Infrastructure Density and Frequency Reuse for Wireless LAN Systems at 17 GHz in an Office Environment

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ABSTRACT: Using Wireless LANs (WLANs) in offices is becoming increasingly popular and operators start now offering access to wireless services via WLANs also in public areas. WLANs operate mostly at 2.4 GHz or 5 GHz. Propagation properties at these frequencies require a relative high frequency reuse even for typical indoor environments, which limits their spectral efficiency. In the 17 GHz band, which is also intended for operating HiperLAN, propagation conditions should allow a dense reuse, hence better spectral efficiency.

In this paper, we will therefore propose a basic system design for the 17 GHz band and study the infrastructure density required for achieving coverage as well as evaluate the spectral efficiency of the system. Simulation results in a typical office environment show that data rates of 100 Mbps can be achieved with a frequency reuse of 4.

We further analyze different infrastructure deployment scenarios and show that the installation of the wireless Access Points (APs) is not very critical. Hence, additional wiring for connecting the APs to the backbone network can be reduced without significantly lowering the system performance if suitable antennas are used.

1. Introduction

Wireless communication is expanding rapidly. The increasing number of wireless devices together with new, bandwidth-consuming applications fuel the growing demand for more bandwidth and higher data rates.

Large-area coverage for low data rates is almost everywhere available and new 3rd generation systems for medium data rates will be deployed in the next years. The trend goes to providing higher data rates in suitable areas, such as offices, homes or public places, e.g. train stations, shopping malls or airports. This is the domain of WLAN system, which are low-cost, easy to deploy and robust due to their specific design for unlicensed operation. The two main standards, IEEE 802.11a and HiperLAN/2, provide theoretically data rates up to 54 Mbps. Both are harmonized for the 5 GHz band and use an Orthogonal Frequency Division Multiplex (OFDM) air interface with link-adaptation and dynamic frequency selection (DFS), which allows the system to adapt to a different propagation and interference situations.

Simulations for HiperLAN in an indoor office environment [1] showed that indeed a system throughput of 52 Mbps can be achieved, however with a relative high frequency reuse of 19. The figure reduces to 27 Mbps if the system is operated at a reuse of 8. Intra-cell interference through walls, open doors and across hallways forces the system to use frequently lower-order modulation schemes and strong coding.

Using higher frequency bands is an alternative if higher data rates and spectral efficiency should be reached. A 200 MHz band is allocated for the operation of HiperLAN at 17 GHz according to the CEPT recommendation 70-03 E [2]. The higher penetration loss for common building materials (e.g. a 10 cm plasterboard wall has an approximately 3.4 dB higher absorption loss at 17 GHz compared to 5 GHz) shields rooms more effectively, hence suppresses interference across cells. However, since the free-space propagation loss at 17 GHz increases by 10.4 dB compared to 5 GHz, coverage is also more difficult to achieve. We will therefore in this paper propose a relative simple system and investigate:

1. How many access points are required to achieve coverage in a typical office environment?
2. What frequency reuse yields the highest spectral efficiency while maintaining a given minimum signal quality?
3. What average data rates can be transmitted?
4. How much does the system performance change for different installation procedures?

Assuming that certainly more advanced system designs can be developed, we can from the obtained results conclude what data rates and system capacities are feasible in the 17 GHz band.

The paper is structured as follows. Section 2 starts with a discussion of the office environment and the installation scenarios. Then, the physical layer characteristics of the proposed system are presented. We discuss appropriate propagation and shadowing models as well as introduce suitable performance measures to evaluate the proposed system. Section 3 shows the results of link-layer simulations. In section 4, we determine the minimum AP density required to provide coverage in the given office environment. A fully loaded system is evaluated in section 5, including appropriate frequency reuse factors, average throughput and spectral efficiency. Conclusions are and proposals for further research are presented in section 6.

2. System Models

Office environment and installation of access points

Very high data rates are most likely required in private indoor environments, such as offices and homes, or public places, e.g. shopping malls airports or train stations. We will limit our attention to a typical office scenario for two reasons:

1. Very high data rate applications, such as virtual reality or video conferencing, are perhaps not that often used in public places.
2. An average home is similar to an office environment with respect to radio coverage. However, capacity demands are usually higher in an office due to the larger number of users.

