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EXHIBIT A

AN OVERVIEW OF MILLIMETER WAVE INDOOR WIRELESS COMMUNICATION SYSTEMS

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ABSTRACT

With the growing demand of wireless facilities in mobile, indoor and personal communications for speech, data and image services, the millimeter (mm) frequency band appears to be a strong candidate for the future. To motivate researchers and technologists in the field of mm wave technology, an overview of mm wave communication systems is presented in this paper. Channel characteristics, protocols and system performance have been described briefly.

I. INTRODUCTION

Recently, study of millimetric wave communication systems has drawn the attention of many researchers [1]-[27]. Frequency range of 20-60 GHz is selected for the present study because it lies in between the range of UHF and infrared. Therefore 20-60 GHz frequency band combines the advantages of the UHF and infrared and reduces their drawbacks.

The UHF-region has the main drawback that it is also used for radio and TV broadcast. This means that the spectrum is already full so the spread spectrum technique will have to be used for additional radio communications in this range. Even when spread spectrum is used, there will not be much bandwidth available for wireless communication (about 1 Mbps is the highest data rate that could be achieved [28]). The main advantage of the UHF-region is, that the waves can propagate around obstacles, so they do not suffer from Line-Of-Sight (LOS) limitations.

The infrared region has the main drawback that the waves propagate like light, i.e. only in a straight LOS path, thus there always has to be a direct path between transmitter and receiver, which of course can not always be guaranteed (portable phones). The main advantage of the IR-region is, that the signal does not propagate through building materials like concrete and steel, so it can be shielded in a single room.

A system which operates at 20-60 GHz combines the advantages of the UHF and the infrared regions: a signal is generated which can travel around

obstacles in a room (like furniture or people), but is shielded within this room by the concrete or steel walls. Another advantage is the fact that this frequency region is not in use by any other communications medium, so every channel can be allocated a large bandwidth: 100 MHz channels can be used without any bandwidth problems. A third advantage of the millimetre wave technology is, that antenna sizes are very small, so the equipment will be convenient. The fourth advantage is that mm wave has the potential to support broad-band service access which is especially relevant because of the advent of Broadband Integrated Service Digital Network (B-ISDN).

A major drawback of this frequency region is the fact that the technology for transmitters and receivers has not yet been fully developed. As a consequence the hardware will be expensive in the early stages. Another drawback is the possible health-hazard of the high frequencies. However, if sufficient low transmitting power is used and users are shielded from the vicinity of the antenna, this hazard is minimal.

II. PROPAGATION CHARACTERISTICS.

This section reviews the multipath delay spread, building materials, path loss, propagation model and health hazards.

A. Multipath Delay Spread

One factor that always has to be taken into account when considering wireless indoor (or outdoor for that matter) communication systems is the multipath effect. It never happens that a signal arrives at the receiver just once. When a signal travels from transmitter to receiver there is (almost) always one strong signal (the direct path), followed by a number of weaker

reflections from walls, furniture, etc. These *multipath* signals always arrive later at the receiver because they travel via a longer path. They are thus time and also phase shifted, giving a distortion to the desired signal (in the analogue case) or bit errors (in a digital channel). The time between the first and the last detectable signal is called the (multipath) delay spread. The delay spread imposes a limit to the

maximum bit rate at which data can be signalled without Inter Symbol Interference (ISI).

Some typical values for the RMS delay spread are given in Table I for the frequencies 1.7 GHz and 60 GHz. For 60 GHz the RMS delay spread will be less than 10 ns with a 90% probability. Measurement results in [5] show that RMS delay spread lies between 15 to 45 ns and 30 to 75 ns for small and large rooms, respectively. A worst case RMS delay spread value of 100 ns was observed.

Table I. Probability distribution for the RMS delay spread [20]

Probability	1.7 GHz	60 GHz
25 %	< 15 ns	< 2 ns
50 %	< 23 ns	< 7 ns
75 %	< 35 ns	< 8 ns
95 %	< 45 ns	< 13 ns

The multipath effect, which is in fact the main difference between mobile radio links and cable links, results in a time-variant behaviour of the channel. One can consider time selective channels and frequency selective channels.

