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Ultra-Wideband Signal Impact on the Performances of IEEE 802.11b and Bluetooth Networks

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This paper presents the results of a coexistence study investigating the impact of ultra-wideband (UWB) interference on IEEE 802.11b and Bluetooth networks. The results are based on the experimental test measurements made at the University of Oulu, Finland. Simple high-power UWB transmitters are used to interfere with victim networks. Preliminary results show that only under extreme interference conditions with thousands of equivalent Federal Communications Commission– (FCC)-compliant devices in close proximity, will the IEEE 802.11b and Bluetooth networks experience significant performance degradation. The impact of the UWB interference on the IEEE 802.11b network was insignificant if the distance to UWB transmitters was greater than 40 cm. The impact on Bluetooth was even less noticeable. In our study, several high-power UWB transmitters that greatly exceed the FCC radiation regulations have been used, and the measurement settings presents the worst case scenario because of the very short distance between the interferers and the victim system. Effectively our study approximates the use of thousands of FCC-complaint UWB devices in the same space.

KEY WORDS: Coexistence; Bluetooth; IEEE 802.11b; signal-to-noise ratio; throughput; ultra-wideband; WLAN.

1. INTRODUCTION

Huge numbers of IEEE 802.11b-enabled wireless local area network (WLAN) devices have been deployed worldwide, representing a huge investment in a popular wireless technology. At the same time, Bluetooth-enabled devices also have become popular for short-range wireless connections between computers and mobile phone peripherals. Depending on the final UWB spectrum regulations, the huge bandwidth of UWB devices might overlay both 802.11b [1] and Bluetooth [2]. This has, in some cases, led to concerns for the performance of these other unlicensed radio systems.

Similar coexistence studies with one interfering UWB transmitter have been published, for example, in [3,4]. The contribution of this study is the use of a large number of UWB transmitters. Some of the results presented in this paper can be found in [5,6].

In this paper, the performance of IEEE 802.11b and Bluetooth connections are examined when intentional UWB interference is present. A large number of high-power UWB transmitters were used to disturb the short-range network transmission links. Throughput and signal-to-noise ratio (SNR) levels from the victim networks were recorded. Effectively the measurement scenario represents a scenario of thousands of FCC-compatible UWB devices being simultaneously active in a small area. The UWB transmitters used in the study exceed the current FCC radiation limits [7] and cannot be commercially used, but they are

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suitable for modeling the aggregate phenomena of a dense UWB population.

The paper is organized as follows. Section 2 introduces the hardware used in the study. In Section 3, the test networks and tools are described. Section 4 gives the results of the experimental coexistence tests, and finally, Section 5 presents conclusions.

2. UWB HARDWARE DESCRIPTION

The UWB transmitters used in the study were designed and built by PJ Microwave Ltd., Oulu, Finland. These UWB signal sources are impulse waveform generators without data transmission capabilities. The pulse generators are based on a technique introduced in [8] and generate a train of short pulses. The UWB signal sources are encapsulated in metal boxes to reduce the unintentional radiation, so all the emission comes through the antenna.

The pulse generator is built on a single-sided circuit board alongside a free-running oscillator, which is used to trigger the pulse that is generated using a step recovery diode. The pulse repetition frequency in the prototypes is fixed to PRF 87 MHz (approximately). The characteristics of the received signal have been measured using a digital sampling oscilloscope. Both the generated and received pulse waveforms are measured from the PCB, and are presented in Figure 1. In the time domain, the generated pulses have a width of approximately $T_p = 500$ ps. These first prototype devices, however, produce a ringing effect, which also can be seen in Figure 1. The received waveform seen by WLAN or Bluetooth is different to that presented because of the narrower bandwidths of their antennas. However, the figures indicate the spectral characteristics of the transmitted UWB pulse train. To produce this figure, the same antenna type as used at the transmitter was used at the receiver because neither the stand-alone WLAN or Bluetooth antennas were available. The center frequency of the UWB transmission is around 1.8 GHz, as seen in Figure 2. The frequency domain presentation is calculated from the measured time domain pulse waveform using the Fourier transformation.

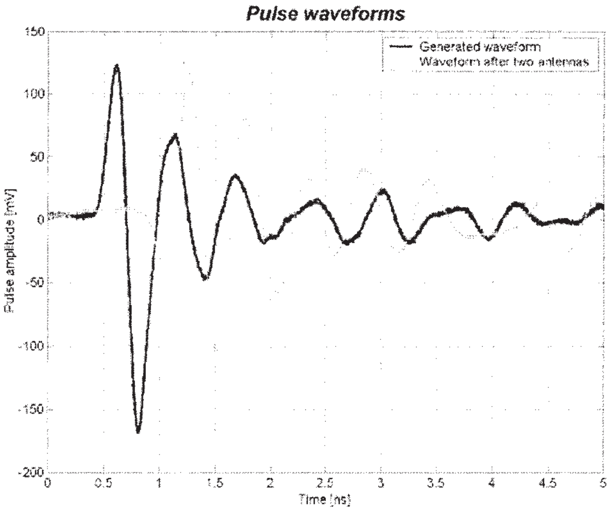

Fig. 1. Generated and received pulse waveforms. Measured at the PCB.

