS data injected by the server of the main network (see Section 3 describing the co-existence mechanisms).

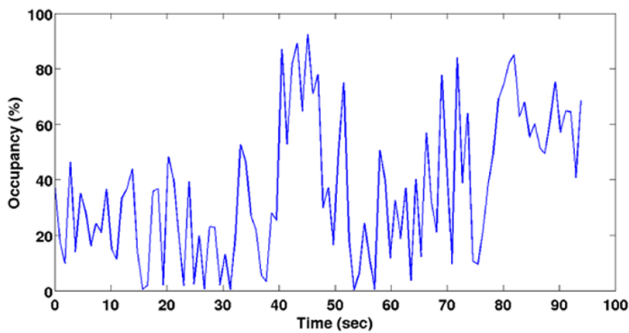
Finally, it is observed that a period of high congestion can be identified by the high amount of respectively RTS, CTS and duplicate Block ACK frames. It turns out based on this experiment that Block ACK frames are a sign of congestion for 802.11e systems.

### 4.3.2 Experiment 2: 802.11e WLAN Interferer Network at 5 m Distance

In this experiment the 802.11e WLAN interferer network is positioned at a larger distance from the main network, i.e. at 5 m distance. The configuration settings are similar to those in experiment 1. First, the PHY monitoring results are depicted in respectively Figure 8(a) and Figure 8(b), i.e. the RF spectrum and the spectrum occupancy of channel 11. Second, the MAC link layer monitoring results are shown in Figure 9(a) (packets with destination client),



(a) Spectrum analyzer RF recordings (field strength values are in dBm)



(b) The occupancy of WLAN channel 11

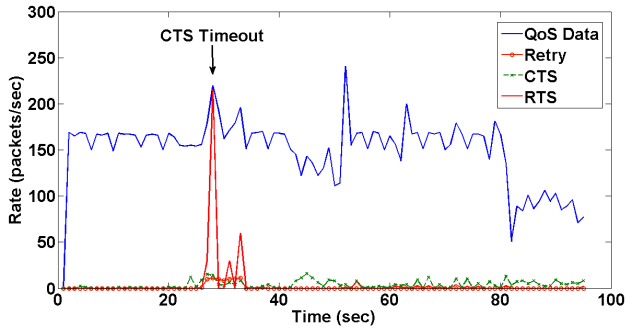
Figure 8 Experiment 2: the RF spectrum monitoring results with interfering 802.11e WLAN at 5 m. Two periods of congestion are visible, i.e. between 40–50 seconds and 80–95 seconds, by the higher level of RF field strength values.



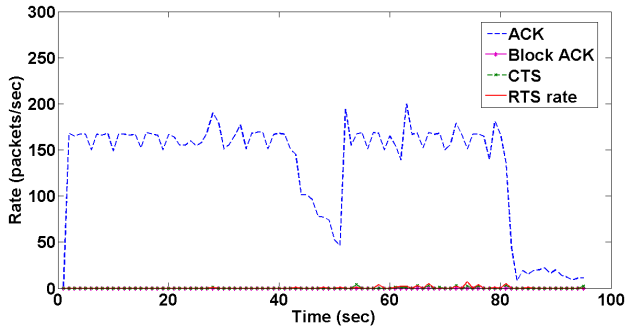
Figure 9(b) (packets with destination server), and in Figure 9(c) (packets with a destination in the interferer network).

