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On the number of non-overlapping channels in the IEEE 802.11 WLANs operating in the 2.4 GHz band

Peter Miklavčič

Faculty of Electrical Engineering, University of Ljubljana, Tržaška 25, 1000 Ljubljana, Slovenia
miklavcic.peter@gmail.com

Abstract. There are up to fourteen (thirteen in Europe) overlapping IEEE 802.11 channels in the 2.4 GHz band. A well known set of the *non-overlapping* channels are 1, 6 and 11, meaning that the spectral overlap does not affect the performance of networks which use them. However, as channels 1, 5, 9 and 13 are theoretically also non-overlapping, the first contribution of this paper is visualization of the spectral overlap of different WLAN signals when using channels 1, 6 and 11 vs. channels 1, 5, 9 and 13. The paper also explores and summarizes the related work done on the topic of channel overlap in the 802.11b, 802.11g and 802.11n networks. The paper ends with a discussion incorporating comments on the previous experimental results and proposals for future research. Based on the available experimental results, the possibility of four non-overlapping channels when used in the low- to medium-density 802.11b and 802.11g networks and the possibility of specifying the conditions under which the fourth non-overlapping channel becomes available provides an opportunity for future research. As the results for the 802.11n networks are inconclusive, the experimental work should be continued. However, in the high-density networks, new effects are observed, less non-overlapping channels are available, and at the nodes operating in a close vicinity, only one non-overlapping channel remains available.

Keywords: overlapping channels, out-of-band interference, OOB interference, adjacent-channel interference, ACI, channel orthogonality, 2.4 GHz band, 802.11b, 802.11g, 802.11n, WLAN, Wi-Fi

O številu neprekrivajočih kanalov v IEEE 802.11 brezžičnih lokalnih omrežjih, delujočih v 2,4 GHz pasu

IEEE 802.11 omrežja imajo v 2,4 GHz pasu na voljo do štirinajst (trinajst v Evropi) prekrivajočih se kanalov. Znan nabor *neprekrivajočih* kanalov so kanali 1, 6 in 11, kar pomeni sicer da se še vedno delno prekrivajo, a je vpliv prekrivanja na zmogljivosti omrežja zanemarljiv. Obstaja pa tudi možnost, da je nabor kanalov 1, 5, 9 in 13 tudi neprekrivajoč in tako je prvi prispevek tega članka grafična predstavitev prekrivanja spektrov različnih WLAN signalov pri uporabi kanalov 1, 6 in 11 ter pri 1, 5, 9 in 13. Članek tudi razišče in povzame prejšnja dela okoli tematike prekrivanja kanalov v 802.11b, 802.11g in 802.11n omrežjih. V zadnjem delu članka pa je razprava na temo prejšnjega eksperimentalnega dela in predlogi za nadaljnje raziskave. Iz povzetih eksperimentalnih rezultatov je podan zaključek, da je v 802.11b in 802.11g omrežjih z nizko ali srednje veliko gostoto naprav v omrežju v določenih primerih možno uporabljati štiri neprekrivajoče se kanale, določitev natančnejših pogojev kdaj se pojavi četrti neprekrivajoči se kanal pa predstavlja priložnost za raziskovalno delo. Rezultati za 802.11n omrežja so nedokončni, tako da bi bilo potrebno eksperimentalno delo nadaljevati. V primeru zelo gostih omrežij pa se pojavijo novi problemi in število neprekrivajočih kanalov pri napravah, ki delujejo zelo blizu skupaj, se zmanjša tudi do enega samega neprekrivajočega kanala.

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1 INTRODUCTION

Depending on the local legislation, there are up to fourteen IEEE 802.11 WLAN channels in the 2.4 GHz band. Channels 1 to 13 are evenly spaced every 5 MHz from 2412 MHz to 2472 MHz. Channel 14 has a special central frequency of 2484 MHz and is allowed to be used only in Japan. As the 802.11 family of standards (with a market name Wi-Fi) defines the waveforms used in the 2.4 GHz band with the bandwidth of 20, 22 or 40 MHz, these channels overlap. As already established [9], the only non-overlapping channels of the first eleven ones are channels 1, 6 and 11. In the mathematical theory, all channels overlap to some degree, but in practice, the overlap is negligible unless it affects the network performance. The *non-overlapping* channels are the ones whose spectral overlap is so small that it does not affect performance of networks which use them. This means that where at least thirteen channels available (for example in the Europe), there is a possibility that channels 1, 5, 9 and 13 are also non-overlapping in the low- to medium-density networks which will be discussed in more detail below.