The considered office environment is shown in fig. 1, where the dark dots represent an exemplary installation of 16 APs. WLAN systems are normally installed by the users themselves. We can therefore not assume that the APs are optimally placed when modeling the wireless infrastructure, where optimal means that prior radio network planning determines the positions of the APs in a way that mutual interference between cells is minimized. In fact, the high infrastructure density we expect to be required at 17 GHz precludes sophisticated coverage planning due to the computational complexity of suitable indoor propagation prediction tools. Results would be either too inaccurate or time consuming, hence costly. We will therefore assume that instead some coarse network planning is done by simply subdividing the service area in equally sized rectangles, or cells. Adaptive resource management algorithms will then fine-tune the network parameters while the WLAN is in operation [3].

We consider for the evaluation of the system performance the following two scenarios, which are also illustrated in fig. 2:

1. APs are installed below the ceiling and in the center of the cell. This guarantees a relative uniform illumination of the cell area and reduces potential shadowing by persons walking inside the room. However, additional wiring will generally be necessary, since LAN outlets are mostly found alongside walls in a room.
2. APs are placed close to available LAN outlets. A 1…2 m long network cord would allow mounting the AP on the wall at approximately 1.5…2 m height. In this scenario, the illumination of the cell area is more difficult and requires antennas with specially adapted radiation pattern. Further, the probability of shadowing is larger due to the lower height difference between transmitter and receiver.

Propagation and shadowing models

Ray-tracing was used to simulate the indoor propagation in the given office environment, since it more accurately captures the actual situation than statistical pathloss models. The exact reproduction of the building structure is also necessary to evaluate the impact of the tow different installation scenarios on coverage and system capacity.

Shadowing caused by persons walking inside the rooms has a strong impact on the radio link. Measurements at 17 GHz [4] showed that a human walking through the LOS attenuates the received signal power by approximately 13 dB. In this paper, we consider two different types of

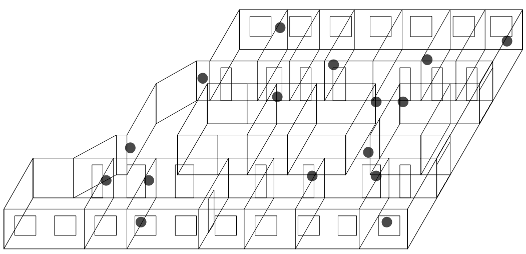

Figure 1: Typical office environment

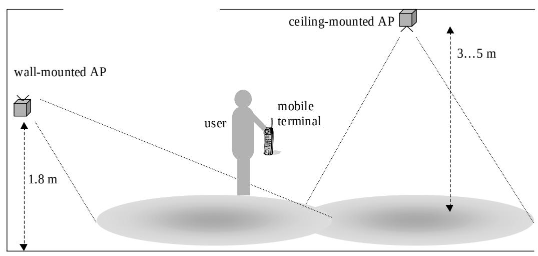

Figure 2: Installation of APs.

shadowing. Persons walking inside a room will attenuate a certain number of all rays arriving at a receiver, which is incorporated by a statistical model based on geometric considerations [5]. However, also the user himself will also cause shadowing if the receiver is carried close to the body, e.g. in a jacket pocket or attached to the belt. We will call this effect, which in fact reduces the *"visibility"* of the receiver to a half-sphere, self-shadowing and model it by appropriately modifying the receiver antenna.

Physical layer characteristics

An OFDM air interface was selected to combat the *Inter-Symbol-Interference* (ISI) caused by strong multipath propagation effects. The system uses 256 subcarriers in a 50 MHz bandwidth. The guard interval is set to 210 ns, according to measurements at a number of indoor settings [6], which showed that the RMS delay spread does normally not exceed 100 ns. With a sampling frequency of 50 MHz and the 210 ns guard interval, a total symbol time of 2.77 μs is used. Three different modulation schemes, 4-/16-/64-QAM, allow some basic form of link-adaptation, where the system employs a high-order scheme for good channel conditions and falls back to lower-order schemes when the channel quality deteriorates. A half-rate Reed-Solomon RS(31,15) code is used to correct bit errors caused by fast fading.