- 0–40 seconds: the transmitted frame rate at the server is around 170 frames/sec in normal transmission mode; the same holds for the client rate (ACK frames). The average RF occupancy is below 40%. The packet loss in the network, i.e. retry rate, is negligible low.
- 40–50 seconds: the first period of congestion. A rise of RTS, CTS and Block ACK frames from the interferer 802.11e WLAN. At the start of this congestion period there is a peak in the number of RTS frames at the server. Subsequently the QoS data rate in the main network drops in conjunction with the ACK rate at the client site. In addition, the retry rate remains very low. Regarding the PHY layer, the RF activity is very high ( $> 80\%$ ) and an extra 20 MHz channel is visible in the spectrogram of Figure 8(a).
- From 50–80 seconds: QoS data frame rate at normal level in the main network; same holds for the ACKs at the client site. The number of RTS, CTS and Block ACK frames drops - compared to the preceding period of congestion - but is still present at a significant high level (peak rates: 150-200 frames/sec). In addition, it is observed from the recorded data readings that the QoS data - injected by the server of the interfering 802.11e WLAN - occur in EDCA-TXOP block burst mode. Regarding PHY layer, there is a decline in RF activity but the occupancy level is significantly higher compared to the first period of congestion.
- From 80–95 seconds: the second period of congestion. A rise in the number of RTS, CTS and Block ACK frames occurs in the interferer 802.11e WLAN up till a level of 500 frames/sec. However, this is half the amount compared to the first period of congestion. On the other hand, the decline in QoS data and ACK frames is more significant compared to the first period of congestion. The RF occupancy is in the range of {50–80%}, i.e. significantly lower compared to the first congestion period.

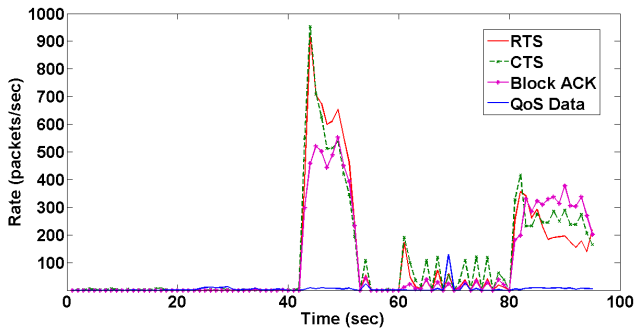
In general, the impact of an overlapping co-channel 802.11e WLAN at 5m distance is comparable to the 1 m case. Similarly, the interference network shows cycles of respectively activity and inactivity as stated in [13] for the aggregate AP throughput. During these active cycles the service level of the main network degrades to a lower level, i.e. the QoS data rate drops by half the amount. This is in line with [4] where experiments show that the impact on the aggregate throughput is irrespective of distance as long as the WLANs are in carrier sense range of each other.



(a) Packets with destination client.



(b) Packets with destination server.



(c) Packets with a destination in the interferer network.

Figure 9 The MAC link layer monitoring results from experiment 2 with the interfering 802.11e WLAN at 5 m. The impact of the interference network is visible mainly in the periods 40–50 seconds and 80–95 seconds. Here the CTS and Block ACK frames in the interferer network are counted twice by the sniffer application because these frames are retransmitted by the AP and are not filtered as such.

In accordance with the analysis of co-existence mechanisms in Section 3, the experimental results show the CTS timeout mechanism which occurs at the start of the congestion period as depicted in Figure 9(a).

According to the experiments the influence of interferer distance on the service level is limited but still perceptible. Key is that due to higher separation distance, i.e. 5 m instead of 1 m, the channel is more often sensed idle. This means that more timeslots are available to initiate transmissions for the interferer 802.11e WLAN. This is visible in the period {50–80} seconds where the level of RTS/CTS frames – injected in the network by the interferer 802.11e WLAN – is higher compared to the 1 m case. In addition, to capture channel access the 802.11e block burst transmission mechanism becomes active at the interferer AP. Note that the moderate level of RTS/CTS packets from the interferer does not harm the QoS data rate during this interval. However, the moderate RTS/CTS load causes the CW to be adjusted to a larger size for both WLANs. As a consequence, in the subsequent period of congestion the interferer network injects RTS and CTS packets at a lower rate into the wireless medium. Note that this is also the case for the amount of QoS data injected by the server of the main network, i.e. visible as strong steep drop of QoS data in Figure 9(a).

## **5 Live Measurements**

In this section the setup and the results are presented of measurements in a live environment.

### **5.1 Setup**

A modified measurement setup has been used compared to the setup employed in the interferer measurements. Three WLAN sniffers are used in parallel to analyze the packets on channels 1, 6 and 11. The setup is shown in Figure 10. Compared to the interference measurement modifications have been made to monitor all packets and distinguish between packet types (data/management/control). Besides, the monitoring system runs for a longer period of time to obtain a better estimate of the packet type statistics at a particular location. In addition, the measurement setup is installed in a live environment, i.e. no controlled conditions.