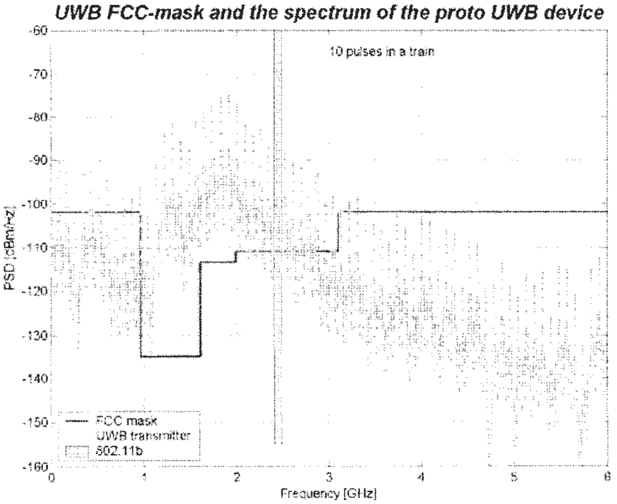

Fig. 2. Spectrum of the UWB pulse train. FCC mask and the WLAN band are also depicted.

The peak-to-peak voltage for the pulse measured from the output port of the circuit board is approximately 300 mV. The circuit board uses a 9-V power source, with a total power consumption of less than 300 mW per device.

The UWB antennas used have an omnidirectional radiation pattern, and they are manufactured using standard PCB processes. The EIRP power depends on the frequency and is approximately −2 dBm . . . +3 dBm. It should be noted that these first prototypes are not compatible with the FCC regulations, and they are classified as *'extremely high-power'* UWB devices. A total of 20 UWB transmitters are currently available. With these devices the FCC radiation mask is exceeded by more than 20 dB in the 2.4-GHz ISM band. Each device can be considered to correspond to hundreds of FCC-complaint devices operating coherently within a small area, and the interference coming from the different UWB devices is noncoherent.

3. TEST NETWORK

The WLAN laboratory measurement network is based on off-the-self IEEE 802.11b Orinoco WLAN cards, which were installed in laptops, and the data flow has been monitored by publicly available software. The Bluetooth network is based on the integrated Bluetooth chips in the laptops. With the IEEE 802.11b network, both the peer-to-peer and forwarding link connections were studied, whereas only peer-to-peer links were studied with the Bluetooth link. The operating system used for the laptops is Linux, which allows greater tailoring of the monitoring tools. The general measurement configuration for a victim receiver is presented in Figure 3, in which the WLAN receiver is a PCMCIA card installed to the corresponding PC port.

3.1. IEEE 802.11b Network

The WLAN measurements were performed in an anechoic chamber and a typical office environment separately, whereas the Bluetooth measurements were carried out only in the office environment during the regular office hours. The basic setup for both of these tests were, however, the same; two laptops with either WLAN or Bluetooth network cards communicated with each other using TCP protocol in peer-to-peer mode. In addition, the WLAN measurements in the office environment were performed using forwarding mode, that is, using a managed mode through the access point (AP).

The IEEE 802.11b WLAN operates at 2.4 GHz ISM frequency band. The supported bit rates by the cards are 11 Mbps, 5.5 Mbps, 2 Mbps, and 1 Mbps, depending on the available link quality. However, even without UWB interference, the highest data rate was never achieved, even for short link distances or in an anechoic chamber.

The WLAN network cards reported the measured signal-to-noise ratio, signal quality, and the number of successfully received packets of the local and remote device both in managed and peer-to-peer modes. To measure higher layer performance, additional network traffic analyzing tools are required. In this work, TTCP [9] and MGEN [10] are used. TTCP is a command-line sockets-based benchmarking tool for measuring TCP and UDP performance between the communicating terminals, allowing SNR and throughput measurements of the network. In our study, TCP was considered. TTCP does not consider the quality of the link, so there were no packet retransmissions if a data packet was lost. The throughput achieved can be calculated by comparing the number of transmitted and received packets in data post processing. TTCP differs from MGEN in that the latter is trying to maintain a constant throughput. This constant value is then maintained

Fig. 3. UWB transmitters and WLAN receiver presented as used in a typical measurement setup.

even if the link quality changes. After a long period of time the throughput might change because the MGEN tool has observed a change in the link quality. This property makes TTCP more reliable tool for throughput studies.

