# Wireless Communications for Office Information Networks

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A brief look at the growth of wireless communications for office use

THE NUMBER OF TERMINALS for indoor use is rapidly growing in offices, manufacturing floors, shopping areas and warehouses. In the near future, one will expect to see several terminals clustered within a small indoor area. To avoid cable pulling to every forseeable location, and to provide flexibility in the placement of terminals, the concept of *wireless* communication for indoor applications is appealing. There have been two independent approaches to implement this concept: one using infrared radiation, and the other using spread-spectrum microwave technology.

Optical and radio signals both employ electromagnetic waves, with optical frequencies ranging approximately $10^5$ GHz and microwave signals in the 1-30 GHz range. The depth of penetration of an electromagnetic signal is inversely proportional to the square root of its frequency, so optical signals cannot pass through most of the objects around us, while radio frequency signals can.

In an indoor application, IR does not interfere with existing RF systems and there is no FCC regulation for this particular band of the electromagnetic spectrum. The FCC is only concerned with radio frequencies belows 300 GHz. IR radiation is essentially restricted to a room in which it is generated; it cannot be detected outside a room and will not interfere with similar systems in neighboring offices. However, IR is not suitable for very large offices or rooms with double blind corners. The data rate and, consequently, the number of users in IR systems is also restricted as compared to RF systems.

To select a frequency band for radio communication in an office environment, we face problems similar to those that exist in packet radio operation. As described in reference [15], the vicinity of ultra-high frequencies (UHF), from 300 MHZ-3 GHZ, is suitable for this purpose. The allocation of the 862–960 MHZ band for mobile radio and low power communication devices has stimulated interest in using this band for applications such as cordless telephones [1]. The same band or its vicinity is appealing for wireless office information networks.

Several radio propagation studies at 900 MHz within an office setting have been undertaken [1,2]. The experimental results show a maximum received power fluctuation of around 25–30 dB. This power fluctuation results from terminal movement and/or multipath fading of the channel, (see, for example the sample measurements in [2,3,4]). For these available measurements, it was found that the office environment exhibits frequency selectivity for RF propagation around 900 MHz, (for example, Fig. 1 of [3]).

One of the conventional techniques to counteract the consequences of frequency selective fading is to increase the transmission bandwidth using spread-spectrum techniques [15]. Spread spectrum will reduce the interference of the RF signal with any existing system and the detectability of the signal outside the office building.

The section on infrared communications reviews the propagation of optical infrared (IR) signals and modulation techniques used in IR channels. The section titled "Spread Spectrum" discusses applicable IR and RF (radio frequency) spread-spectrum techniques, and determines the number of simultaneous users in code division multiple access (CDMA) based systems. In the last section of this article different systems are compared and conclusive comments are presented.

### Infrared Communications

In this section, we first describe existing limitations of IR communications. Then, the application of several modulation

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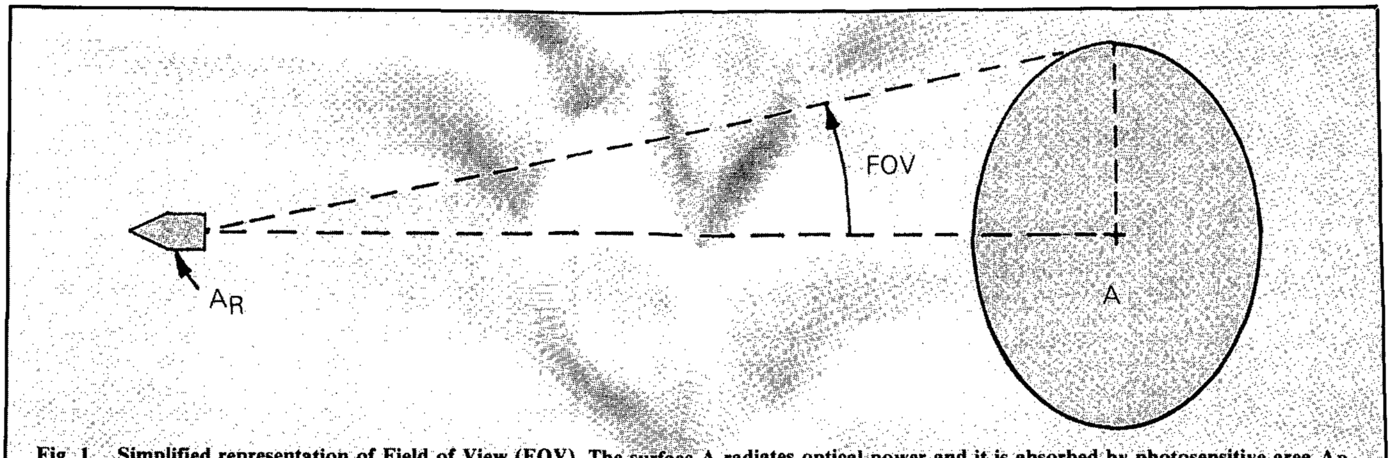

**Fig. 1.** Simplified representation of Field of View (FOV). The surface A radiates optical power and it is absorbed by photosensitive area $A_R$.

techniques in IR communication is discussed. Finally, different IR multiple access techniques used in multi-users environments are reviewed.

### *Limitations for IR Communications*

The rate of data transmission with IR is limited by three sources: multipath, ambient lights, and transient time of the Light Emitting Diodes (LED's). In this subsection these three limitations are briefly reviewed.

### *Limitation Due to Multipath*

Analysis of the IR optical channel is based on a simple model. If a surface $A$ radiates $W$ watts per unit surface area, the optical power incident on a photosensitive area $A_R$ is given by [5]:

$$P_R = W A_R \operatorname{Sin}^2 (FOV);\ 0 < FOV \leq 90°$$

where the angle FOV (Field of View) is shown in Fig. 1. As indicated by this equation, the received power $P_R$ for the area $A_R$ is independent of the position and angular orientation of the photo detector with respect to $A$, if the surface covers the entire FOV.

In practice, the FOV is less than 30°. This reduces the application of IR in an open environment if only a line-of-sight transmission path is considered, because the diffusing surface has to be in the FOV of the photosensitive diode. In an office environment, however, all the walls reflect the source of light and even if the transmitter and receiver are not in a line of sight, a photosensitive diode can absorb power reflected from the walls, ceiling, and other objects in the room that are located in its FOV.

The above discussion implies that IR communication in an office environment is performed through many different paths. Thus, the IR channel in an office is a multipath one. If the differential gain for each path is represented by $F(\tau)d\tau$ where $\tau = dp/c_\lambda$ is the delay related to a particular path, (see Fig. 2), with dp the path length and $c_\lambda$ the velocity of the optical waveform, it can be shown that [5]:

$$F(\tau) = \begin{cases} \dfrac{2\tau_o^2}{\tau^3 \operatorname{Sin}^2 FOV}\ ; & \tau_o \leq \tau \leq \dfrac{\tau_o}{\operatorname{Cos} FOV} \\ 0 & ;\ \text{Otherwise} \end{cases}$$

Considering the above discussion, a wave having the shape $f(t)$ that is incident on the reflecting surface is received as $g(t)$ at the photo sensitive diode, where:

$$g(t) = \int_{-\infty}^{+\infty} f(t-\tau)\, F(\tau)\, d\tau$$

The multipath causes a spread of the transmitted symbol in time, and the resulting intersymbol interference will restrict the digital transmission rate. As room dimensions become larger, the multipath spread is increased, and the supportable bit rate is decreased. The theoretical limitation for the transmission rate is 260 Mb-meter/s [5]. So, for a room with a length of 10 meters, we expect a transmission rate of 26 Mb/s, if multipath is the only cause of data rate limitation.

### *Limitation Due to Ambient Lights*

The infrared content of ambient light can interfere with IR radiations and if extensive, can overload the receiver photo diode and drive it beyond its operating point. These are three sources of ambient lights: daylight, incandescent illumination, and fluorescent lamps—all of which potentially interfere with IR communications. Figure 3 [5,6] shows the power spectral density of these three ambient light sources, and also indicates a GaAs diode's spectral center. Incandescent light, being rich in long wavelength (red) light, has the worst effect because its spectrum peak overlaps that of the GaAs diode spectral center.

Daylight contains less IR radiation, but if sunlight falls directly on the receiver lens, whether it is indoors or outdoors, it may jam an IR link. Fluorescent light normally has a small amount of IR radiation, and during turn-on time emits a 120 Hz interfering baseband signal rich in harmonics [6] which may reach up to 50 KHz [5].

The effects of ambient light are reduced by modulating the transmitted IR signal. The modulation carrier frequency should be at least several hundred KHz to avoid it being compressed with fluctuations of the ambient light. Figure 4 represents the maximum theoretical transmission speed of PCM systems for different room sizes in the presence of fluorescent light, daylight, and multipath distortion for a probability of error of $10^{-9}$.

### *Limitation Due to LED Transient Time*

The transmission speed of IR links has a basic limitation from the rise and fall times of light emitting diodes. For example, for the Siemens LD-271 or Gilway-E14, the LED rise and fall times are about 1 $\mu$s, limiting the data rate to 500 Kb/s.

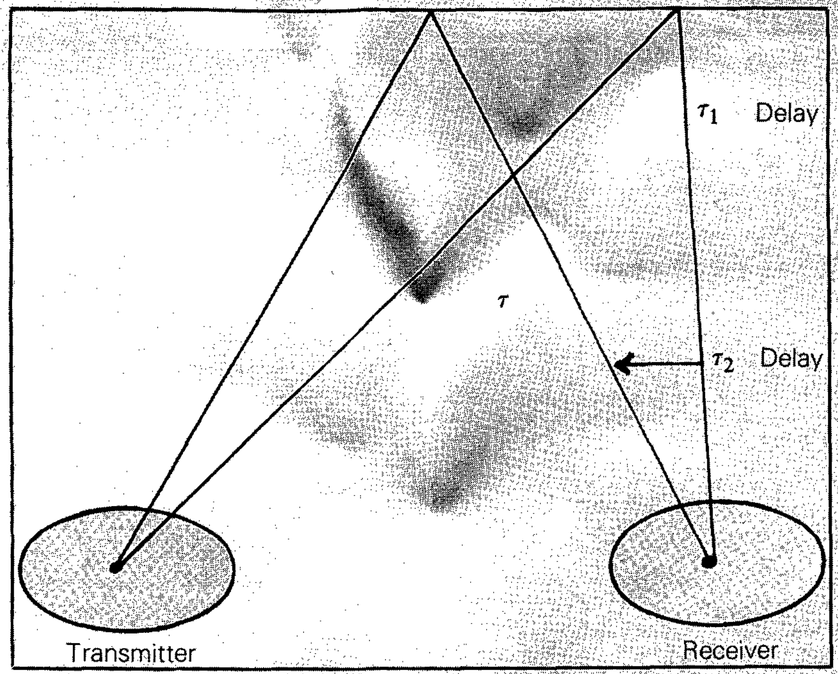

Fig. 2. Multipath in a closed environment, two paths between transmitter and receiver are shown. The corresponding delays for the paths are represented by $\tau_1$ and $\tau_2$.

### *Modulation Techniques for IR Communications*

In this section, possible applications of different modulation schemes in an IR communication link are investigated through several examples. These schemes are considered in three classes, analog modulation techniques, pulse modulation techniques, and digital modulation techniques.

In IR communications, modulation may take place in two stages. First the transmitted message modulates a carrier, and then this modulated signal intensity (amplitude) modulates the emitted infrared light. In practice, no type of direct amplitude modulation by the message is preferred, because IR links suffer from extensive amplitude fluctuations.

### *Analog Modulation* [6,7]

For indoor applications, analog modulation is generally used for audio signals. Modulation of the message on a carrier shifts

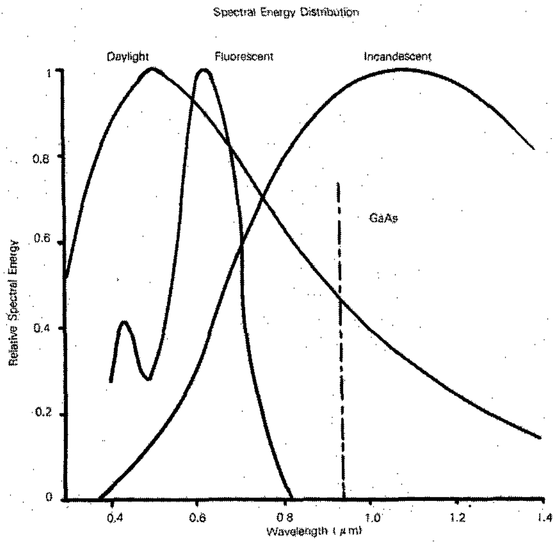

Fig. 3. Relative spectral energy distribution of various kinds of light sources: incandescent lamp, daylight, fluorescent light, and GaAs diode spectrum center [5,6].

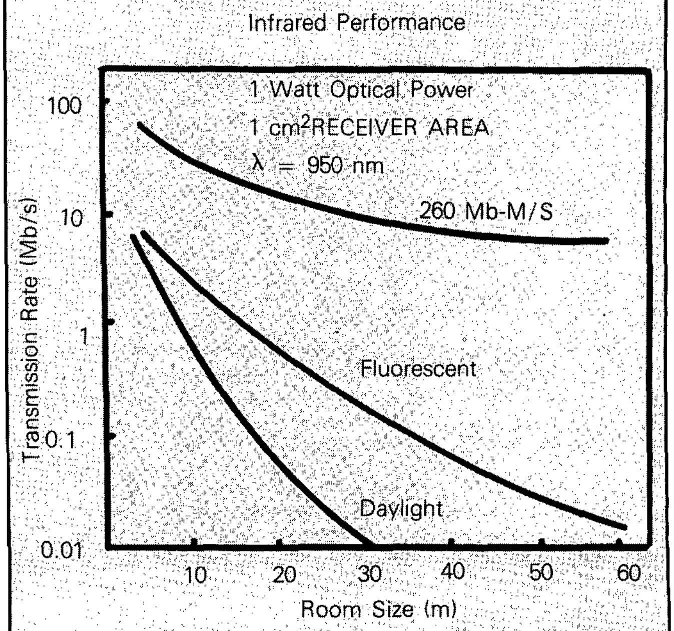

Fig. 4. Maximum transmission speed for different room sizes in the presence of fluorescent light, daylight, and multipath distortion [5].

the spectrum of the signal away from the spectrum of the ambient light, and provides an opportunity for multi-user applications using frequency-division multiplexing (FDM).

Since amplitude modulation is not a suitable choice for IR links, an audio signal may frequency modulate a carrier. The resulting signal then intensity modulates the IR light, as shown in Fig. 5.

One example of such an AM/FM system is given in [6]. In this system, the carrier frequency is 95 KHz and the maximum frequency deviation of the FM modulation is 50 KHz. The carrier frequency in this system can be effectively increased up to 500 KHz. In a multichannel environment, a nine-channel FDM system has been developed for simultaneous interpretation in multilingual conferences and exhibits [6].

### *Pulse Modulation Technique*

Analog signals (such as voice) can be sampled and then transmitted using analog pulse modulation techniques such as Pulse Amplitude Modulation (PAM), Pulse Duration Modulation (PDM) or Pulse Position Modulation (PPM). PAM is amplitude modulation, so it is not suitable for infrared links which suffer from extensive additive noise, but either PPM or PDM is suitable for this purpose. Siemens AG has implemented a cordless infrared telephone system using PPM with a sampling rate of 9000 samples per second [8]. Figure 6 represents the principles of operation of this system. Positions of the IR light pulses are moved according to the amplitudes of the transmitted samples of the audio signal. The same technique is used for both directions, and the pulses in one direction are inserted in the gaps between the pulses of the opposite transmission direction.

Samples of the signal may be quantized in digits to form a digital pulse modulated signal such as Pulse Code Modulation (PCM). As shown in Fig. 7, the Non Return to Zero (NRZ) data can be Manchester coded and the result can intensity modulate the IR light. The spectrum of the data before and after Manchester coding is given in Fig. 8. The spectrum of the coded signal includes weak low frequency components and it is possible to filter out ambient light interferences at these frequencies using a high pass filter. Manchester coding also provides a better timing extraction [29]. The obvious disadvantage of this coding is the doubling of transmission pulse rate.

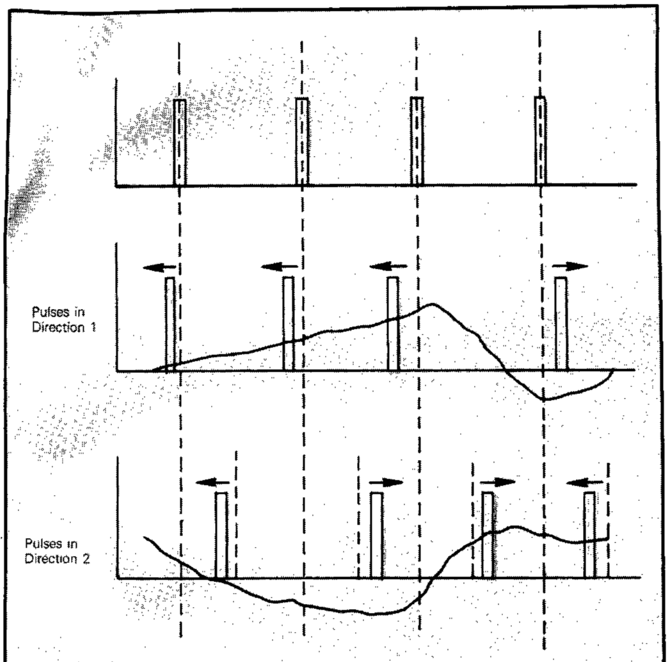

**Fig. 6.** Two directional Pulse Position Modulation for cordless phone. Position of the IR light pulses are moved according to the amplitude of the transmitting sample of audio signal [8].

An experimental PCM system has been developed by IBM Zurich with a data rate of 125 Kb/s [5]. The resulting error

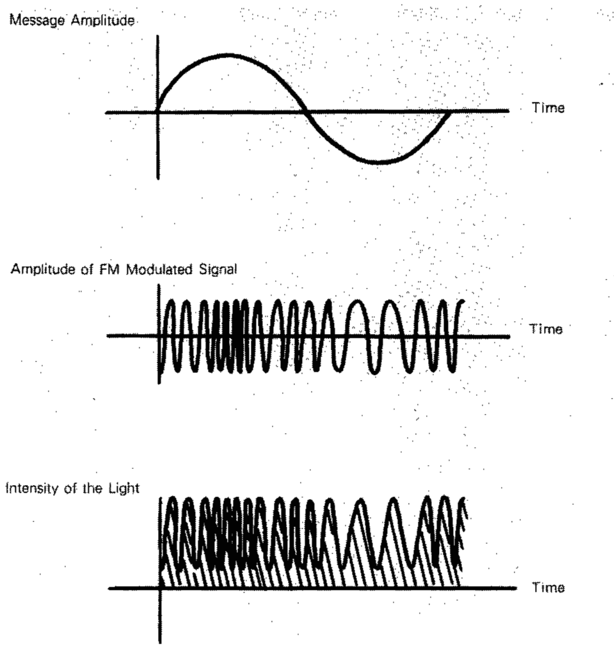

**Fig. 5.** AM/FM modulation for IR links. The audio signal frequency modulates a carrier, and the resulting signal intensity modulates the IR light.

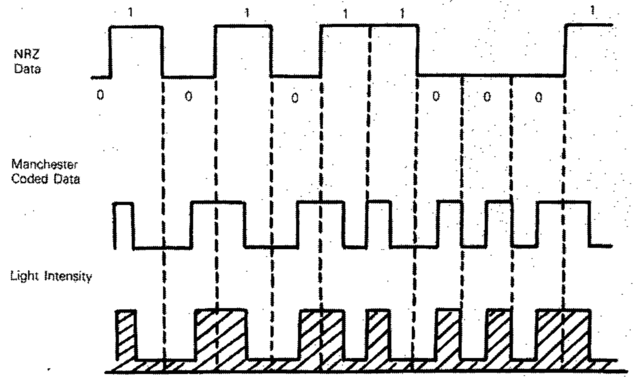

**Fig. 7.** Baseband PCM using Manchester coding for IR links. NRZ signal is Manchester coded and the result intensity modulates the IR light.

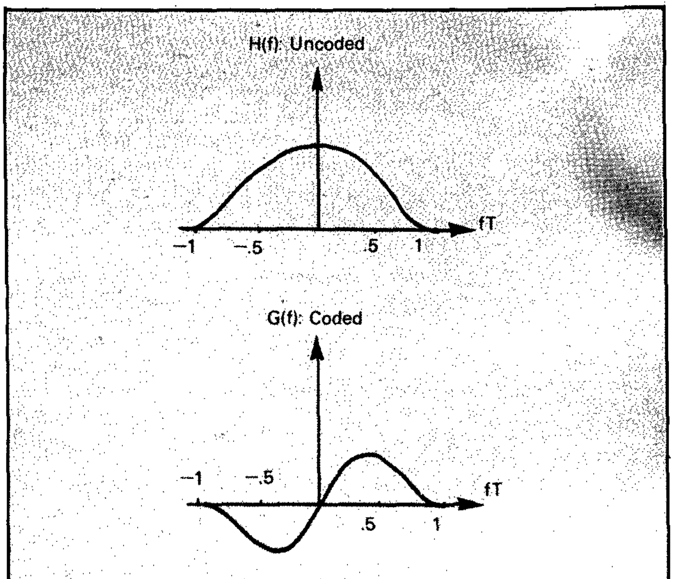

**Fig. 8. The normalized spectrum of the data before and after Manchester coding [29].**

performance of the system is close to its theoretical value; however, it is vulnerable to ambient light, and in the vicinity of fluorescent lamps additional transmission errors occur. Greater rejection of ambient light fluctuations can be achieved by first modulating the signal on a carrier.

### *Digital Modulation Techniques*

The most commonly used non-amplitude-modulation systems are PSK and FSK systems. Since data terminal information is usually in binary form, binary PSK and FSK are natural candidates. However, for efficient use of the channel bandwidth, more bandwidth efficient modulation schemes such as multilevel PSK and FSK should be considered. Of course, their choice adds to the complexity of the system. The application of more bandwidth efficient modulation techniques are under investigation at the University of Thrace [13]. Figure 9 represents a simple example of the binary systems.

Experimental PSK [9] and FSK [10] systems have been developed by IBM Zurich. The experimental PSK system uses a transceiver with a data rate of 64 Kb/s and a carrier frequency of 256 KHz, so that there are 4 carrier cycles per bit. The receiver has two-phase locked loops for carrier and bit synchronization. In this system, no interference was observed from the fluorescent lamps under normal conditions, and a probability of error of about $10^{-7}$ was observed under a 380 LUX ambient light environment [5]. However, during one lamp switching time (about 100 ms), the probability of error increased to about $10^{-3}$.

As an extension of the PSK project, IBM Zurich developed an FSK system [10] with carrier frequencies of 200 KHz and 400 KHz for the down-link and up-link, respectively. In a multipath environment, carrier synchronization is troublesome, so in practice, non-coherent communications systems are more flexible. Therefore, in an office environment, if non-coherent FSK and differentially coherent PSK both perform adequately in providing the desired error rate, FSK is preferable, even though PSK theoreticaly outperforms FSK in 3 dB. Also, PSK is less flexible to changes in data rate. Thus, FSK is a better choice for multichannel usage. Also, FSK is cheaper and easier to implement. Lucky et al. [11] and Bennett et al. [12] provide comprehensive comparisons between these systems.

### *IR Multiple Access Techniques*

In a multi-user environment, a multiple access method is needed to provide transmission capacity for individual users. The basic methods for multiple access are FDMA and TDMA. In these schemes, the transmitted signals are orthogonal in frequency and time, respectively.

Although FDMA is relatively simple to implement, the channel bandwidth is not efficiently used except when all users are sending information simultaneously. Besides, in both analog or digital IR systems, we have interchannel interference caused by the nonlinearities of the system.

In TDMA, all receivers are identical and monitor the same channel while the transmitters operate on different assigned slots of time. However, due to the bursty nature of TDMA, synchronization among all users is required. This adds to the complexity and cost of the system.

There are some controlling methods for channel multiple access in which access is not preassigned in time. Examples of these schemes are ALOHA and Carrier Sense Multiple Access (CSMA) [14]. The multiple access system developed by IBM Zurich uses CSMA/CD [10] for an IR network using FSK modulation, and two different carrier frequencies are allocated to the up-link and down-link, respectively.

## Spread Spectrum

Spread Spectrum techniques are widely used in military communication systems. This type of modulation enjoys several advantages including:

1) Simultaneous access to a given channel bandwidth by CDMA (code-division multiple-access).
2) Resistance to multipath fading.
3) Low spectral power density per user, resulting in low interference with existing systems and the related health aspects.
4) Resistance to interception.
5) Resistance to intentional and unintentional interference.
6) High-resolution ranging.

Spread spectrum has been applied to packet radio [15] (which is a wireless extension of packet switching), to the Joint Tactical Information Distribution System (JTIDS) for jamming-resistance, and to the Position Location Reporting System (PLRS) for ranging and data communications involving military vehicles [16]. More recently, spread spectrum utilization in civil applica-

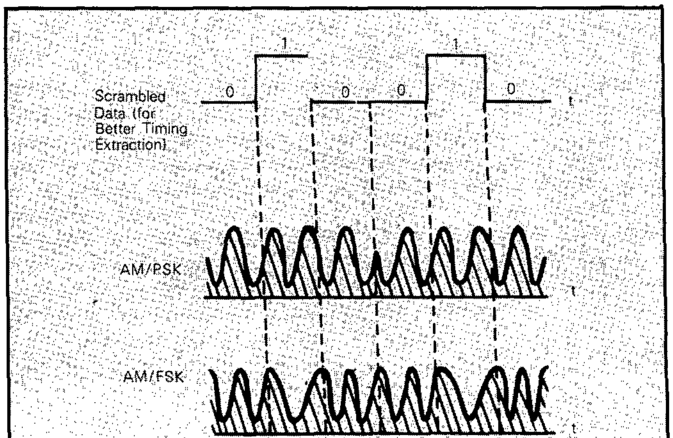

**Fig. 9. Binary PSK and FSK modulation for IR links.**

tions is suggested for mobile radio [17], and is already implemented for wireless terminal communications [13], satellite communication [18], and low data rate security systems over voice channels [19].

### *Spread Spectrum in an Office Environment*

The motivation for adding spread spectrum to packet radio systems comes from the following factors: improved multipath resistance, ability to coexist with other systems, and the antijam nature of the code [15]. Although spread spectrum is desirable for many applications, it is not a prior requirement for packet radio. Cooper and Nettleton [17] suggest using spread spectrum in mobile radio to gain more bandwidth efficiency (more users) compared with FDMA systems. In an office environment, spread spectrum seems to be a promising choice. Spread spectrum use can reduce the effects of multipath caused by reflections from the walls and, consequently, increase the mobility of the terminals or telephone sets within the office environment. The low spectral power density per user of spread spectrum increases the possibility of overlay with certain existing systems, and reduces the sensitivity to health related issues in high-power transmission. Compared with infrared, spread spectrum offers the potential for greater range and higher data rates. Spread spectrum improves interception reisistance and hence traffic privacy. It allows each user to occupy the entire channel bandwidth rather than a portion of it as happens with FDMA techniques.

The experimental implementation of a direct-sequence spread spectrum wireless terminal is reported by Hewlett-Packard (HP) Labs [3,4]. This system has the following specifications:

| | |
|---|---|
| Data Rate | 100 Kb/s |
| Code Length | 255 chips |
| Code Rate | 25.5 MHz |
| Carrier Freq. | 1.5 GHz |
| Modulation | BPSK |
| Bandwidth | 51 MHz |
| Transmit Power | 5 mW |
| Operating Range | 300 Meters, 1000 Meters (with 50 mW) |

For this experimental system, a central computer would alternately poll two remote terminals. At the time of the report, development of a more advanced system using CSMA methods was mentioned that was expected to support approximately 100 nodes.

One of the interesting features of spread spectrum is the possibility of employing Code Division Multiple Access (CDMA). CDMA can provide higher throughput than the ALOHA scheme used in packet radio [20–22]. It could be argued that it is more efficient than FDMA for mobile radio [17]. And, it is possible to implement CDMA without any sort of synchronization, as compared with TDMA.

The interesting question here is the number of users supported by a CDMA system. This question has been subjected to various studies and the next section is devoted to this topic. Calculations provided in this section give an upper bound to the number of users and do not include the effects of multipath fading.

### *Number of Simultaneous Users*

Given a data stream with $R_b$ bits/sec and a coded data rate of $R_c$ bits/sec, where $R_c >> R_b$, the required bandwidth for the coded signal is $K = R_c/R_b$ times the required bandwidth for the uncoded data (K is usually referred to as the processing gain). Since K is greater than one, coding results in the spreading of the narrowband signal spectrum. In conventional spread spectrum systems, shift register codes are desired, because they provide good correlation properties [23].

If the codewords for different users are selected to be orthogonal (or approximately orthogonal), the users can share the common channel bandwidth without any severe mutual interference. This is the basis for CDMA. If there are M such orthogonal codes corresponding to M simultaneous users accessing the common channel, then:

$$\eta = M R_b / B_T \text{ bits/Hz}$$

expresses the bandwidth efficiency of the system, where $B_T$ is the transmission bandwidth. This definition for bandwidth efficiency could also be used for other multiple access techniques such as TDMA or FDMA. For example in an ideal Single Side Band (SSB) FDMA modulation with no guard band, $\eta = 1$.

For a more precise estimate of the number of users or bandwidth efficiency, a more detailed examination of CDMA is required. This topic is treated in the next two subsections for synchronous and asynchronous spread spectrum systems.

### *Bounds on the Number of Users in Synchronous CDMA*

This subsection provides an estimate of the number of simultaneous users in a spread spectrum system with synchronous transmitters within one code "chip." Although not practically attractive for implementation, this model provides the reader with useful bounds and introduces published work in this area.

Suppose there are $M$ codes with a cross-correlation peak of $C_{max}$. Then Welch's bound [24] relates these two parameters by:

$$C^2_{max} \geq [M/K - 1]/(M - 1)$$

or equivalently,

$$M \leq K(1 - C^2_{max})/(1 - C^2_{max} K)$$

where $K$ is the number of binary elements in the code. This bound is tight for many sequences normally used for spread spectrum [25].

From the last equation, it is observed that for $C_{max} = 0$ we have $M \leq K$. By increasing $C_{max}$, the number of potential users $M$ increases. Note that for $K = 1/C^2_{max}$ the bound for the number of users approaches infinity. However, for a non-zero value of cross-correlation, each user creates interference with the others. Therefore, a large number of users may provide unacceptably poor performances.

Neglecting the effect of additive noise compared to interference caused by other users, the signal-to-noise ratio at the correlator output of the receiver is given by:

$$E_b/N_o = [(M - 1) C_{rms}^2]^{-1}$$

where $C_{rms}^2$ is the ensemble average of the squared normalized cross-correlation between different codes [16].

Using an approach similar to that of Welch [24], one can show that for synchronous codes within one chip, $C_{rms}^2$ is subject to the same bound as $C_{max}$ [16,30]:

$$C_{rms}^2 \geq [M/K - 1]/(M - 1)$$

Moreover, it can be shown that the upper bound on $C_{rms}^2$ is attainable. Considering this upper bound for the maximum number of users, $M_{max}$, then:

$$E_b/N_o = [M_{max}/K - 1]^{-1}$$

or

$$M_{max} = K[(E_b/N_o)^{-1} + 1]$$

The procedure for determining the maximum number of users is first to compute the required $E_b/N_o$ to provide an acceptable probability of error ($P_e$) and then to substitute this value into the last equation.

Assuming BPSK modulation, the probability of error is given by:

$$P_e = 1/2\ erfc\left\{(E_b/N_o)^{1/2}\right\}$$

where,

$$erfc(x) = 2/\sqrt{\pi}\int_x^{\infty} e^{-t^2}\,dt$$

Using definition of bandwidth efficiency and the last equation for $M_{max}$, we have:

$$\eta = 0.5\,[(E_b/N_o)^{-1} + 1]$$

The following two examples give numerical results for the number of users served by infrared and RF spread spectrum systems using BPSK modulation.

*Example 1*

For illustration purposes, we compare the nine channel analog system of reference [6], for IR transmission of audio signals with a multi-user IR spread spectrum system. Assuming a 32 kbs digitized voice with maximum allowable error rate of $2\times10^{-3}$ using BPSK spread spectrum modulation. We require an $E_b/N_o\approx4$ (6dB), in the worst case, to maintain the required error rate. With the transmission bandwidth of 500 KHz from the equation for $M_{max}$ we have:

$$M_{max} = (250/32)(1/4. + 1]\approx 10\ channels$$

and,

$$\eta = .5\,[1/4. + 1] = .63$$

*Example 2*

Consider using a spread sprectrum CDMA system rather than a TDM or FDM system as used for cordless telephone systems as described in [27]. The bandwidth is 4 MHz, with the same data rate and modulation technique as in example 1:

$$M_{max} = (2000/32)[1/4 + 1]\approx 78;\ channels\ in\ one\ direction$$

The bandwidth efficiency remains the same as in example 1. If we reduce the acceptable error rate to $2\times10^{-2}$, we have $E_b/N_0 \cong 2$ and $M_{max}\approx 94$, $\eta = .75$.

*Number of Users in Asynchronous CDMA*

CDMA can be employed with no access coordination among various users. This is a major advantage of CDMA, which makes this approach practically attractive.

To determine the number of users for an asynchronous CDMA, one may treat all the interfering users as additive Gaussian noise for a particular receiver. This assumption is reasonable when the number of users is large and for long code sequences. The quality of these approximations have been shown to be excellent [28].

Suppose there are $M$ users simultaneously sharing the available bandwidth of a direct sequence spread spectrum system with processing gain of $K$. Moreover, assume the received power from each user is the same. Then the signal-to-noise ratio before correlator is $1/(M-1)$ for a particular receiver, if we neglect the effects of additive noise. After correlation, the statistics of the noise created by the other users remains the same, but the peak power of the desired signal is increased by a factor of $K$. Therefore, similar to [28] the signal-to-noise ratio after the correlator is approximated by:

$$E_b/N_o = K/(M-1)$$

This calculation provides the worst case where all interfering signals are aligned in time. As shown in [31], if the transmitted symbols are not aligned the amount of interference reduces by, a factor of three. Therefore, we have:

$$E_b/N_o = 3K/(M-1)$$

or,

$$M = [3K(E_b/N_o)^{-1} + 1]$$

$$and\ for\ M>>1,\ \eta = 3/2\,(E_b/N_o)^{-1}$$

For a particular modulation technique and required bit error rate, $E_b/N_o$ is calculated. Using the last equation for M, the number of users is determined.

*Example 3*

If we repeat example 1 for asynchronous systems, for probability of error of $2\times10^{-3}$, we have:

$$M = [3(250/32)/4+1]\approx 7\ \text{channels}$$

$$\eta = 7\times 32/500 = .45$$

*Example 4*

The system in example 2 in asynchronous form provides:

$$M = [3(2000/32)/4 + 1]\approx 48;\ \text{channels in one direction}$$

$$\eta = 48\times 32/4000 = .38$$

*Comparison of TDMA, FDMA, and CDMA*

In low traffic (low user duty cycle) when the summation of bit rates of all users is much less than the bit rate supportable by the channel, many time slots in TDMA or frequency slots in FDMA remain effectively unused. However, in CDMA, the chip rate for each individual user is the same as the aggregated bit rate and each user occupies the complete available bandwidth. Therefore, channel resource utilization of CDMA is superior to the other two.

If no energy is transmitted during speech pauses (which occur at least half the time in a two-way conversation), then the average number of simultaneous users in spread spectrum is at least doubled. This is not true for TDMA or FDMA because when a channel is dedicated to a particular user, no other user can utilize that particular channel. This point is illustrated in example 6, which is presented below.

In addition, CDMA is more resistant to multipath and this increases the mobility of the terminals; it provides more secure data communications. As compared with TDMA, there is no coordination required for CDMA.

Another important issue in comparing CDMA, FDMA, or TDMA is the number of users served by each system. This comparison depends on the practical assumptions such as guard band, modulation technique, and the type of data (digital or analog) used. For example, in 1977 Cooper and

Nettleton [17] claimed that the frequency-hopped spread spectrum system using DPSK is more bandwidth efficient than the FM-modulated FDM approach employed in the cellular mobile radio systems. We provide two simplified examples to support our case.

### *Example 5*

In the discussion related to infrared, the implementation of a nine-channel FDMA audio system with AM/FM modulation using infrared light was described. In comparison, the infrared asynchronous spread spectrum system of example 3 can provide seven channels with a bit error rate of 0.002. If no energy is transmitted during speech pauses, this number can increase for spread spectrum.

### *Example 6*

In comparing FDMA and TDMA with CDMA, consider the multi-channel cordless telephone system reported by Philips Research Laboratory [27]. This system provides a maximum of 100 channels using a 32 kb/s speech-coded signals using TDMA. If CDMA is used instead and for BPSK with error rate of $2 \times 10^{-3}$, (as shown in example 4) this system can provide 48 channels with the same data rate of 32 kb/s. With $P_e = 0.02$, the number of users is 98. If there is no energy transmission during speech pauses, the average number of users for spread spectrum is doubled.

## Summary and Conclusions

Principles of IR communications and different modulation schemes used in this area were reviewed. Examples for analog, digital, and pulse modulation techniques were presented. The application of various modulation systems to office information networks were described, and the number of possible users for each system was evaluated. Based on the presented discussions, Table I demonstrates a comparison of different possibilities for wireless office information networks.

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TABLE I

COMPARISON BETWEEN DIFFERENT SYSTEMS FOR WIRELESS IN-HOUSE COMMUNICATION

| | IR | IR/SS | RF | RF/SS |
|---|---|---|---|---|
| 1. Interference with existing systems | None | None | Large | Small |
| 2. Mobility (shadowing or fading) | Good | Good | Better | Best |
| 3. Detectability outside the office | None | None | Some | Little |
| 4. Range | Low | Low | Medium | Medium |
| 5. Data Rate | Low | Low | Medium | Medium |
| 6. Cost | Low | High | Medium | High |
| 7. Effected by Ambient light | Yes | Some | No | No |
| 8. Interception Resistance | No | Yes | No | Yes |
| 9. Random Multiple Access | No | Yes | No | Yes |
| 10. Selective Addressing | No | Yes | No | Yes |

## References

[1] S. E. Alexander, "Radio propagation within buildings at 900 MHz," *Proc. ICAP '83*, pp. 177–180.

[2] H. H. Hoffman and D. C. Cox, "Attenuation of 900 MHz radio wave propagation into a metal building," *IEEE Trans. Antennas and Propagation*, pp. 808–811, Jul. 1982.

[3] P. Freret, "Wireless Terminal communication using spread spectrum radio," *IEEE COMPCON '80*, pp. 244–248.

[4] P. Freret, "Application of spread spectrum radio to wireless terminal communication," *NTC '80*, pp. 69.7.1–4.

[5] F. R, Gfeller and U. Bapst, "Wireless in-house data communication via diffuse infrared radiation," *IEEE Proc.*, Vol. 67, No. 11, pp. 1474–1486, Nov. 1979.

[6] H. A. Ankerman, "Transmission of audio signals by infrared light carrier," *SMPTE Journal*, Vol. 89, pp. 834-837, Nov. 1980.

[7] "NASA developed IR transceivers for intra-shuttle communications," *Electronic Engineering Times*, p. 54, March 14, 1983.

[8] E. Braun and S. Schon, "A cordless infrared telephone," *Telecom Report*, Vol. 3, No. 2, pp. 83–86, 1980.

[9] F. R. Gfeller, H. R. Miller, and P. Vettiger, "Infrared communications for in-house applications," *IEEE COMPCON '78*, Washington, DC, pp. 132–138, Sept. 1979.

[10] F. R. Gfeller, "Infranet: infrared microbroadcasting network for in-house data communication," *ECOC '81*, Copenhagen, Denmark, pp. 27-1–27-4, Sept. 1981.

[11] R. W. Lucky, J. Salz, and E. J. Weldon, Jr., *Principles of Data Communications*, McGraw-Hill, New York, 1968.

[12] W. R. Bennett and J. R. Davey, *Data Transmission*, McGraw-Hill, New York, 1965.

[13] C. J. Georgopoulous, "Advanced telephone concepts," GTE Laboratories, Mar. 1982.

[14] Tenenbaum, *Computer Networks*, Prentice Hall, 1981.

[15] R. E. Kahn et al., "Advances in packet radio technology," *Proc. IEEE*, Vol. 66, pp. 1468–1496, Nov. 1978.

[16] W. C. Scales, "Potential use of spread spectrum techniques in non-government application," NTIS: FCC-0320, Dec. 1980.

[17] G. R. Cooper and R. W. Nettleton, "A spread spectrum technique for high capacity mobile communication," *IEEE Trans. on Veh. Tech.*, Vol. VT-27, pp. 264–275, Nov. 1978.

[18] H. J. Kochevar, "Spread spectrum multiple access communication experiment through a satellite," *IEEE Trans. on Comm.*, pp. 853–856, Aug. 1979.

[19] W. P. Olson, "Spread Spectrum Breakthrough for Security Systems," Telephone Engineers and Management, Jun. 1, 1982.

[20] D. Raychaudhuri, "Performance analysis of random access packet-switched code division multiple access systems," *IEEE Trans. on Comm.*, pp. 895–901, Jun. 1981.

[21] M. Kavehrad, "An accessing technique for information packet network," *EASCON '81*, pp. 42–45.

[22] J. M. Musser and J. W. