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Outdoor radiolinks for 2.4 GHz-frequencies: measurement results and experiences within the radio communication network "Intermobil Region Dresden"

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Abstract. The radio communication network "Intermobil Region Dresden" was developed and built up for data transmission of traffic videos and other traffic data. It uses Point-to-Point (PtP) and Point-to-Multipoint (PtM) bridges, forming the backbone structure. The traffic camera radio clients link up with Accesspoints, installed at the nodal points of the backbone. This paper analyses the physical and technical conditions, building up such radio communication networks. The radio channel properties (e.g. total path loss, multipath propagation) and the technical parameters (e.g. transmission power, sensitivity, antenna gain) belong to this conditions. Based on calculation and spreading measurements it is shown, that reserves have to be considered during the planning already. As well special problems, like Fresnel-zone clearance and shadowing are discussed. The choice of the antenna plays a key role for planning and building of wireless networks. It determines decisively the range and gives an important contribution to elimination of wireless disturbances (interferences). Dependent on topological facts, installation environment and wireless distance omnidirectional-, yagi-, patch- and parabol-antennas are used. Based on antenna measurements the paper discusses the use and property of decoupling. WLANs are working in the license free 2.4 GHz-band. The number of radio systems in this band increases permanently, which leads to a lot of interferences among each other. The paper makes a classification of possible interference sources and discusses their influence on transmission quality. Technical solutions are shown for increase interference robustness.

1 Introduction

Modern traffic information and management systems require usable data channels permanently. Economic solutions are wireless networks, based on ISM-band frequencies. But each ISM-band differs in frequency range and usage. Only the 2.4 GHz-ISM-band with 83 MHz bandwidth has enough bandwidth for high data rate communication systems. That's why the traffic research BMBF-project "Intermobil Region Dresden" uses this frequency band.

The wireless network, reaching far beyond the town Dresden, consists of Wireless Local Area Networks (WLANs) components according standard IEEE 802.11b. It consists of Point-to-Point (PtP) and Point-to-Multi-point (PtM) bridges, forming the backbone structure. Traffic camera radio clients have a link to Accesspoints, installed at the nodal points of the wireless backbone, cp. Fig. 1 (Michler, 2002).

The paper has four main sections. First the technology and topological aspects of WLANs are presented in Sect. 2. Planning aspects, based on propagation and coverage measurements are described in Sect. 3. A classification of possible interference sources, their influence of transmission quality are discussed and technical solutions for interference elimination are presented in Sect. 4. Finally the paper is concluded in Sect. 5.

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2 Technology and topological aspects

WLANs use two different, incompatible spread spectrum technologies, which spread the signal power over a band of 83 MHz. The spread spectrum modulators base on the two methods: Frequency Hopping Spread Spectrum (FHSS) and Direct Sequence Spread Spectrum (DSSS). FHSS spreads the signal across 79 one-MHz subchannels, continuously skipping between them. DSSS breaks the band into 13 overlapping channels with a bandwidth of 22 MHz and uses permanently one channel. The DSSS technology provides raw data rates of 1, 2, 5.5 and 11 Mbit/s. The data rate of 1 Mbit/s uses Binary Phase Shift Keying (BPSK), the data rate of 2 Mbit/s uses Quadrature Phase Shift Keying (QPSK) and the 5.5 or rather the 11 Mbit/s uses the modulation technology Complementary Code Keying (CCK). Two operating topological modes are defined: Infrastructure and Ad-hoc mode.