3.2. Bluetooth

The theoretical maximum bit rate for Bluetooth cards is 1 Mbps. The signal center frequency is also approximately 2.4 GHz. During the study, the maximum payload data rate achieved without interference was 545 kbps. Including the packet overhead, this data rate was 721 kbps. At present, the Bluetooth cards do not report any lower physical layer measurements, making it necessary to rely solely on the network traffic analyzing tool to investigate the effect of UWB disruption on Bluetooth throughput.

All of the results discussed in this paper are based on the information reported by the network cards themselves. Payload packet size for both studies was 1472 bytes, which is the maximum UDP payload packet size. With IP and UDP headers, the transmitted packet size was 1514 bytes.

3.3. Measurement Scenarios

Connections between the laptops were established both in a peer-to-peer unmanaged mode without connection to access point and in managed mode with access point in between the terminals. Initially, the distance between the communicating devices was set so that the system operated at the limit of performance for the stable data rate to more readily see the impact of the UWB devices. As a reference, a short-distance WLAN connection operating with relatively high SNR was also studied.

Figure 4 presents the locations of the WLAN transceivers and the UWB interferers during the experimental tests in the anechoic chamber. The distance between the communicating WLAN devices was approximately 8 m. The transmitted signal power level was attenuated by placing the absorbing material around the WLAN transmitter.

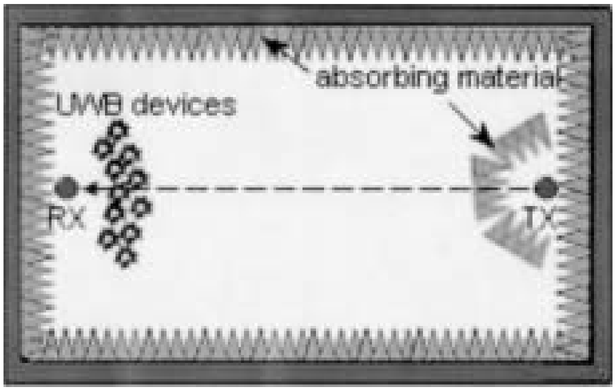

Fig. 4. Measurement layout used in an anechoic chamber.

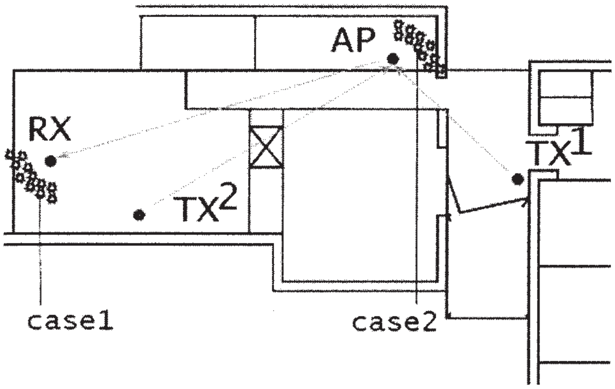

Fig. 5. Measurement layout for the office measurements.

In the office environment, two different scenarios were studied. The link distance in peer-to-peer mode was 25 m in the NLOS connection. In peer-to-peer mode the transmitter is located in the AP position represented in Figure 5. Another case examined corresponded to a typical LOS office installation with a WLAN link distance of 10 m (TX2-receiver). In the case of managed forwarding mode including AP, two link connections were studied. In both cases, the first hop was approximately 15 m (TX1-AP and TX2-AP) and the second hop 25 m (AP-receiver). The Bluetooth network performance was studied only in peer-to-peer mode in an office environment with a link distance of 10 m.

4. MEASUREMENT RESULTS

Whilst WLAN throughput measurements were being performed, spectrum analysis of the relevant radio frequencies was also performed. Figure 6 presents the IEEE 802.11b spectrum operating at Channel 1 ($f_c = 2.412$ GHz) with 20 active UWB transmitters at distances of 100 cm and 15 cm from the measurement antenna in the anechoic chamber (measured using a high-quality log-periodic reference antenna). This figure clearly shows the spectrum of the UWB interferers as they are moved closer to the antenna of the spectrum analyzer. The stationary WLAN transmitter operates with constant power at all times. The reference receiver, which is a spectrum analyzer, can see the effect of the UWB emission when the distance between the interferers and the antenna decreases. If the distance is 100 cm, the effect is insignificant. With the distance of 15 cm between the UWB devices and reference antenna, spectral components will arise, as can be seen in Figure 6c.