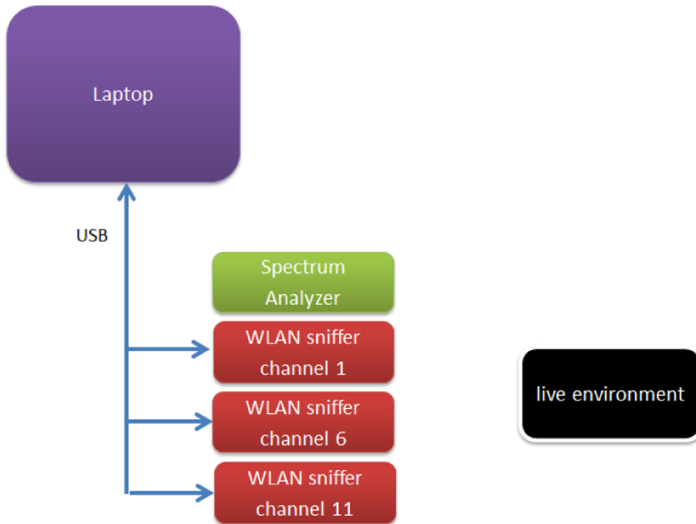


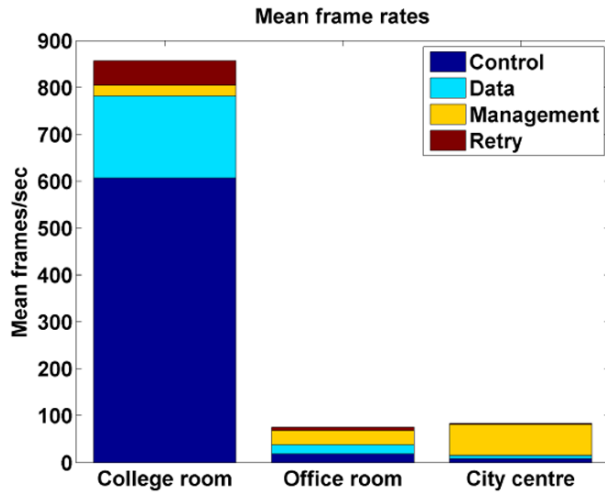
Figure 10 The measurement setup for the live recordings.

## 5.2 Experiments

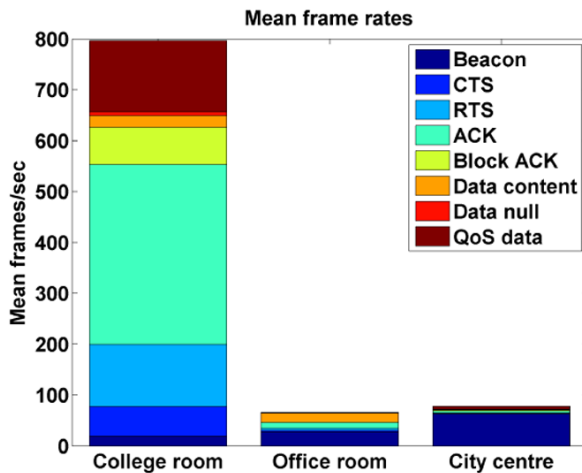
Three live situations have been evaluated: college room, office room and city center. The first location, college room, was selected because it is a very crowded place with a large population of WLAN devices in one room. Secondly, in the college room also experiments take place of which some of them use Bluetooth and/or WLAN connections. The second location, an office room, is selected as this is a location which consists of managed WLAN access points, similar the college location. Finally, the third location, city center, was selected as this is a place with unmanaged WLAN access points. Moreover, the place is know for WLAN problems on certain channels.

## 5.3 Results

Figure 11(a) shows the mean number of frames per second per location. It has been split up into management, control, data and retry frames. First of all the results show that the college room location has most traffic which is due to measurements that were carried out during a college with 75 to 100 students. Secondly in this location about 70% of the traffic are control frames and roughly 21% is actual data traffic. Figure 11(b) depicts the same locations, but here the frames are split up into the most important sub fields.



(a) The occurrence of the different type of packets



(b) The occurrence of the different subtype of packets

Figure 11 Results for live measurements on three different locations.