When a signal is transmitted through a channel, and if the coherence bandwidth B_c is small in comparison to the bandwidth W of the transmitted signal, the channel is said to be frequency selective. In this case the signal is subjected to different gains and phase shifts across the band and is severely distorted by the channel. On the other hand, if the coherence bandwidth is large in comparison to the bandwidth of the transmitted signal, the channel is said to be frequency non-selective. All the frequency components in the transmitted signal undergo the same attenuation and phase shift in transmission through the channel.

When we select the signalling interval T smaller than the coherence time of the channel, the channel attenuation and phase shift are essentially fixed for the duration of at least one signalling interval. When this condition holds, we call the channel slow fading, otherwise it is fast fading.

The coherence bandwidth of a millimetre wave link is several MHz. Hence, only for bit rates up to 1Mbps the channel is non-frequency selective. As the quotient of the speed of the mobile unit and the wavelength is very small compared with bit rates of more than 200 kbps the channel is non-time selective too [10]. Thus for high data rates the indoor radio channel can be characterized as a slow fading, frequency selective channel.

Because the multipath delay spread is the most limiting factor in mobile communications, several

methods have been proposed to decrease the influence of this problem, thereby achieving a higher maximum data rate. One of the most commonly used solutions is using antenna diversity, i.e. multiple transmit and/or receive antennas. When a diversity antenna is used, the chance of receiving at least one LOS signal that is very strong compared to the multipath signals that arrive at the receiver is much greater. One practical antenna diversity technique that is often used is maximal ratio combining, whereby the signals received by multiple antennas are weighted and combined to maximize the SNR, thereby reducing the outage probability (the probability that the received signal BER for a user is greater than some required value).

Other techniques for increasing the maximum bit rate include: higher level modulation, adaptive equalisation, frequency diversity and OFDM (Orthogonal Frequency Division Multiplex).

B. Building materials

The effect of different building materials on the signal propagation is discussed in several papers. It appears that 'hard' building materials, such as concrete and steel, give a high attenuation, while 'soft' materials like sheet-rock, glass and gypsum give a much lower attenuation. For example: at 35 GHz, the attenuation of gypsum is 5 dB, while the attenuation of concrete is approximately 45 dB. From measurements it can also be concluded that for all the considered materials the attenuation increases as the frequency increases [22].

This knowledge can be used in the design of an indoor wireless communication system, because we know that all buildings nowadays have concrete for floors and outside walls, which gives a good shielding, but have sheetrock or gypsum for internal walls.

C. Path loss

The mean received signal power P decreases as a function of distance d according to the general attenuation law

$$\bar{P} = k r^{-\alpha} \quad (1)$$

where k is a constant and α is the path loss law. In free space $\alpha=2$. The value of α depends on the morphology of the building and also on the particular type of environment, e.g. office, hospital, etc. In [25] it is shown that the estimated path-loss exponents are less than 2 for the corridors. These results indicate the waveguiding effect in the corridors for the 20-60 GHz frequency band.

D. Propagation model

In the indoor environment, due to the presence of a Line-Of-Sight (LOS) path and the multipath effect, the distribution $f(r)$ of the signal level r may be given by a Rician distribution:

$$f(\tau) = \frac{\tau}{p_0} \exp \left[-\frac{r^2 + s^2}{2p_0} \right] I_0 \left(\frac{rs}{p_0} \right) \quad (2)$$

$$K = \frac{s^2}{2p_0}, \quad 0 \leq r < \infty, \quad s \geq 0$$

where $I_0()$ is the modified Bessel function of the first kind and zero order, s is the peak value of the specular radio signal, p_0 is the average of the fading signal and K is the Rician factor, which is defined as the ratio of the signal power from the dominant signal path and that of the scattered signal.