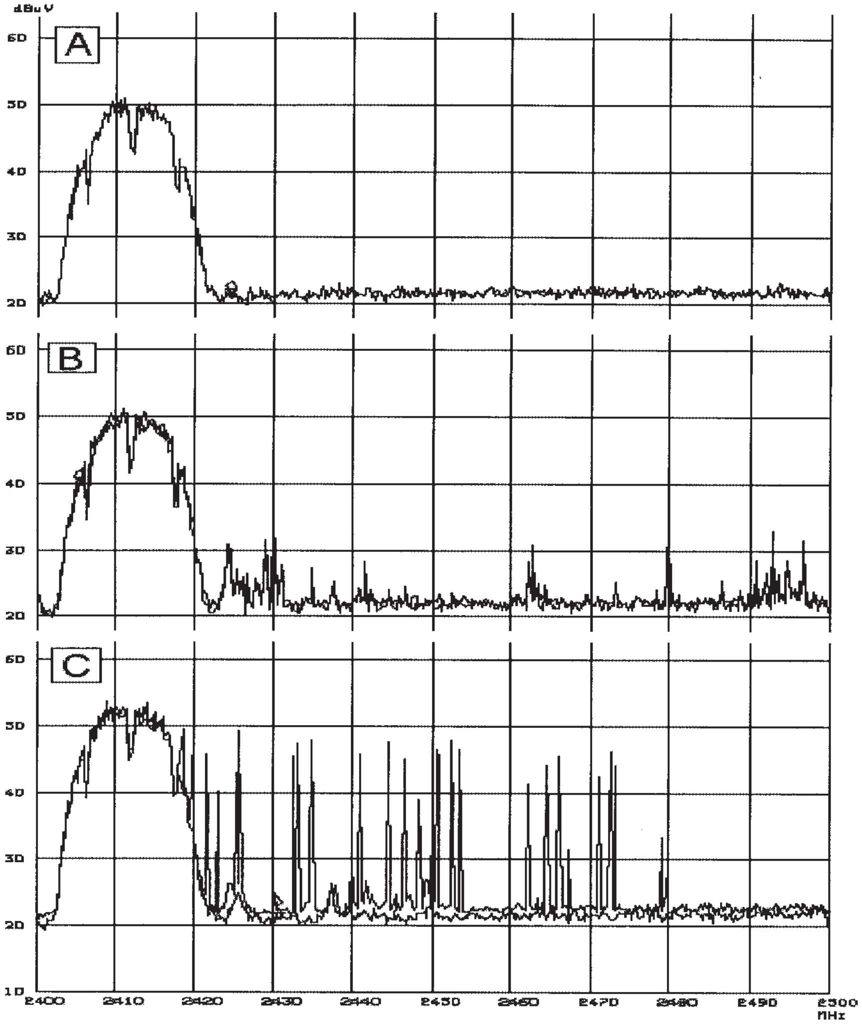

Fig. 6. Received signal spectrum of WLAN Channel 1. (A) without UWB signal, (B) with 20 active UWB transmitters 100 cm, and (C) 15 cm from the reference antenna.

The UWB radiation is not clearly visible in the WLAN operating frequency band because the spectrum analyzer is only recording the peak value at each frequency and the WLAN device is the dominant radiator.

The Bluetooth measurements followed the same procedure as the WLAN measurements described above. The test site in this case was a typical office environment during the working hours, which implies that other, unintentional radio interference sources cannot be controlled during the measurements.

4.1. Signal-to-Noise Ratio Measurements

The current Bluetooth setup does not allow measurements of the physical properties of the connection; therefore SNR results are only presented for the 802.11b system. Figure 7 presents the instantaneous and averaged SNR for the IEEE 802.11b network as reported by the device in the NLOS configuration (cf. Figure 5, link AP-receiver). Between minutes 0 and 18, all 20 UWB transmitters were regularly active, and between minutes 18 and 36 only 10 UWB sources were used. The active/inactive intervals were 3 min. The distance from the UWB transmitters to the victim WLAN card was approximately 50 cm. Average SNR degradations of 4 dB and 2 dB were observed for 20 and 10 UWB sources, respectively. The averaged SNR presented in Figure 7 is calculated using a moving averaging process over 1024 packets.

Without UWB interference, the maximum instantaneous variation of the measured SNR in the 802.11b network was almost 10 dB (with MGEN running). However, when the UWB interference is present, the instantaneous

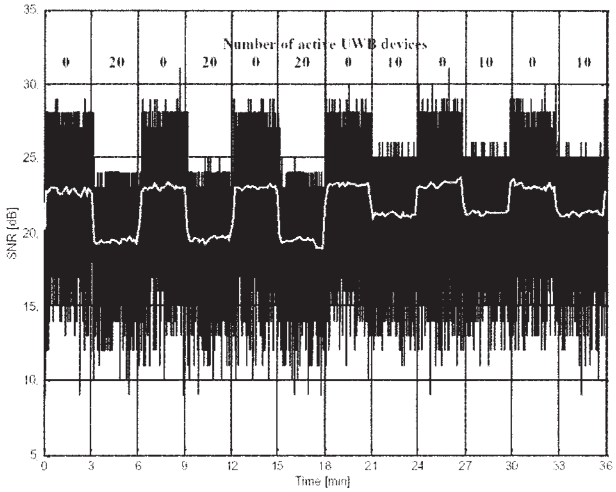

Fig. 7. Averaged and instantaneous SNR values reported by the WLAN card.

variation is smaller, with maximum variations of approximately 7 dB.

SNR values have also been examined as a function of distance between the UWB interferers and the victim system for various numbers of UWB interferers. The results are presented in Figure 8, in which the solid lines and dashed lines represent NLOS and LOS links, respectively. The legend indicates the number of active UWB devices used in the measurement (15/20 means that 15 active devices out of 20 devices were used).

The results show that if the distance between the extremely high-powered UWB devices is greater than 50 cm, no significant reduction occurs in the reported SNR. For distances of less than 50 cm, the SNR reduction was as much as 10–15 dB. SNR is, however, only one performance measure. The throughput of the network is the most important measure and is discussed in the following section.

Similarly, the SNR of the forwarded link connection can be measured. In Figure 9, SNRs are reported for the situation when the UWB devices are in the proximity of the WLAN receiver. The solid and dashed lines correspond to the result measured at the access point (AP) and the receiver, respectively. The results correspond to those presented above. Because of the distance between the AP and receiver, the impact of UWB at the AP is negligible. More interesting results can be seen from the error-free throughputs, which are discussed in the next section.

4.2. Throughput of the 802.11b and Bluetooth Networks

Figure 10 shows the throughput achieved for the 802.11b connection as a function of the number of active UWB transmitters. These results correspond to the SNR results presented in Figure 8. In the no-interference case, the throughput achieved is approximately 4,100 kbps both in LOS and NLOS links. In the LOS case in which the WLAN SNR is good, the impact of the UWB interferers on 802.11b throughput is insignificant even for very short distances.

When the available SNR degreases, for example, in a case of NLOS connection, the network throughput decreases as well and is more readily affected by the UWB interference. If the distance between the 802.11b

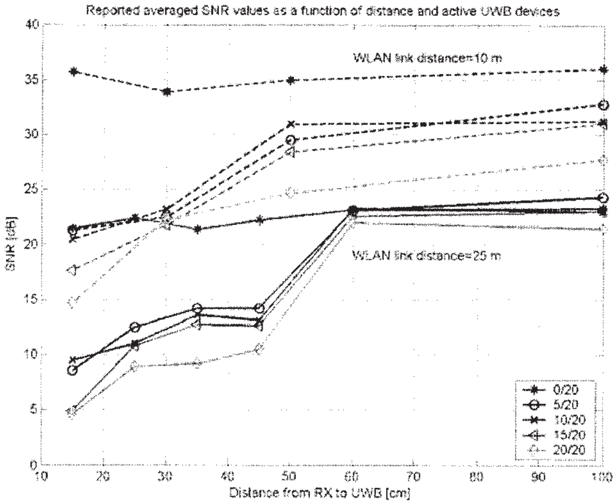

Fig. 8. Average SNR values of peer-to-peer link as a function of interference distance.

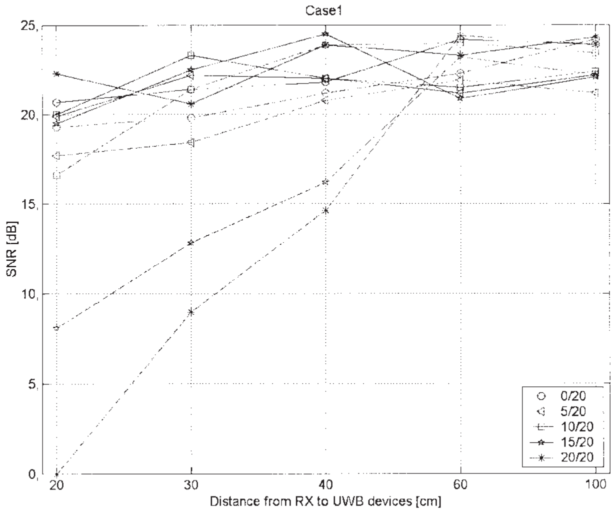

Fig. 9. SNR of the forwarded link. WLAN receiver is interfered. Solid and dashed lines represent the SNR values measures at AP and receiver, respectively.

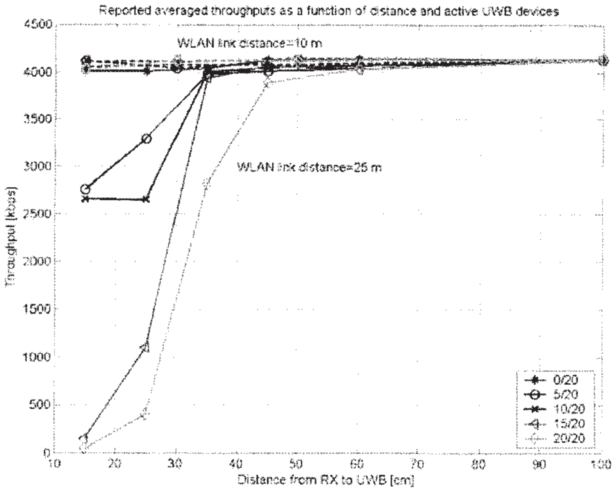

Fig. 10. Average throughput of the peer-to-peer WLAN as a function of interference distance.