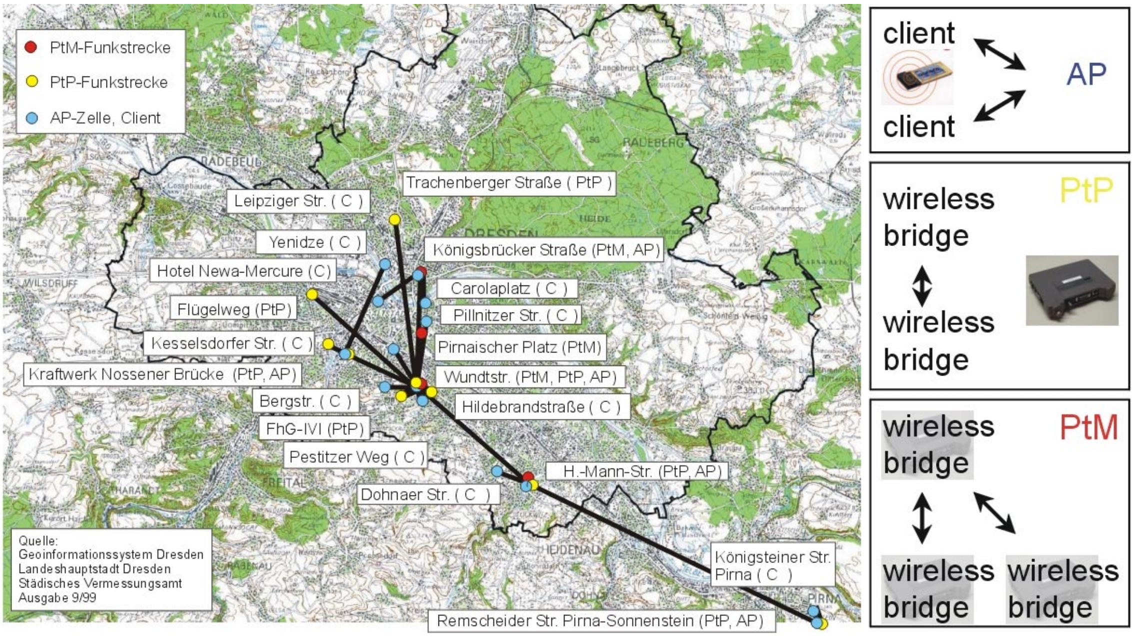

Fig. 1. Radio communication network "Intermobil Region Dresden" as of September 2002.

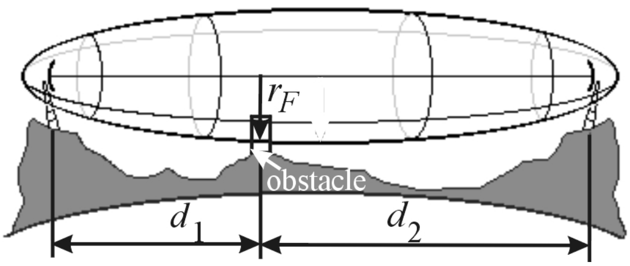

Fig. 2. Fresnel-zone with an obstacle.

The Ad-hoc mode allows simple client to client nodes to participate a Peer-to-Peer network without additional hardware. Additional hardware like AP, PtP and PtM-bridges provides the Infrastructure Network. It allows basic bridging, routing and client roaming between the Accesspoints (Bing, 2000).

The technical preconditions for using WLAN devices in Europe are defined in the ETSI-standard ETS 300328. The maximum Equivalent Isotropic Radiating Power (EIRP) of 20 dBm (100 mW), the license free activity of WLANs and the duty of notification to Regulatory Authority Telecommunications and Posts (RegTP) for radio links, crossing over land belong to the main preconditions.

3 Planning aspects for outdoor WLANs

3.1 Radio link engineering

Radio waves of GHz-frequencies propagate quasi-optical. The total loss due to obstacle absorption, reflection or scattering usually provides not enough receive level. That's why radio links have to meet the Line of Sight (LOS) condition. In addition to the gain of the receiving antenna, cable loss and receiver sensitivity, the total path loss determines the achievable link distance of an outdoor WLAN.