E. Oxygen absorption

At 60 GHz, a new phenomenon occurs, known as oxygen absorption. This means, that around this frequency the attenuation is much larger than at other frequencies. Oxygen absorption gives an extra attenuation of about 14 dB/km [18]. In some references (e.g., [11]) the attenuation due to oxygen absorption at 60 GHz is reported about 15 dB/km. In indoor wireless, oxygen absorption is an advantage, because it helps keeping the cells as small as possible, which helps creating a short reuse distance.

F. Health hazards

Another factor that has to be taken into account when considering these frequencies is the fact that a communication link operating at 20-60 GHz may give health hazards, especially when the high frequency transmitter is transmitting at too high a power. It was found that a transmit power of 1 mW is low enough. A better way to bring down the possibility of harmful biological effects is using the Spread Spectrum technique. Transmitting at different frequencies excludes overexposure to one high frequency for a long time.

III. SYSTEM PERFORMANCE

Considering the desired signal as Rician distributed and interfering signals as Rayleigh distributed, the bit error rate P_e is derived in [3] for a cellular system using DPSK modulation and frequency-nonselective channel.

$$P_e = \sum_{n=0}^6 \binom{6}{n} a_c^n (1-a_c)^{6-n} \int_0^{\infty} \frac{1}{2} \exp(-x) \cdot (1+K) \left[\frac{1}{SNR} + \frac{n}{SIR} \right] \exp \left[- (1+K) \left(\frac{1}{SNR} + \frac{n}{SIR} \right) x \right] \cdot I_0 \left[2 \left[xK(1+K) \left(\frac{1}{SNR} + \frac{n}{SIR} \right) \right]^{1/2} \right] dx \quad (3)$$

where a_c is the carried traffic per channel, n is the number of active cochannel interferers, SNR is the signal-to-noise ratio and SIR is the signal-to-interference rate. Fig. 1 shows the BER as a function of cell radii (R). For pico cell-radii [30] the interference dictates the BER, while for larger distances (micro [31] and macro [32]) the SNR is dominant. In picocell systems the cluster size should be made larger to reduce the interference.

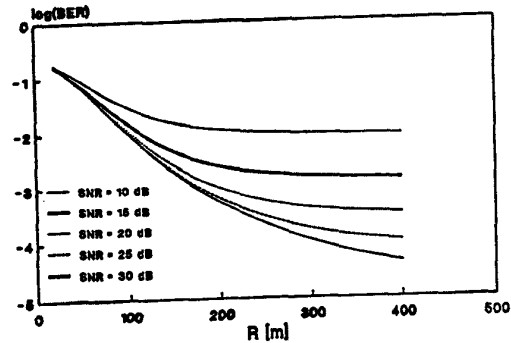


Fig. 1. The BER against R with the SNR as parameter (picocell sizes, $K = 6.8$ dB).

IV. LEVEL CROSSING RATE AND FADE DURATION

It is always useful to evaluate the average duration of deep fades because it gives a rough idea about the average length of occurrence of burst errors. If interleaving has to be applied, the successive bits must minimally be shifted over the expected duration of the burst. Here the average fade duration is obtained in terms of level crossing rate (LCR). The level crossing rate is defined as the expected rate at which the envelope crosses a specified signal level L in the positive direction. Average fade and non-fade duration in seconds for $K=6.9$ dB and 11 dB considering the speed of a slowly moving person as 0.5 km/h are given in [2]. It is concluded in [2] that the average fade duration for $K=6.8$ dB is in the same order as the fade duration for $K=11$ dB. However, the non-fade-duration increases dramatically as Rice parameter K increases. It is almost 1000 times larger for $K=11$ dB than that for $K=6.8$ dB.

V. PROTOCOLS

In [4] the throughput of packet radio cellular systems is analyzed using the interference model in Rician and Rayleigh fading environment with capture effect. The performance is investigated in mm wavelength at a typical frequency of 60 GHz, by taking account for the extra oxygen absorption (14 dB/km). Three types of random access protocols are considered, namely i) slotted ALOHA, ii) unslotted nonpersistent ISMA [33], and iii) slotted nonpersistent ISMA [34].

The mobile terminals are considered as communicating with a centrally located base station using packet radio. During the access to communicate to the base station, the terminals compete with each other.

Fig. 2 shows the throughput characteristics for pico-cellular systems [4] for a developed spatial distribution using capture ratio $Z_0=4$ dB and 0 dB, spatial spread $\sigma_d = 10$ and 2, inhibit delay fraction $d = 0.05$ and 0.01 , and $K = 0$ dB. The performance of the three protocols is compared. It can be seen from Fig.2 that the slotted nonpersistent ISMA gives the best performance. It is also shown in [4] that an increasing Rician parameter K leads to an enhanced performance. It is concluded in [4] that the throughput for 60 GHz is worse than for the case without oxygen absorption. In general, the best performance is given by slotted np-ISMA. Unslotted np-ISMA is second best while slotted ALOHA gives the worst performance.

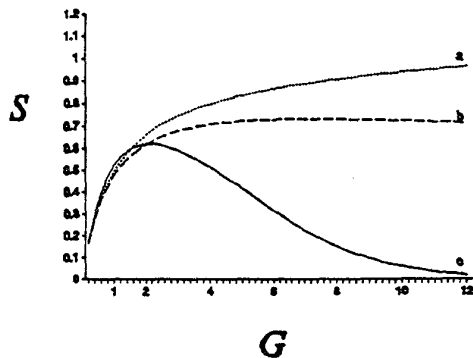


Fig. 2. Throughput curves of the three protocols in a pico cellular environment ($\sigma_d=2$, $d=0.01$, $z_0=0$ dB, desired $K=0$ dB, undesired $K=0$ dB).

VI. CONCLUSIONS AND RECOMMENDATIONS

An overview of the 20-60 GHz is presented in this paper considering propagation measurement results, performance analysis and protocols. It is evident now that mm frequency band will be a favourable choice for indoor wireless communications as well as outdoor wireless communications with small radii (microcells). It is concluded that a significant potential exists for the application of the 60 GHz oxygen absorption band for the indoor wireless communications as compared with the 1 GHz indoor systems.

The following topics are recommended for further investigations:

- * Propagation measurements for developing statistical model of the channel
- * The relation between cell-size, transmitted power and outage probability.
- * Antenna diversity and adaptive equalization..
- * Study of protocols combining voice data and images.
- * Detailed study of TDMA, FDMA and CDMA plus comparisons.
- * OFDM.
- * Dynamic channel allocation.

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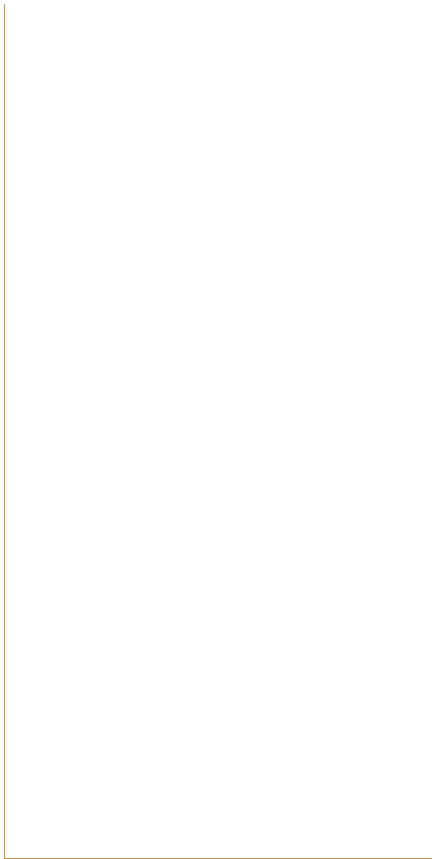
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