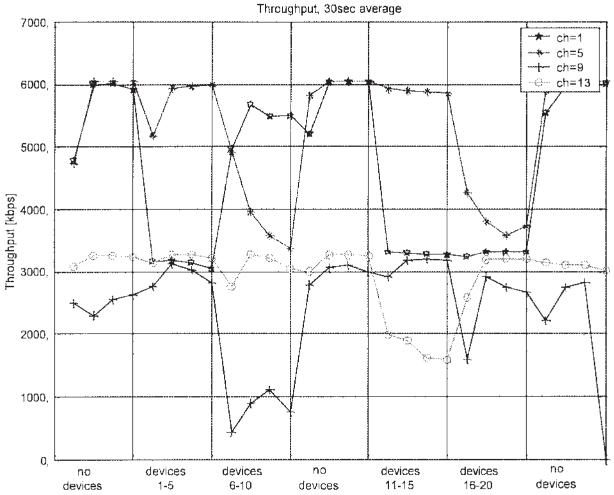

Fig. 12. Measured throughputs for WLAN channels 1, 5, 9, and 13.

receiver and UWB transmitters is small (<30 cm in our study) the WLAN throughput drops dramatically when 15 or more active "high-power" UWB devices are used. If the distance is greater than 40 cm, the deterioration is negligible and the throughput is the same as during the no-interference case.

In the case when the WLAN SNR is higher and no other RF interference is present, as for the measurements in the anechoic chamber, the link performance degrades when the distance is less than 30 cm, as can be seen from Figure 11. For greater distances, the UWB impact is insignificant.

In Figure 12, the measured throughputs are presented for four different 802.11b channels. The distance between UWB devices and victim receiver, and distance between 802.11b transceivers were about 5 cm and 4 m, respectively. The 20 UWB devices were divided into blocks of five devices. A block of five devices can all be turned on or off at the same time. The results indicate that there is also some difference between the individual UWB devices (which are constructed manually) and the different WLAN channels are affected differently in the presence of UWB interference.

As a reference, the variation in throughput without UWB interference but in the presence of movement (two people) near the WLAN devices is presented in Figure 13. This case study is done using the forwarding link connection. In the legend in Figure 13, the first parameter defines the device with which throughput was measured. The parameter in the parentheses indicates the WLAN device

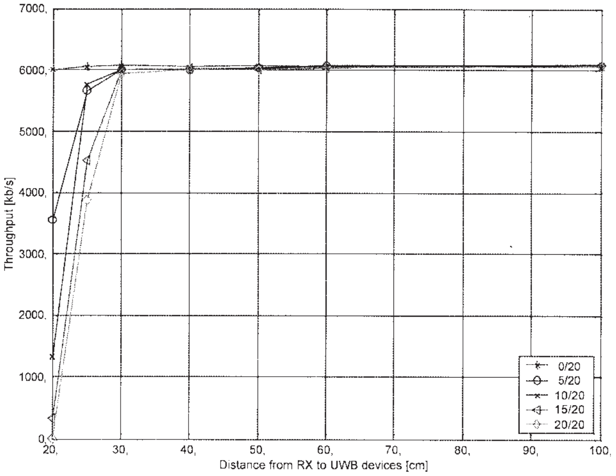

Fig. 11. WLAN throughput measured in an anechoic chamber.

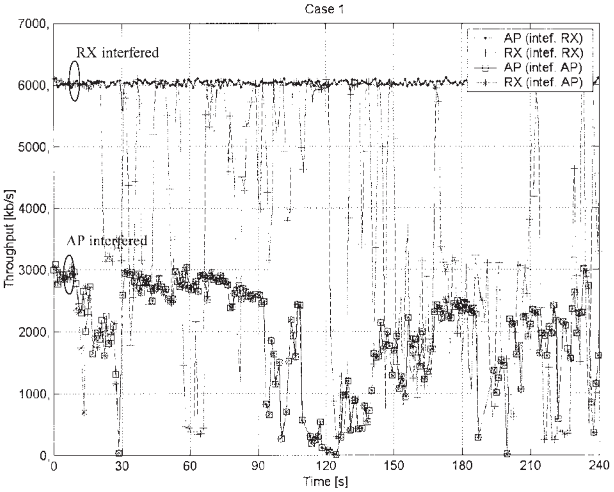

Fig. 13. Measured WLAN throughput in the presence of human interference.

walked around. As can be seen from the results, movement near the WLAN access point causes the whole network performance to degrade. No difference between the throughput of the access point and WLAN receiver can be seen. When movement was near the WLAN receiver, the throughput of the receiver changed significantly. No impact on AP performance was observed. The average results are comparable with the interference caused by 20 high-power UWB transmitters at the distance of 25 cm.