Retry frames and less frequent sub field packets are omitted from this figure. This figure reveals that most of the control frames are ACK and Block ACK packets.

Note that the results are in line with the conducted experiments in Section 4.3; here high amounts of Block ACK frames are detected for 802.11e WLAN systems in times of high congestion due to overlapping WLANs.

In addition, Figure 11(b) reveals that only 21% are actual data packets, which is in line with the research conducted by [37]. Moreover, we observe that most of the data frames are QoS frames (16%). This type of frame indicates the use of 802.11e WLAN communication which is more dominantly present compared to the legacy 802.11 WLAN systems (indicated by the regular data content type). Also the figure shows that almost 20% of all traffic are RTS/CTS frames. This means that there is significant interference, probably due to the many WLAN devices. This is also depicted by the retry frame rate (7%) in Figure 11(a). At the office location the mean frame rate is much lower, the actual data frame seems to be similar to the college location, but there are almost no ACK frames. Also the beacon rate is about twice of this rate at the college location. One explanation for this is that in the office location more WLAN networks were active. In the city center, most traffic consists of beacon frames.

### **College Room Location**

The measurements carried out in the college room are most interesting and highlighted below in more detail. These measurements were performed during a college which ended around 1400 seconds. Figure 12 shows the RF spectrum. This is followed by figures showing the occupancy in Figure 13(a), the sub field type versus time in Figure 13(b), and the figure showing the cumulative probability curves for the different types of frames in Figure 13(c). The figures are depicted for channel 1 where during the measurement 119 WLAN devices were identified. The other channels show similar behavior, and for brevity these results are omitted.

From Figure 13(b) it can be seen that the WLAN traffic is very spiky as expected. Interesting enough, when the college ends (at 1400 seconds) a sharp downwards transition is observed in the RF channel occupancy of Figure 13(a). Moreover, at this particular moment the occupancy drops from values around 65 to 20%. The RF monitoring results are supported by the experimental results in Figure 13(b) which shows high traffic in the first monitoring interval (i.e. 0–1400 seconds) and a significant lower traffic load in the second monitoring interval of 1400–2100 seconds. The first interval

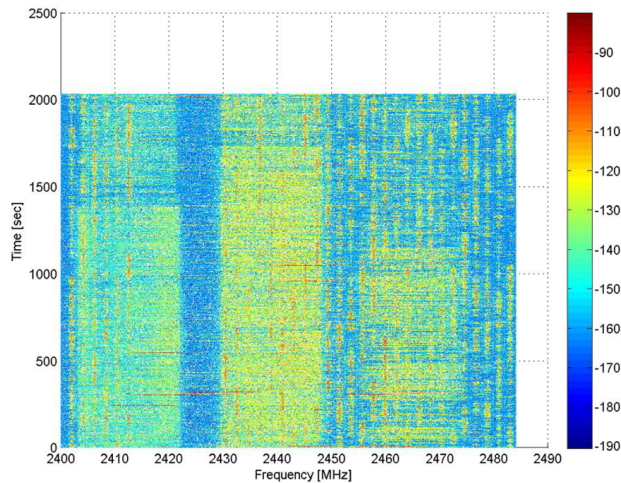
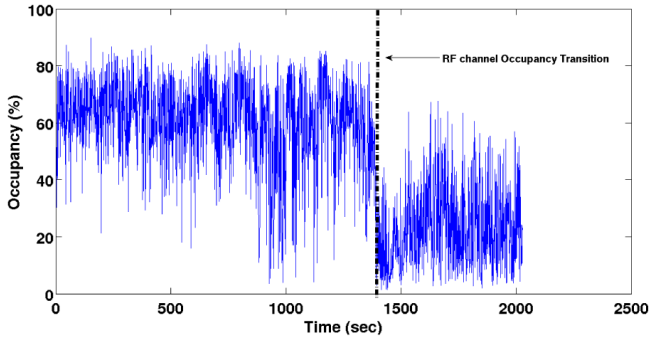


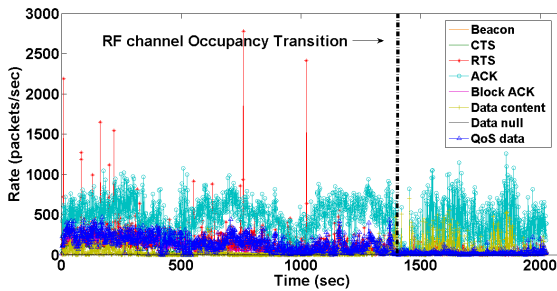
Figure 12 RF monitoring results for live measurements in a crowded college room (field strength values in dBm).

entails high amounts of RTS and Block ACK frames which is not the case for the second interval. Another observation is that the amount of legacy 802.11 data packets is more strongly present during the second monitoring interval in Figure 11(b). However, the amount of ACK frames seems to be steady throughout the entire monitoring session (0–2100 seconds). Interestingly, the results in Figure 13(b) roughly indicate that most of the traffic in the highly congested first interval comprises 802.11e traffic which tends to capture channel access. On the other hand, the second interval shows a rise in the legacy 802.11 traffic whereas the portion of 802.11e QoS data and RTS/CTS is considerably low.

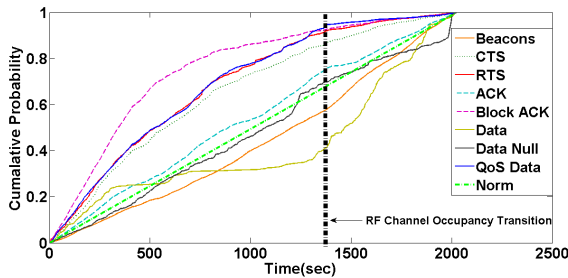
To give more insight in the time characteristics the Cumulative Density Function (CDF) curves in Figure 13(c) are provided. Here as a comparison metric, the norm curve represents the situation of constant offered traffic load over time. This figure shows that the QoS data, RTS, CTS and Block ACK CDF curves are constantly positioned above the norm curve. Moreover, the cumulative probability of these packet types is above 80% at the 1400 seconds landmark. On the other hand, the legacy 802.11 data CDF curve displays a flat characteristic during the first interval of high congestion together with a cumulative probability of only 35% at 1400 seconds. However, a steep increase of this type of data packet is observed in the second interval. Thus in line with [35] it seems that 802.11e QoS stations capture the wireless medium in case of congestion, i.e. many WLAN stations. Moreover, this coincides with



(a) Occupancy of channel 1. At 1400 seconds a significant drop in RF occupancy occurs which is marked by the *transition landmark*.



(b) Individual packet rates on channel 1.



(c) The CDF curves for the different packet subtypes on channel 1.

Figure 13 Results for live measurements in a crowded college room on channel 1. The college ends at 1400 seconds. In the first interval of high congestion ( $\{0-1400\}$  seconds) most of the traffic load is associated with 802.11e WLANs which comprises RTS, QoS data, and Block ACK frames. In the second interval ( $\{1400-2100\}$  seconds) most of the traffic entails the legacy 802.11 type of frames, i.e. data content and ACK frames.



high amounts of RTS/CTS and Block ACK packets which are therefore good indicators of 802.11e induced congestion. This is confirmed by the sniffer readings which show that the QoS data packets are transmitted in blocks bursts.

## **6 Conclusions**

In this paper we have analyzed the spectrum utilization and congestion of 802.11 networks in the 2.4 GHz ISM band. It can be concluded that it is possible to assess the service level. This approach can be applied to other frequency bands where 802.11 technology is deployed such as the 5 GHz band. A cross-layer approach is provided to measure the spectrum utilization and congestion in this band. For this purpose it turns out that packet sniffing allows to identify congestion and that on the other hand spectrum sensing allows to identify utilization. Two situations are investigated using the latter techniques for monitoring.

First, results are presented on the impact of interference between 802.11e WLAN networks sharing the same radio channel in a controlled environment. The results show that the interfering network leads to severe congestion on the wireless medium which in turn occurs in cycles of respectively inactivity and activity. The situation of interferer activity, i.e. congestion, is caused by the RTS/CTS mechanism since the 802.11e WLAN networks often seem to identify each other as hidden nodes. Finally, the conducted experiments in a controlled environments show that the impact of overlapping 802.11e WLANs is relatively irrespective of distance, as long as the WLANs are in the carrier sense range of each other.

Secondly, monitoring sessions in real uncontrolled environments illustrate that only a small portion is actual data traffic. For instance, the live recordings taken in a college room – a location with up to 100 people – indicate that a significant number of packets is classified as control packets (e.g. RTS/CTS), where in turn the number of actual data content packets is quite low (less than 21%). This is in line with the conducted experimental results of the controlled environment, showing that RTS/CTS significantly degrades the performance when two networks are in range of each other; in addition, Block ACKs are identified as a good indicator of congestion in 802.11e WLAN environments. Moreover, the live readings show that 802.11e WLANs typically capture channel access over legacy 802.11 systems, e.g. by using data block burst transmissions. At two other locations, i.e. an office room and a city center site, the traffic mainly consists of management pack-

ets and control packets. It can be concluded that the WLAN devices cannot properly handle interference of other IEEE 802.11(e) networks, which leads to very inefficient use of the radio spectrum. Thus there is room for further improvement for more efficient use of the radio spectrum. Further research is needed how this commodity wireless standard can be made more efficient.

## 6.1 Future Research

It turns out that interference mechanisms are complex and often unexplored in practical situations. Therefore the following topics are interesting for further research. First it is interesting to look at the mechanisms causing interference between WLAN clients of the same network due to packet collisions. Secondly, many open questions remain regarding the interaction between 802.11e and legacy 802.11 systems with respect to for instance overlapping WLANs, e.g. the high amount of Block ACKs and the 20/40 MHz protection mode operation. Moreover, additional research could aim at many WLAN networks on the same channel, and interfering WLAN networks on adjacent overlapping WLAN channels. Thirdly, it is interesting to investigate how the packet rate on the MAC link layer and the spectrum utilization are related and whether an analytical expression can be provided. The relation should take into account the different packet sizes that are possible (e.g. an ACK packet is in general significantly smaller than a data content packet). Finally, to improve on the 802.11(e) standard we recommend adjustments w.r.t. to the RTS/CTS protocol in order to cope with the high amount of RTS/CTS packets once two APs are in range of each other. In line with this, we recommend further inspection of the CSMA/CA protocol so that neighboring APs could share the channel more fairly including improvements on the back-off procedure.

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## Biography

**Jan-Willem van Bloem** received his M.Sc. in Electrical Engineering from the University of Twente in 2007. He did his internship for British Telecommunications (UK) to work on the BT-FON project in 2006. Since 2010 he follows a PhD trajectory at the Signals and Systems Group of the University of Twente. As part of this trajectory he conducts research for the Radio Communication Agency Netherlands to investigate the service level in the ISM band and the GSM band. Also as part of this trajectory he was employed as researcher at British Telecommunications from October 2011 until April 2012 to work on white-space database assisted collaborative sensing in the TV band.

**Roel Schiphorst** received his M.Sc. degree with honors in Electrical Engineering from the University of Twente in 2000 for his research on Software-Defined Radio. In 2004 he received the PhD degree for his research on Software-Defined Radio for WLAN standards. Since then, he is a researcher of the chair Signals and Systems. He was also project leader of large T-DAB field trial in Amsterdam which was on-air from 2004

until 2006. His research interests include Software-Defined Radio, digital broadcast systems and digital signal processing for wireless applications.

**Taco Kluwer** is an innovation advisor for the Radio Communication Agency in the Netherlands. He is currently managing a project where advanced spectrum monitoring and analyses is combined with business intelligence. He received his M.Sc. degree in Electrical Engineering from the University of Twente in 2001, and his research was focused on software defined radio and smart antennas. Since then he has worked as a market specialist and senior technical specialist in numerous projects in the field of radio spectrum monitoring, spectrum management and telecommunication regulation.

**Cornelis H. Slump** received the M.Sc. degree in Electrical Engineering from Delft University of Technology, Delft, The Netherlands in 1979. In 1984 he obtained his Ph.D. in physics from the University of Groningen, The Netherlands. From 1983 to 1989 he was employed at Philips Medical Systems in Best as head of a predevelopment group on medical image processing. In 1989 he joined the Network Theory group from the University of Twente, Enschede, The Netherlands. His main research interest is in digital signal processing, including realization of algorithms in VLSI.