A non-overlapping configuration is preferable, for example, in the RF-clean or experimental environments, large-area networks such as campuses, com-

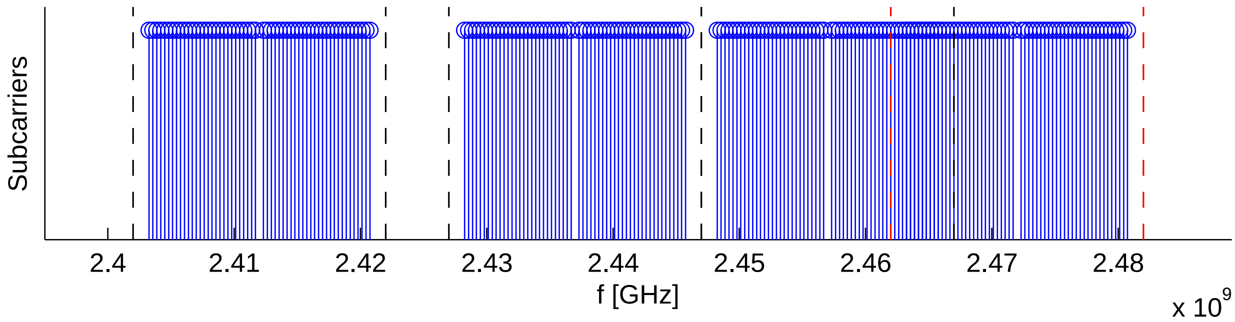

Figure 1. IEEE 802.11n OFDM subcarrier frequencies plot on channels 1, 6, 10 and 13. The dashed lines represent the specified bandwidth (i.e. 20 MHz).

mercial TDMA networks and in networks using later WLAN standards with the OFDM waveforms. The paper explores, summarizes and comments the work done on the number of the non-overlapping channels in the 802.11b, 802.11g and 802.11n standards, implemented in the current off-the-shelf hardware. Channels 1, 6 and 11 will be referred to as a *three-channel configuration* with a separation of five channels between them (i.e. 25 MHz), and channels 1, 5, 9 and 13 will be referred to as a *four-channel configuration* with a separation of four channels (i.e. 20 MHz). Section 2 provides a brief theory review and an overlap visualization.

Finding no accounts on the previous experimental work using these channel configurations (with three and four concurrent networks), the literature on the network performance (measured by the throughput) vs. the channel distances for each of the currently used 802.11 standards was reviewed. The reviewed experiments were conducted using two concurrent networks, one fixed at a certain channel and the other channel was varied. The results indicate whether the four-channel non-overlapping configurations are possible in the current 2.4 GHz WLAN standards, and based on their summary in Section 3, a discussion on the possible number of the non-overlapping channels is conducted and the future research is proposed in Section 4. In Section 5, conclusions are drawn.

2 Overlap visualization

The IEEE 802.11 standards regulate the co-channel interference with the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) MAC protocol which senses the channel idle before transmission. The co-channel interference is complemented with the adjacent-channel (out-of-band) interference. In order to minimize it, the 802.11 standards define the transmit spectrum masks which limit the power *leakage* in the neighbouring channels (i.e. the power of the spectral components causing the adjacent-channel interference). In Table 1, a brief review of the most important spectrum properties of the currently used 2.4 GHz WLAN standards is shown. There is also a legacy 802.11-1997 standard which is not implemented in modern WLAN devices and is also excluded from the latest 802.11-2012 maintenance standard. As for the future of WLAN in the 2.4 GHz band, the next standard which might define a refined PHY layer is the 802.11ax standard which is currently in the very early stages of its development.

Table 1. Spectrum properties of the current IEEE 802.11 standards operating in the 2.4 GHz band.

802.11	**b**	**g**	**n**
Max. PHY rate [Mbps]	11	54	288.8/600
Bandwidth [MHz]	22	20	20/40
Waveform	DSSS	OFDM	OFDM
Subcarriers		52	56/114
Null subcarriers		12	8/14

As seen from the Table 1, 802.11g and 802.11n use Orthogonal Frequency Division Multiplexing (OFDM) with 52 (802.11g) or 56 (802.11n) subcarriers when using the the 20 MHz bandwidth and 114 subcarriers in the 802.11n 40 MHz *channel bonding mode*. The 802.11n OFDM subcarrier plot in Fig. 1 shows that 20 MHz is the smallest theoretically possible separation.

The 802.11b networks use the Direct-sequence Spread Spectrum (DSSS) waveform which has a typical squared sinc function spectrum shape. The OFDM spectrum has a more rectangular shape with steeper side lobes which is in the included figures modelled as a sum of the squared sinc functions representing subcarriers. The distance between the first two networks is 25 MHz (as in the three-channel configuration), the distance between the second and third network is 20 MHz (as in the four-channel configuration) and the last two networks are only 15 MHz apart which causes a complete overlap of nine 802.11n subcarriers. From plotting the signals and their transmission masks of the three above standards in Fig. 2 it is seen that the 802.11g and 802.11n signals have more restrictive transmit masks in the channel but

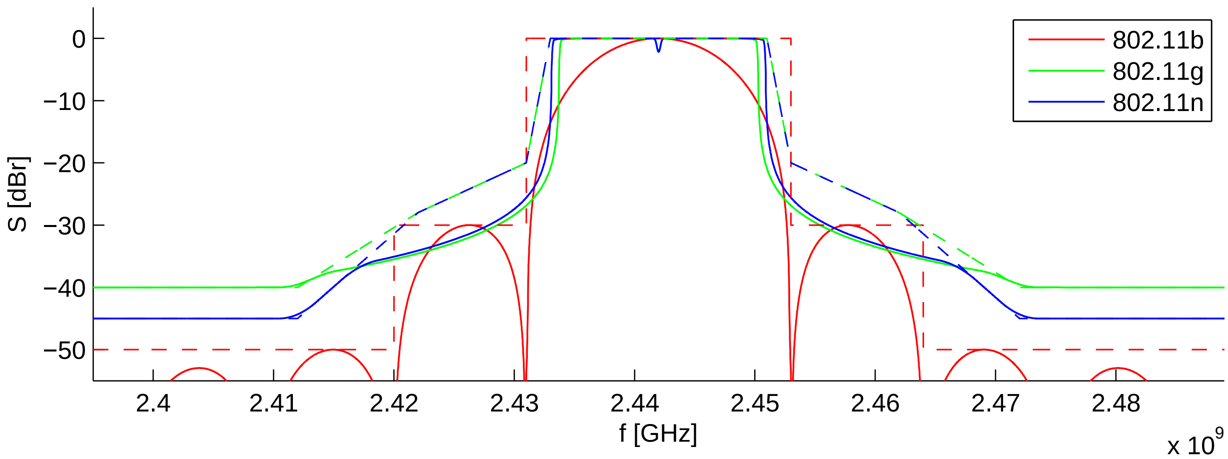

Figure 2. Spectrum and transmission mask plot of 802.11b (red), 802.11g (green) and 802.11n (blue) signals on channel 7.

the 802.11b signal has a more restrictive mask out-of-band. Comparing the two OFDM signals (802.11g and 802.11n) shows that the additional subcarriers make 802.11n to have more power concentrated in the channel than 802.11g and it also has a more restrictive transmission mask out-of-band. These properties and the fact that the 802.11n devices have a newer design, and therefore should have more processing power running more capable DSP, indicate that the 802.11n networks are less prone to the adjacent-channel interference than the 802.11g is. However, the experimental results given in Section 4 are inconclusive whether that is the case.

The 802.11b, 802.11g and 802.11n signals are plotted in the three-channel configuration in Fig. 3 and in the four-channel configuration in Fig. 4. The 802.11g signal is not plotted in these figures to provide for clarity and because of its similarity with 802.11n. The overlap can be observed by comparing the sum of all the signals with the dominating signal in the observed channel.

3 Related work

3.1 *802.11b*

In [1] (titled *Exploiting Partially Overlapping Channels in Wireless Networks: Turning a Peril into an Advantage*), the authors define the *interference factor* as a normalized ratio between the received powers of particular signals on two different channels at the same location. It determines the *channel leakage* or how much of the signal power causes the adjacent-channel interference. Also, its effect on the 802.11b networks is determined by measuring the TCP, UDP throughput and collisions vs. the channel separation. The results in [1] show that the 802.11b channels need at least a four-channel separation in order to be non-overlapping indicating that the four-channel configuration may be possible in the 802.11b networks. The authors continued their research and in [2] (titled *Partially Overlapped Channels Not Considered Harmful*) developed a model for partially overlapping channels and defined the interference factor as a convolution of the transmitter signal spectral power density and the receiver bandpass filter frequency response. The interference factor function is then discretized and compared with the measured values confirming their theory.

3.2 *802.11b and 802.11g*

In [3] (titled *Effect of adjacent-channel interference in IEEE 802.11 WLANs*), the interference factor for the 802.11b DSSS and 802.11g OFDM channels is obtained analytically. The calculated results for different channel spacings are of the same order for both the 802.11b and 802.11g signals with the only exception at the channel separation of four. The 802.11g signals are attenuated for around 10.5 dB more than the 802.11b are when the two signals are four channels apart, indicating that the four-channel configuration may also be possible in the 802.11g networks. The paper [3] also confirms the previous results [1] for the 802.11b network throughput that is almost unaffected at the channel separation of four.

In [5] (titled *About the practicality of using partially overlapping channels in IEEE 802.11 b/g networks*), the authors first confirm the previous results [1], [3] for the 802.11b networks and then show that the 802.11g signals do not overlap significantly when they are at least four channels apart. As also seen from the same results, the 802.11g performance declines more rapidly than the 802.11b performance when the channel distance decreases which is consistent with the theory in this paper. The authors in [5] come to the conclusion that the four-channel configuration is preferable where available and that the three-channel configuration leads to an underutilized spectrum.

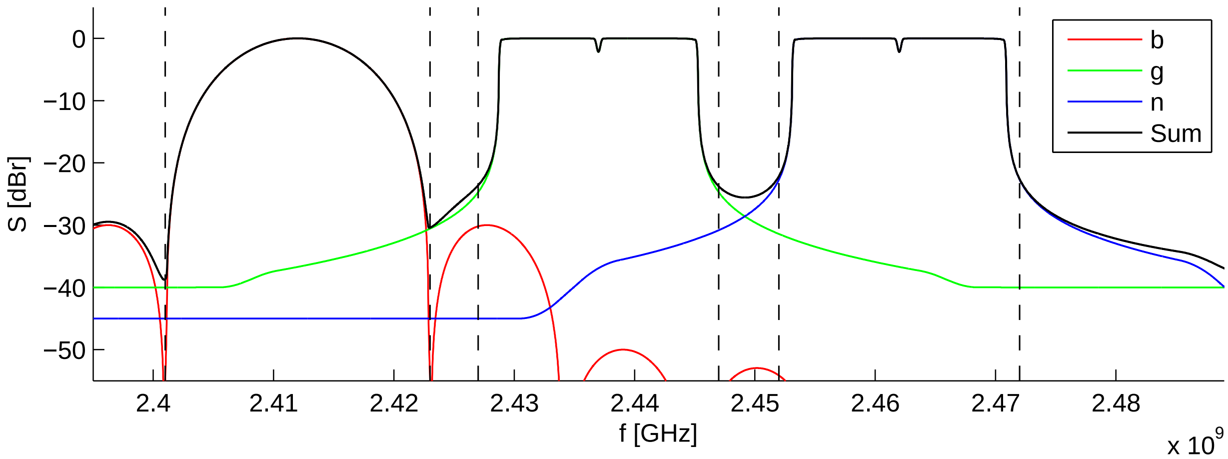

Figure 3. Spectrum plot of the 802.11b signal on channel 1 (red), the 802.11g signal on channel 6 (green) and the 802.11n signal on channel 11 (blue) and the sum of all the four signals (black). The dashed lines represent the specified bandwidth of each standard.

3.3 ***802.11g***

In [4] (titled *Measurement study of adjacent channel interference in mobile WLANs*), the authors measure the adjacent-channel interference in an 802.11g network by measuring the throughput vs. the channel distance. Their results show that the 802.11g network throughput is practically the same for the channel separation of five and four confirming the previous results [5] and indicating that the four-channel configuration may also be possible in the 802.11g networks.

3.4 ***802.11n***

In [6] (titled *Reinvestigating Channel Orthogonality-Adjacent Channel Interference in IEEE 802.11n Networks*) and similarly in [7], the authors provide experimental results of the 802.11n network performance using partially overlapping channels, but they observe access points operating in the vicinity, thus making the near-far or exposed-node effect to be very distinct. It can only be noted that in the 802.11n networks, the adjacent interference effects quickly mellow with the increasing distance for the channel distances of five and above. Because of the near-far effect, no conclusions can be drawn from the same results whether the interference in the channel four channels apart is not significant as well.

4 Discussion

An almost ideal scenario using a four-channel configuration produces such a small difference in the nodes' SNR that consequently the difference in the throughput performance is neglible. Using the four-channel configuration in such networks therefore represents a tradeoff between the adjacent-channel interference and the number of the non-overlapping channels, but as the latter is relatively small, this tradeoff is keen in some network usage scenarios, whose examples are given in the introduction. Even though the partially overlapping channels enable better spectrum utilization in the first versions of the 802.11 standard [2]; later revisions use OFDM and MIMO because of a better spectral efficiency and higher PHY rates. They are also more susceptible to the adjacent-channel interference and interference from the 2.4 GHz sources other than WLANs.