Next, the forwarding link throughputs were studied in more details. In Figures 14 and 15 the throughput of the network are represented. Throughputs of the access point and receiver are presented (in the figure solid and dashed lines, respectively). The interfering UWB devices are located around the WLAN receiver (case 1) or around the access point (Case 2). The results correspond to those from Figure 13. The network performance degrades more if the interference is near the AP. The throughput of the receiver follows that of the AP. If the interference is around the receiver, the performance of the AP is not affected.

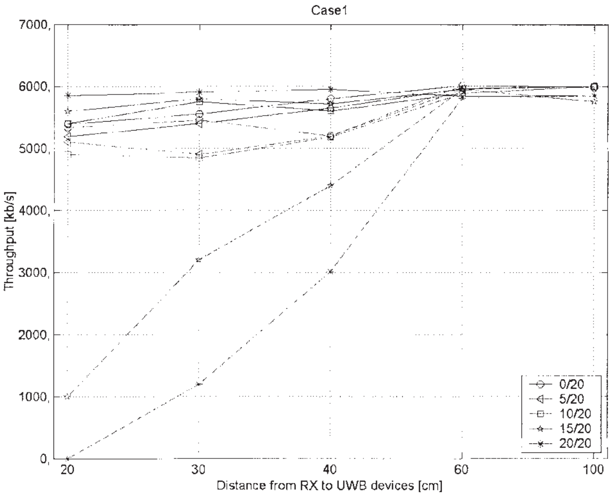

Fig. 14. Throughput of the forwarded link when WLAN receiver is interfered. Solid and dashed lines represent the throughputs of access point and WLAN receiver, respectively.

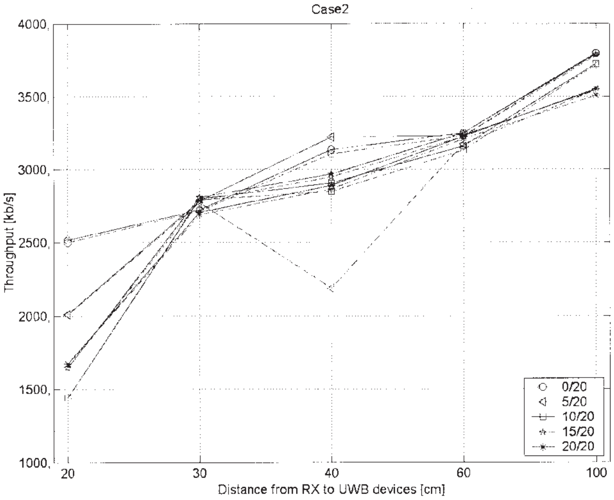

Fig. 15. Throughput of the forwarded link when access point is interfered. Solid and dashed lines represent the throughputs of access point and WLAN receiver, respectively.

The throughput of the Bluetooth network also has been examined at two selected link distances, 3 m and 10 m. The UWB interference sources were about 15 cm apart from the Bluetooth receiver. The results are presented in Figure 16 as a function of the number of active UWB devices. The throughput reduction in the Bluetooth connection is much milder even under the heavy interference conditions. The effective TCP peer-to-peer throughput without any interference was around 500 kbps and remained approximately constant when all 20 high-power UWB transmitters were active. The UWB devices were placed in an arc 15 cm from the Bluetooth receiver.

These results indicate the relative insensitivity of the frequency hopping Bluetooth devices to UWB interference. As seen earlier, the fixed pulse repetition interval of the UWB transmitters leads to a distinct line spectrum. The Bluetooth system is a frequency hopping system, and therefore the effects of bad channels will be averaged over the time. A small degradation in the throughput is noticed when the link distance is increased from 3 m to 10 m, which is also the maximum distance for the 1-mW Bluetooth system, as defined by the specifications.

Due to the ~87 MHz PRF, the spectral line separation is larger than the 83 MHz ISM band where Bluetooth operates. In addition to the continuous UWB spectrum also line

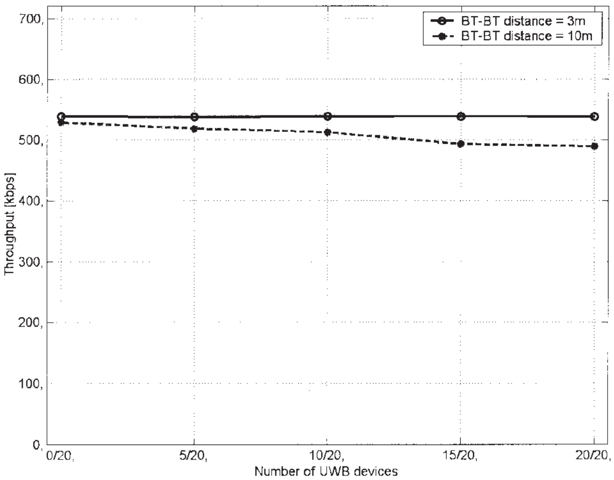

Fig. 16. Throughput of the Bluetooth network.

spectrum components appear. The overlapping between the latter and Bluetooth spectrum are not full time guaranteed. However, the spectral variation due to the manually manufactured UWB devices gives still enough reliability to the results.