3.1.1 Free path loss

Unhindered propagation of radio waves demands the Fresnel-zone clearance. This means, that the Fresnel ellipsoid with the parameters d_1, d_2 and r_F have to be free of obstacles (cp. Fig. 2). The radius is

$$r_F = \sqrt{\lambda \frac{d_1 \cdot d_2}{d_1 + d_2}}. \tag{1}$$

If Eq. (1) complies with the clearance condition, the free path loss for $f = 2.4$ GHz is calculated by

$$\frac{L_0}{\text{dB}} \approx 100\,\text{dB} + 20 \cdot \lg\left(\frac{d}{\text{km}}\right). \tag{2}$$

This means that 1 kilometer radio distance follows a loss of 100 dB and every doubling of the radio distance increases the path loss about 6 dB. Based on Continuos Wave (CW) field measurements, selected radio links were investigated. The analysis of the measurements shows, that the variations of short radio distances are less than 1 dB and the variations of large radio distances are less than 2 dB.

3.1.2 Additional path loss in consequences of fresnel-zone clearance violation

Based on theoretical aspects (Freeman, 1998; Heinrich, 1988) the additional path loss is neglected for an obstacle,

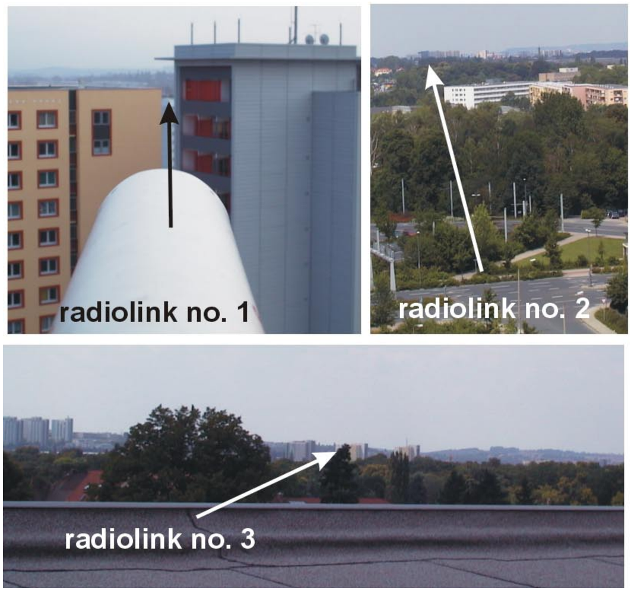

Fig. 3. Radio links without Fresnel-zone clearness.

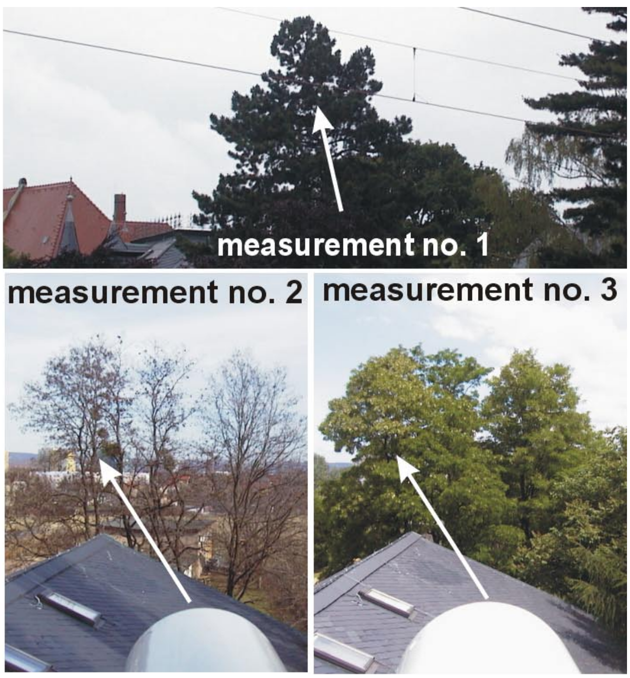

Fig. 4. Attenuation through vegetation.

rising less than 60 percent into the Fresnel-zone. The additional path loss Lfre increases up to 6 dB, if an obstacle is approximated to the line of sight.

Measurements of radio links without Fresnel-zone clearance are provided in Table 1 based on Fig. 3, which shows a view of the Fresnel-zone clearance violation. Especially the high path loss of 15 dB belonging to radio link no. 1 is based on the small clearness window of 1.5 m through the tower blocks. In this case two tower blocks neglect the Fresnel-zone one from the left and one from the right site. The Fresnel zone parameters are d_1 = 90 m and d_2 = 200 m. It follows from Eq. (1) r_F = 2.75 m, with what the violation is 75 percent and determines a theoretical additional loss of 12 dB.

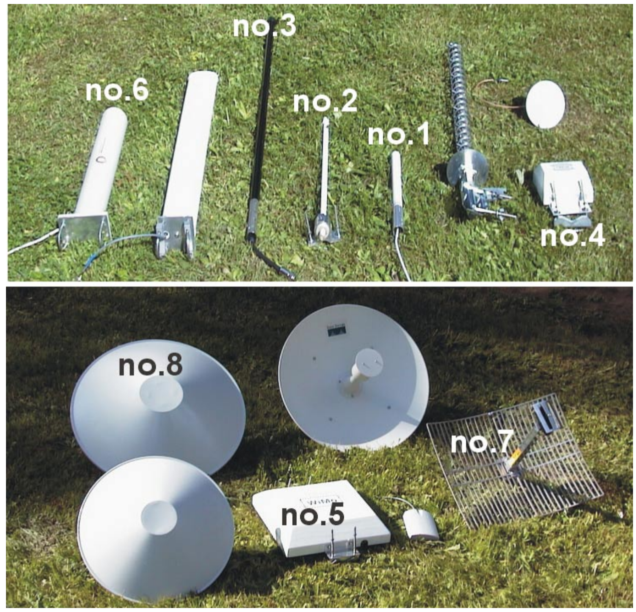

Fig. 5. Choice of measured antennas.

Table 1. Fresnel-zone measurements

Radio-link no.	Distance d	Kind of Fresnel clearness violation	Loss L_{fre}
1	290 m	small gap between two tower blocks	12 dB
2	5108 m	tree peaks	1.9 dB
3	2480 m	tree crown	2.6 dB

3.1.3 Shadowing-attenuation through vegetation

Shadowing is given, if obstacles reach over the line of sight. Bad penetrable obstacles lead to attenuation more than 30 dB, which is to much for outdoor radiolinks. Only poor penetrable obstacles as several trees or groups of trees are tolerated. Based on empirical models the attenuation Lveg of such a vegetation should be 4 to 5 dB, depending on tree dimensions, vegetation density, foliation clamminess, etc. (Morucci et al., 2000).

But the measurements results give a higher values of attenuation, cp. Table 2 and Fig. 4, which shows a view of the shadowing obstacles. Measurements no. 2 and 3 are the same radiolink, but with different foliation in winter and spring time.

3.1.4 Rainfall loss

It is well known, that rainfall loss is damaging to radio propagation above 10 GHz (Freeman, 1998; Heinrich, 1988). Mea-

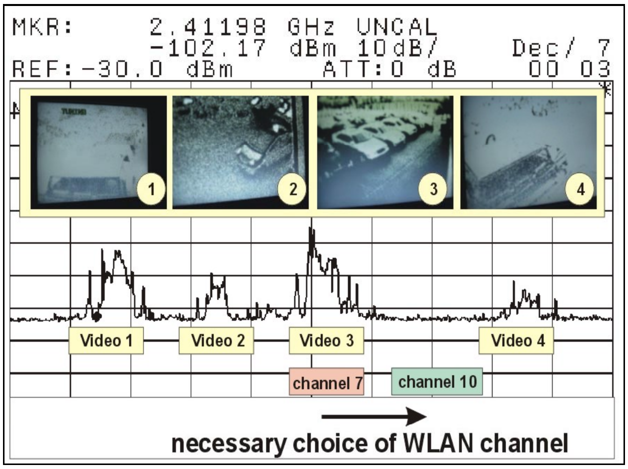

Fig. 6. Measured example of an analog video interference source with four channels.

Table 2. Vegetation measurements

Meas. no.	Distance d	Kind of shadowing	Loss L_{veg}
1	920 m	full tree crown	21.1 dB
2	850 m	tree without foliation	2.9 dB
3	850 m	tree with full foliation	20.7 dB

sured attenuation of 1 dB, getting from WLAN-radiolinks by different rainfall rates confirm this fact.

3.2 Antenna-selection

WLAN-antennas are commercial products with a high variety of types and implementations. They divide into two groups: cross-radiation antennas (e.g. omnidirectional-, planar- and parabolic antenna) and along-radiation antennas (e.g. yagi- and helix antenna) (Stirner, 1986). A lot of antenna types are measured, delivering parameters, which are essential for radiolink planning and optimization, cp. Fig. 5. That are the impedance VSWR, gain G, beamwidth φ_b, minor lobe angle φ_m, the minor lobe damping MLD, cross polarization damping XPD.

3.2.1 Omnidirectional-antennas

Non directional accesspoint links belong to the main application area of this antenna type. Point-to-multipoint wireless bridge links with star-shaped link directions are the second application area. Omnidirectional WLAN-antennas are completed as $\lambda/4-$, $3/4-$ or $5/4-\lambda$-radiator. Table 3 lists the main antenna parameters.

Table 3. Measured parameters of omnidirectional-antennas

No.	G (dBi)	VSWR	$\varphi_{b,vert.}$
1	4,2	1,35:1	25,7°
2	7,3	1,74:1	12,7°
3	10	$>$ 2:1	6,5°

Table 4. Measured parameters of planar- (no. 4 and 5), yagi- (no. 6) as well as parabol-antennas (no. 7 and 8)

No.	G (dBi)	VSWR	$\varphi_{b,horiz.}$	MLD (dB)	φ_m	XPD (dB)
4	8	1,44:1	54°	–	–	20
5	18,5	1,60:1	17°	13	31°	44
6	13,5	1,70:1	29°	12	40°	28
7	17,5	2,61:1	11°	9	18°	32
8	18	1,43:1	13°	19	27°	20

3.2.2 Planar-antennas

Accesspoints with a link range about 90° belong to the main application field of planar antennas with one radiation element. Bigger planar antennas, adding on vertical and horizontal elements inertially have a high antenna gain and a small angle of beam spread. They are used for Point-to-Point radiolinks up to 5 kilometer. For two of the measured planar antennas the main antenna parameters are listed in Table 4.

3.2.3 Yagi-antennas

The antenna parameters are designated through the number of directors. In the wireless network, viewing in Fig. 1 mostly 16-directors-yagi-antennas are used. Table 4 lists the parameters of this antenna type. Client link antennas and Point-to-Point or Point-to-Multipoint links of average distance up to 3 kilometer belong to the main application area.

3.2.4 Parabolic-antennas

Point-to-point links of 5 kilometer in average belong to the main application field of this antenna type. The parabolic antennas, installing in the radio network, presenting in Fig. 1 have a diameter of 60 cm. For two of the measured parabolic-antennas the main antenna parameters are listed in Table 4.

3.3 Receiver sensitivity

Sensitivity is characterized as the minimum signal above the noise level at which reliable communication is possible. The RF-device decides the sensitivity level on the one site. On the other site, the choice of the data rate decides the kind of modulation and the modulation decides the sensitivity level P_{in}, cp. Table 5.

Table 5. Measured sensitivities, depending on the data rate and the kind of modulation respectively

Data rate	Kind of modulation	Sensitivity P_{in}
11 Mbit/s	CCK (64 Codes)	−83 dBm
5.5 Mbit/s	CCK (4 Codes)	−89 dBm
2 Mbit/s	QPSK	−91 dBm
1 Mbit/s	BPSK	−95 dBm

Table 6. Calculated maximum WLAN radio-link distance for the parameter set: P_{out} = 20 dBm, G = 18 dBi, L_{cab} = 3 dB, L_{fad} = 6 dB

Data rate	Max. WLAN radiolink distance d_{max}
11 Mbit/s	4 kilometer
5.5 Mbit/s	8 kilometer
2 Mbit/s	10 kilometer
1 Mbit/s	14 kilometer

3.4 Transmission power

The EIRP-transmission power are strictly limited to P_{out} = 20 dBm (100 mW). Depending on antenna gain G, cable loss L_{cab} it is necessary to limit the RF-power of the WLAN device. Software and hardware stepped power limiters are used.

3.5 Fading reserves

Mutipath propagation leads to time and frequency selected level fluctuations. That's why reserves have to be planed for compensating this fluctuations. Based on measurements and experiences the fading reserves should not be chosen less than L_{fad} = 3 dB for short link distances of up to 1 kilometer and less than L_{fad} = 6 dB for longer link distances.

3.6 Link budget of outdoor WLANs

Based on the measured and calculated technical and physical parameters, which are presented in the Sect. 3.1 to 3.5, the radiolink range d_{max} is calculated below

$$\frac{d_{max}}{\text{km}} \approx 10^{0,05\cdot(L_0-100)} \quad \text{with,}$$
$$L_0 = \frac{P_{out}}{\text{dB}} + \frac{G}{\text{dBi}} - \frac{P_{in}}{\text{dB}} - \frac{L_{cab}}{\text{dB}} - \frac{L_{fre}}{\text{dB}} - \frac{L_{veg}}{\text{dB}} - \frac{L_{fad}}{\text{dB}} \qquad (3)$$

As an example, Table 6 shows a radiolink estimation with some practicable parameters. The calculation instruction (3) is a good aid, choosing respectively planing outdoor WLAN components. Problems and mistakes with the usage of Eq. (3) are given in interference (radio source) environments. In this case the following additional considerations and measurements are necessary.

Table 7. Necessary SIR, depending on the data rate and the kind of modulation respectively (Heeg, 1999; Mäusel, 1988)

Data rate	Kind of modulation	SIR (BER$<10^{-5}$)
11 Mbit/s	CCK (64 codes)	7.8 dB
5.5 Mbit/s	CCK (4 codes)	4.6 dB
2 Mbit/s	QPSK	5.6 dB
1 Mbit/s	BPSK	2.6 dB

Table 8. Decoupling attenuation, depending on antenna distance at a common aerial mast

Type of antenna	Distance	Decoupling attenuation
Yagi-antenna	0.5 m	52.2 dB
	1.0 m	54.5 dB
Planar-antenna	0.5 m	60.6 dB
	1.0 m	65.8 dB
Parabol-antenna	0.5 m	48.5 dB
	1.0 m	56.3 dB

4 Interferences sources and measures to interference reduction

WLANs are working in the license free 2.4 GHz-ISM-band. The usage of this ISM-band increases permanent, which leads to a lot of interferences. Based on experiences within the wireless network outdoor interference sources are classified in coupling within the antenna system, video transmission systems and competing outdoor WLANs. In the future Bluetooth systems will be another source of interference. Within the following section their influence on transmission quality is discussed and a set of technical solutions for increase of interference robustness is shown.

4.1 Requirements on the signal-to-interference ratio

The Signal-to Interference Ratio (SIR) is characterized as the ratio between the minimum signal level over the interference signal at which reliable communication is possible. Based on Heeg (1999), Table 8 presents values of SIR for DSSS-WLAN components, consisting of the so called PRISM-chipset.

4.2 Eigen-interferences through coupling within the antenna system

Theoretical only three DSSS-WLAN channels are working interference free in parallel. Particularly nodes of star-shaped link directions with separated radiolinks use more than three channels (cp. Fig. 1, Wundtstrasse with six parallel antennas). Therefore it is necessary to know the coupling damping between two antennas, installing at a common aerial mast with different types, distances and alignments. Table 8 shows