Performance measures

The quality of a communication link is generally considered as sufficient if a given Bit Error Rate (BER) is not exceeded. Two effects influence the BER or a wireless link: *shadow fading*, which causes a slow changing Signal-to-Interference-Ratio (SIR), and *multipath fading*, which results in fast changing phase and amplitude of the received signal. We will follow the approach proposed in [7] and model both effects separately.

The fast fading component can usually not be tracked and corrected, since even very high sampling frequencies do not enable the receiver to resolve each individual reflection. Suitable performance margins should therefore be included in the system design. At 17 GHz, the multipath fading changes considerably over small distances, due to the short wavelength of 1.7 cm. This would require very close-spaced sampling points, making coverage predictions of large areas impossible. We will instead evaluate the performance loss due to multipath fading in the small-scale, e.g. over an area of 20x20 wavelengths (35x35 cm at 17 GHz). The large-scale coverage properties can then be calculated over entire set of small-scale areas. We now define for the small-scale area a *local outage probability* π on the mean BER by:

$$\pi = \Pr\left\{\overline{BER} < 10^{-4}\right\} \qquad (1)$$

i.e. the probability that the time-averaged BER of a randomly selected sample point in that small-scale area is below 10^{-4}. This value can be considered sufficient if small packets are used and a fast ARQ scheme is employed. For a proper functioning of the system, we require the local outage probability to be below a maximum of $\hat{\pi} = 0.05$. We assume that a user will attempt to slightly change his or the devices position when experiencing a bad link quality, hence we can tolerate such a relative high local outage.

Based on the local outage probability π, we can now define the *large-scale outage probability* Π over the ensemble of small-scale zones as the fraction where the local outage probability exceeds the maximum $\hat{\pi}$:

$$\Pi = \Pr\{\pi > \hat{\pi}\} \qquad (2)$$

The large-scale outage probability is used to evaluate the coverage of the system and we will generally require $\Pi \leq 0.05$ for typical indoor situations, i.e. 95% of the entire service area should be covered.

3. Link-layer simulation results

The multipath fading margins were simulated for a large room with a size of 20x20 m. An AP was positioned in the corner of the room at 1.8 m height. 100 sample points placed in the middle of the room on a 1 cm grid and at 1 m height. The channel impulse response (CIR) including the Direction of Arrival (DoA) of each detected ray was obtained by ray-tracing for each sample position. To simulate shadowing effects, a number of obstacles with 80 cm diameter were placed in the room according to a uniform distribution. The ray trajectory before arrival at the receiver can be calculated from the DoA. In case a ray intersected with a shadowing object, the ray magnitude was attenuated by 13 dB. The density of persons in the room was set to 1 user/20 m^2, representing a typical situation in an office environment [8].

The received subcarriers, distorted by the frequency-selective fading, are obtained by transforming the CIR in the frequency domain with a 256-point FFT. After normalizing the received signal energy to remove slow fading and path-loss, the bit error probability is calculated and

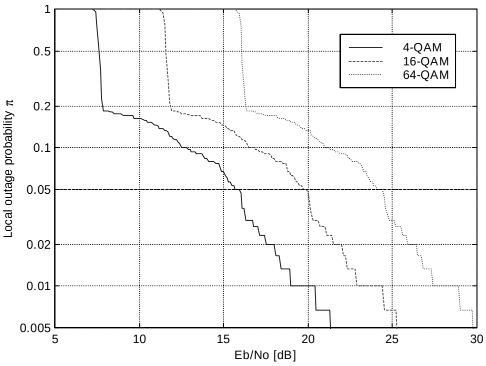

Figure 3: Link-layer results for a 256-carrier OFDM system; shadowing density 1 user/20m^2.