5. CONCLUSION

At present, millions of IEEE 802.11b- and Bluetooth-enabled devices have been installed worldwide. This study has highlighted the level of impact of simple UWB devices on 802.11b and Bluetooth connections. TCP throughput and SNR results are based on the value reported from the network cards. Effectively, one UWB device used in our study corresponds to hundreds of FCC-complaint UWB devices because of its high transmitted power level, in the 2.4-GHz ISM band.

The results showed that under the extreme interference conditions examined, the UWB devices can have an impact on both IEEE 802.11b and Bluetooth networks, depending on the separation from the victim system.

For interference distances of less than 50 cm, the UWB interferers affected the reported SNR for both LOS and NLOS cases. The worst case degradation of the received SNR in the IEEE 802.11b was less than 15 dB for 20 UWB devices (equivalent to several thousand FCC-complaint UWB devices) at 10-cm distance. A corresponding drop in network throughput was observed only for the NLOS case and only for distances of less than 35 cm. In the LOS case, the impact of the UWB devices was insignificant.

The Bluetooth connection examined did not suffer significantly from the UWB interferers. The resulting decrease in throughput was approximately 20 kbps in the worst case.

It should be remembered that the UWB devices used in this experiment generate many hundreds of times more interference power in the ISM band than devices operating in accordance with the FCC UWB spectral mask limits. It is only under these extreme interference cases that any noticeable impact is discerned from the UWB sources.

The next phase of this work will result in new devices with variable pulse repetition frequency and transmit power and FCC compliant spectral characteristics.

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Jani Saloranta was born in Oulu, Finland in 1977. Since 2001, he has been working as a research scientist in the Centre for Wireless Communications (CWC) at the University of Oulu. Between 2001 and 2002 he worked as a research assistant dealing with receivers and channel modeling systems. Since 2002 he has focused on routing in wireless ad hoc networks. Since 2003 he also has worked on his master thesis, which concerns positioning and achieved accuracy in wireless sensor networks. His research interests are in graph theory, statistics, and applied mathematics.

Juha-Pekka Mäkelä received his M.Sc. degree in Electrical Engineering and Licentiate's degree in Communication Techniques from Oulu University, Finland, in 1997 and 2002, respectively. He is now working as a senior assistant in the Telecommunication Laboratory in the University of Oulu and working toward his Ph.D. in the area mobility management and geolocation applications in 4G wireless networks. His interests are intelligent hand-off techniques and mobility management issues in IP-based wireless networks.

Ian Oppermann completed a B.Sc., B.E., and Ph.D. at the University of Sydney, Australia in 1990, 1992, and 1997, respectively. His Ph.D. was related to physical layer aspects of novel spread spectrum/CDMA systems. In 1996 he founded SP Communications, a company that developed network planning tools for 3G mobile systems and IP cores for WLAN chipsets. Ian became an adjunct professor at the University of Oulu, Finland in 2001 and subsequently joined the Centre for Wireless Communications (CWC) in 2002 as Assistant Director, becoming Director in 2003. His main research responsibility is UWB, and he heads several large UWB research and development projects that cover fundamental research, channel measurement/modeling, system design, positioning, antenna, and RF ASIC development. Ian is a senior member of the IEEE and a member of the management committee of the EU 6th Framework UWB project PULSERS. Ian has been a guest editor for the *IEEE Journal of Selected Areas in Communications* (1999/2000) and was general chairman for the International Workshop on UWB Systems (IWUWBS Oulu, Finland, 2003), the international workshop on Wireless Ad-hoc Networks (IWWAN Oulu, Finland, 2004), and the International Symposium on Spread Spectrum Systems and Applications (ISSSTA, Sydney Australia 2004). Ian has coedited several books, holds several patents for wireless communications, and has over 60 publications in international journals and conferences.

Tero Patana received the M.Sc. degree in Physics, with an emphasis on Electrical Engineering and RF Technology from the University of Oulu, Finland. The graduation thesis concerned certain microwave applications. Since 1997 he has been working for Elektrobit Group in various RF, microwave, and antenna projects. UWB research was done when working for PJ Microwave Ltd. His current work at Elektrobit Ltd. includes different telecommunication applications, antennas and network design, and microwave applications.