The experimental results summarized in Section 3 indicate that the four-non-overlapping-channel configuration (i.e. channels 1, 5, 9 and 13) is possible in the 802.11b and 802.11g networks without noticeable performance decrease, which is in the referenced papers measured by the throughput. These results were obtained in similar test environments, each simulating a typical usage scenario with the most important characteristic being a low and medium relative node density. An example of a low-density WLAN is an ISP access network using the 802.11 standard and an example of a medium-dense WLAN is an office building using a common infrastructure. A typical example of a high-density network would be a technical conference with each attendee using more than one 802.11 device and mobile APs.

As seen from the experimental results of the 802.11n networks [6], the high-density networks are a problem on their own. Some other papers considered for inclusion have also discussed such networks. The effects of the adjacent-channel interference in nodes operating in a close vicinity are not limited only to the near-far effect, but with the decreasing distance, some new effects are observable, such as board crosstalk and radiation leakage. For example, adding an additional WLAN card to a laptop and operating it in a (passive) monitor mode can reduce the throughput of the primary card

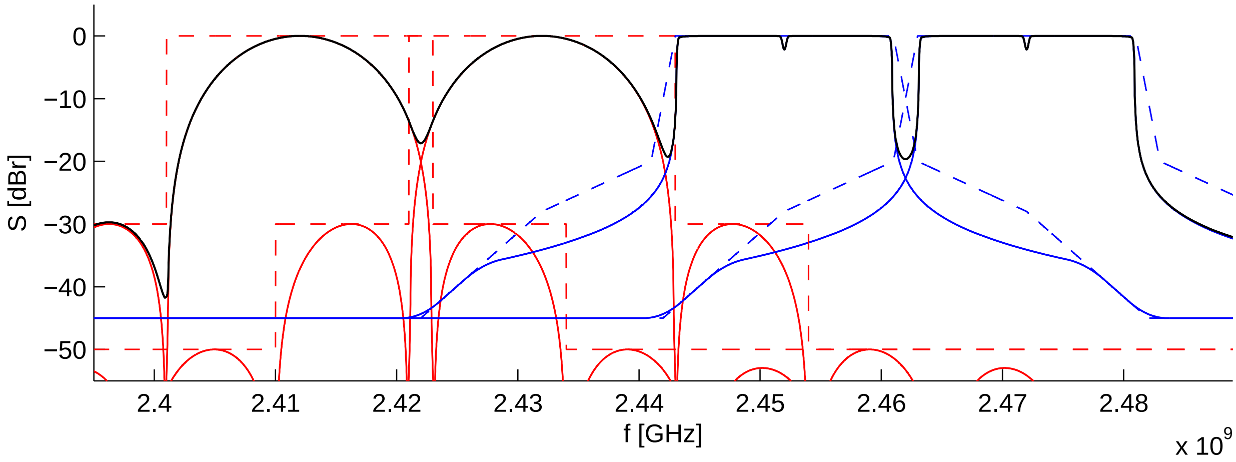

Figure 4. Spectrum and transmission mask plot of the 802.11b signal on channels 1 and 5 (red), the 802.11n signal on channels 9 and 13 (blue) and the sum of the four signals (black).

as demonstrated in [8]. Furthermore, by decreasing the distances between the nodes to the metre region, less non-overlapping channels are available and in the decimetre region, only one channel remains available.

The above results are not applicable in less-dense WLANs and consequently the results for the 802.11n networks in Section 3 are not conclusive. In other words, it has not yet been experimentally demonstrated that at least two 802.11n networks can operate simultaneously and without decrease of their performance when their central frequencies are 20 MHz apart. As the 802.11n standard also narrows the guard bands (it uses four subcarriers more) and, on the other hand, it uses a more restrictive transmit mask, determining the channel-overlapping effect on its performance using the above papers' methodology would be the first proposal for the future research. The second would be to test different combinations of the 802.11 standards with the same methodology, and the last would be to specify the conditions under which the fourth non-overlapping channel becomes available.

5 Conclusions

The experimental results summarized in this paper show that the low- and medium-relative-node density 802.11b and 802.11g networks do not exhibit a noticeable degradation in the throughput performance when the central frequencies are 20 MHz apart, which indicates that a four-non-overlapping channel configuration is possible in such networks. It would be valuable to determine the conditions under which the fourth non-overlapping channel becomes available. However, the experimental results for the 802.11n networks are not conclusive.

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Peter Miklavčič is a student at the Faculty of Electrical Engineering at the University of Ljubljana, Slovenia. He is specializing in telecommunications and his main areas of interest are WLAN and mobile technologies, software-defined radio and antennae, IP networks, and also Linux, computer science, digital forensics and security.