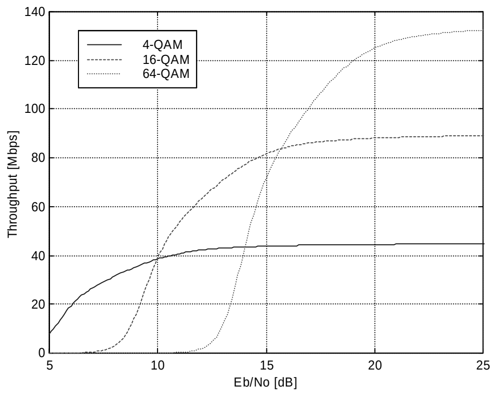

Figure 4: Link-layer throughput vs. E_b/N_0 for a shadowing density of 1 user/20m^2.

averaged over all subcarriers. More details and the link-layer results for DQPSK modulation can be found in [9].

Fig. 3 shows the results for 4-, 16- and 64-QAM modulation. To achieve a local outage probability of $\pi < 0.05$, an E_b/N_0 of 16 dB, 20 dB and 24 dB is required respectively. The BER performance now be used to estimate the expected link-layer throughput as a function of the received E_b/N_0. The throughput for an ideal ARQ scheme can be approximated by R_{max}(1-PER), where the Packet Error Rate (PER) is derived form the packet size and the bit error probability. The maximum data rate R_{max} depends on the useful symbol time (in our case 2.56 µs) and number of bits transmitted per constellation for a particular modulation scheme. The net throughput results after coding are shown in figure 4 and will be used in section 5 to estimate the achievable data rates from the SIR distribution. The key system parameters are summarized in table 1.

4. Coverage

We can now estimate the infrastructure density required for achieving coverage in the office

Parameter:	**Value:**
Number of carriers	256
Frequency reuse	2, 4, 6
Duplex method	FDD
System load	100%
Installation height of APs	
wall-mounted	1.8 m
ceiling-mounted	3 m
Multipath-fading margins	
4-QAM	16 dB
16-QAM	20 dB
64-QAM	24 dB
Large-scale outage probability Π	5%
Transmitted power (EIRP), MT and AP	20 dBm
Antenna gain	8 dBi
Human body shadowing	13 dB
Approximate penetration loss	
10 cm plasterboard wall	5.7 dB
10 cm concrete wall	20.7 dB
Noise floor	-97 dBm

Table 1: System parameter

environment. Fast fading is included in the link-layer performance margins. The received power values are calculated for a large number of uniformly distributed sample points by ray-tracing simulations. Self-shadowing is included by assigning each sample point a random direction in (0, 2π] and attenuating the back-lobe of the receiver antenna according to the shadowing model. Only AWGN with a single-sided spectral density of $N_0/2$ and no interference is considered, which is equivalent to a system with a perfect orthogonal multiple-access scheme and infinite system bandwidth. The transmission power is set to 12 dBm, so that the Effective Isotropic Radiated Power (EIRP) is limited to 20 dBm, a constraint proposed in [2] for the 17 GHz band.

The results shown in fig. 5 indicate that coverage can be achieved with an average density of

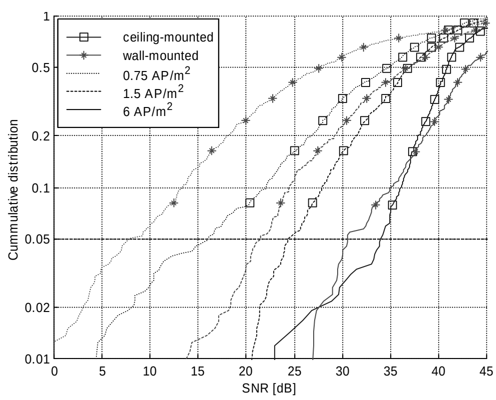

Figure 5: Cumulative distribution of the SNR for different infrastructure densities

1.5 APs/100 m^2, corresponding to 8 APs in the office environment. The wall-mounted installation causes some performance loss compared to the ceiling-mounted infrastructure, which can be compensated by a slightly denser placement of APs. However, potential cost savings due to a simpler installation procedure and avoidable additional wiring might justify a few extra APs. In the following section, we will notice that the directional antennas used for the wall-mounted installation can suppress intra-cell interference and yield higher throughput in some situations.

5. Capacity

The capacity is evaluated with the same system configuration described in the coverage section. However, now interference from other APs (down-link) and a randomly selected set of interfering mobile terminals (up-link) is taken into account. The system uses a frequency duplex scheme (FDD), which is less flexible than time duplex (TDD) in case of asymmetric traffic. But it allows drawing more accurate conclusions about the interference situation and frequency reuse for the different installation strategies, since FDD avoids interference between up- and down-link.

No power control is currently considered, since effective schemes require collecting considerable amounts of system information about received signal and interference levels. Keeping this information updated, becomes a formidable task in a network with a large number of APs, particularly if APs are geographically collocated, however can't communicate with each other.

The system is fully loaded, i.e. we assume in every cell and on every 50 MHz channel a continuous transmission of data. Results will therefore be rather pessimistic, hence providing a lower bound on the achievable system performance. The throughput is provided as *spectral efficiency*, i.e. as *"data rate per cell and 100 MHz"* (Mbps/cell/100 MHz), to facilitate comparison of results for different frequency reuse schemes.

Frequency reuse and infrastructure density

Improving coverage and achieving higher data rates generally requires smaller cells to reduce the radio distance between transmitter and receiver. However, the resulting higher interference level enforces higher frequency reuse factors. A range of combinations has therefore been investigated: infrastructure densities between 0.75…6 AP/100 m^2 and frequency reuse factors of 1…6. An appropriate frequency plan was obtained manually prior to the simulations. From the large amount of simulation data, only the results close to fulfilling the requirements on the large-scale outage probability, i.e. a SIR > 16 dB in 95% of the service area, are provided.

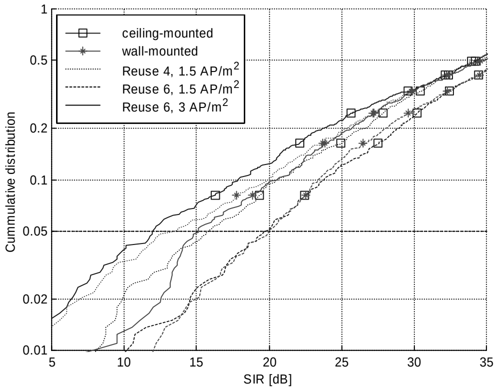

Figure 6: Cumulative distribution of the up-link SIR for a fully loaded system.

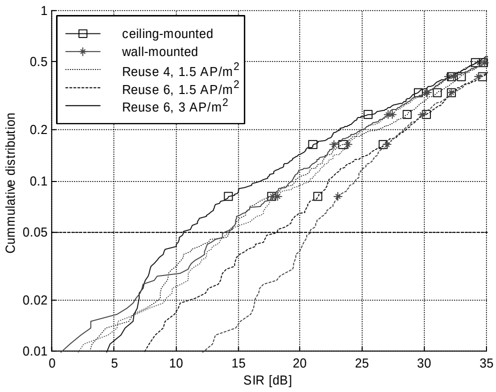

Figure 7: Cumulative distribution of the down-link SIR for a fully loaded system.

Figure 6 and 7 show that a infrastructure density of 1.5 APs/100 m^2 together with a frequency reuse of 6 achieves the best SIR distribution. As expected, a denser infrastructure increases the interference level in the system and causes a worse SIR distribution. The same observation can be made regarding lower frequency reuse. However, using a reuse of 4 instead of 6 results in a higher spectral efficiency, as shown in table 2 for the ceiling-mounted installation scenario. The values here are obtained by map-

AP density [AP/100m^2]	**Freq. reuse**	**wall-mounted up / down**	**ceiling-mounted up / down**
1.5	4	-	63 / 65.5
1.5	6	44 / 44	43 / 44
3	6	42 / 43	-

Table 2: Spectral efficiency in Mbps/cell/100 MHz for up- and down-link in a fully loaded system.

ping the link-layer results from figure 4 onto the SIR distribution and scaling with the frequency reuse factor and bandwidth occupation of the system. Nevertheless, data rates above 130 Mbps per radio link can be achieved in all cases.

Again, results for the wall- and ceiling-mounted installation differ only slightly. In some situations can wall-mounted APs even considerably improve the SIR distribution in both up- and down-link, since the directional antennas suppress co-channel interference. The arbitrary placement and direction of antennas in case of wall-mounted APs however makes general recommendations regarding favorable AP positions and installation procedures difficult. A system with dynamic channel allocation (DCA) and smart AP antennas, which jointly optimizes the frequency reuse and adjusts the radiation patterns, appears as a promising candidate for very high data rate WLANs.

6. Conclusions

The 17 GHz frequency band allows operating very high data rate wireless LANs, which can offer more than 100 Mbps per radio link. The system design proposed in this paper uses a 256-carrier OFDM air interface with half-rate Reed-Solomon block coding.

Two different installation scenarios have been investigated, taking into account that WLAN systems are usually set up by the customers themselves, having generally very little experience in radio network planning. However, it was found that an almost arbitrary placement of APs causes relative little performance loss. The use of specifically adopted antennas can mitigate the effects of the imperfect installation.

In the studied office environment, an average infrastructure density of 1.5 APs/100 m^2 was sufficient for achieving coverage. The relatively high absorption loss of common building materials at 17 GHz compared to 2 or 5 GHz reduces co-channel interference, allowing a higher frequency reuse in the network. The resulting higher spectral efficiency makes the 17 GHz band an interesting alternative to lower frequencies. However, the comparably narrow band of 200 MHz currently planned for HiperLAN systems at 17 GHz makes it difficult to accommodate systems with a throughput of 100 Mbps.

If convenient and cheap system deployment is of primary interest, dynamic channel allocation schemes and smart antennas should receive most attention.

7. References

[1] J. Khun-Jush, G. Malmgren, P. Schramm, J. Torsner, *“HIPERLAN type 2 for broadband wireless communication”*, Ericsson Review No. 2, 2000, www.ericsson.se/review

[2] *“Relating to the Use of Short Range Devices (SRD)”*, CEPT/ERC Recommendation (Tromsø 1997), CEPT/ERC/REC 70-03 E, Distribution B

[3] Borst, S.; Grandhi, S.A.; Kahn, C.L.; Kumaran, K.; Lubachevsky, B.; Sand, D.M., *“Simulation of self-organizing spectrum management in wireless networks”*, Proc. 6th Intl. Symposium on Modeling, Analysis and Simulation of Computer and Telecommunication Systems, pp. 268 -273, 1998.

[4] P. Nobles et al, *“Indoor Propagation Factors at 17 and 60 GHz”*, study carried out on behalf of the UK Radio Communications Agency, London, Dec. 1997, available at www.radio.gov.uk

[5] M. Unbehaun, J Zander, *"Indoor coverage for wearable devices with user deployed access points"*, 2nd PCC Workshop Lund/Sweden, November 1999

[6] P.F.M. Smulders, *"Broadband Wireless LANs: A Feasibility Study"*, Dr. thesis, Univ. of Eindhoven, Dec.1995

[7] Dardari, D.; Tralli, V., *"High-speed indoor wireless communications at 60 GHz with coded OFDM Communications"*, IEEE Transactions on Wireless Communications, Volume: 47 11 , Nov. 1999 , Page(s): 1709 - 1721

[8] ETR 310, *"Digital Enhanced Cordless Telecommunications (DECT); Traffic capacity and spectrum requirements for multi-system and multi-service DECT applications co-existing in a common frequency band"*, pp 26-27, ETSI, August 1996

[9] M. Flament, M. Unbehaun, *"Impact of shadow fading in a mm-wave band wireless network"*, Proc. Int. Symposium on Wireless Personal Multimedia Communications, Bangkok, Nov. 2000