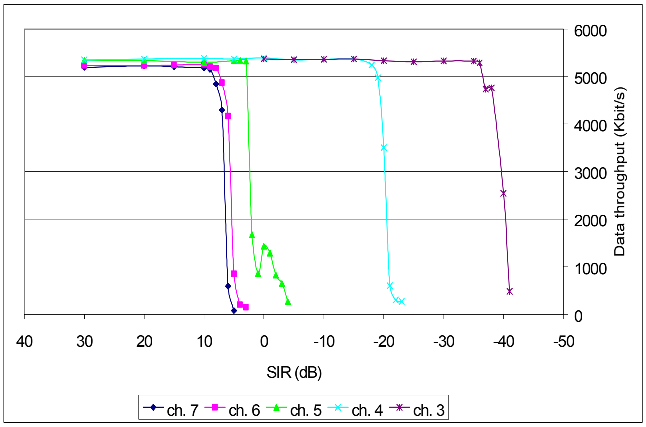

Fig. 7. Interferences through video: Measured data throughput in subject to SIR.

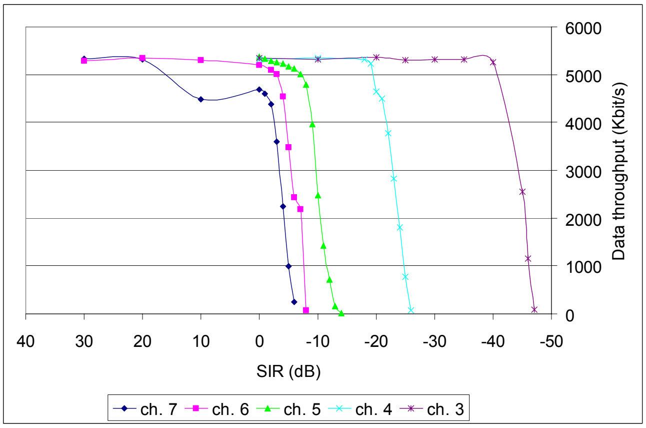

Fig. 8. Interferences through DSSS-WLAN: Measured data throughput in subject to SIR.

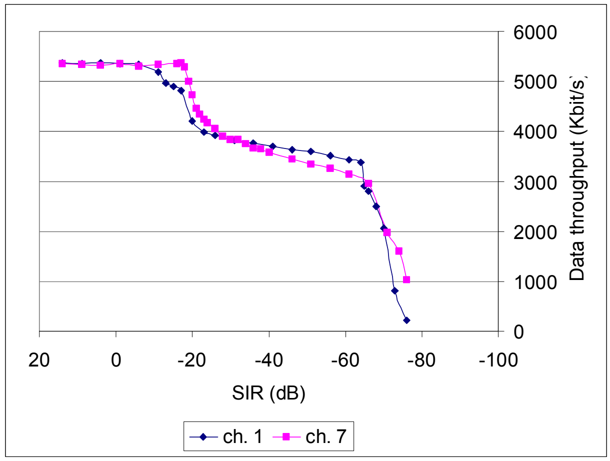

Fig. 9. Interferences through FHSS-WLAN: Measures data throughput in subject to SIR.

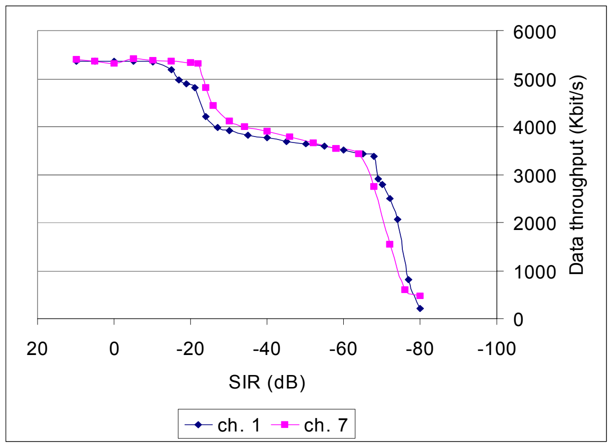

Fig. 10. Interferences through Bluetooth: Measures data throughput in subject to SIR.

a choice of measurement results. The analysis of all measurement results are combined:

- decoupling attenuation values vary between 45 and 70 dB
- decoupling of the antenna distance (0.5 m , 1 m and 2 m) increases the attenuation for about 5 dB
- rotation about 90° or 180° to each other increases the attenuation for about 10 dB
- crosspolarization arrangement of the antennas to each other is negligible

The analysis shows, that the coupling attenuations are to low, that WLANs can work interference free in parallel. Therefore the choice of the type, distance and alignment plays an important role, decreasing the interfering influences.

4.3 Interference through Video Transmission Systems

As experiences within the radio networks in Fig. 1 shows, video transmission systems are the main interference source of outdoor WLANs. In fact this transmission systems have a lower limited EIRP-transmission power of 10 dBm (10 mW) and a lower bandwidth of 6 MHz, however they use four channels mostly and transmit continuous. Therefore outdoor WLANs over big distances are endangered, if video transmission systems are transmitted nearly. Figure 6 shows a measured example of a video control system. A co-channel handling wasn't possible, wherefore the outdoor WLAN has to transmit of the adjacent channel No. 10. Therefore measurements in the lab of co-channel (ch. 7) and adjacent channel (ch. 3–6) interference reduction were necessary. Figure 7 presents a choice of measurement results. The analysis shows, that in the case of a channel distance of two, the necessary SIR decreases significant and for a distance of four channels the systems works interference free.

4.4 Interferences through DSSS-WLANs

Competing outdoor DSSS-WLANs are also a source of interferences. Alike the measurements in Sect. 4.3, co-channel and adjacent channel measurement for WLAN-systems are executed. Figure 8 presents a choice of measurement results. The analysis shows, that in the case of a channel distance of three the value of SIR is relative high. In view of the real level constellation, it is only possible to transmit on five DSSS channels (no. 1, 4, 7, 10 and 13) in parallel.

4.5 Interferences through FHSS-WLANs

Outdoor FHSS-WLANs, competing against DSSS-WLANs are a source of interference, too. The transmission power is also 20 dBm (100 mW), but FHSS-WLANs use the Frequency Hopping Spread Spectrum technology. This means, that all channels of a DSSS-WLAN are interfered uniformly. Figure 9 presents the measurement results of the middle channel 7 and marginal channel 1. The analysis shows, that the interference influence is rather low, but not negligible.

4.6 Interferences through Bluetooth-Systems

Bluetooth is a new transmission system in the 2.4 GHz-ISM-band. The typical transmission power is 0 dBm (1 mW) or 10 dBm (10 mW) only. Bluetooth systems use the Frequency Hopping Spread Spectrum technology, see Sect. 4.5. That obviously means, that the measurement results of interferences are similar to the results of Sect. 4.5, cp. Fig. 10.

4.7 Technical solutions for interference elimination

The usage of WLANs is without warranty of interference free environment. So it is clear, that only technical and conceptual measures can be used to reduce interferences. Some possible measures are:

- WLAN-cannel planning and correction, based on field measurements with a spectrum analyzer
- Special choice of the link antenna, based on antenna interference decoupling parameters
- Substitution of omnidirectional antennas for PtM-links by separate directional antennas with a passive powersplitter/-combiner
- Substitution of omnidirectional antennas for PtM-links by joint beamforming antennas with a active phase splitter (Razavilar et al., 1999)
- Reduction of long, interference sensitive radiolinks through repeater installation
- Adapted choice of data rate (the lowest possible data rate, depending form the personal usage)
- Substitution or completion of interference sensitive radiolinks through alternative ISM-band systems, as the future 5 GHz-ISM-band systems (IEEE 802.11a, HiperLAN/2) and laser link systems.

5 Conclusion

Based on the radiolink network “Intermobil Region Dresden” the physical and technical conditions are ana- lyzed, planning stable outdoor WLAN radio links of the IEEE standard 802.11b. Calculations and propagation measurements show, that loss reserves and additional attenuation have to be considered. Hints for antenna choice, influencing link distance, interference level and application field significant are given. Following the main interference sources are classified. Finally their influence of transmission quality is discussed and a set of technical solutions for increase of interference robustness is shown. The paper results and experiences prove, that link distance optimization and interference reduction of outdoor WLAN radiolinks are carried out successfully, by having special measurement devices and expert knowledge.

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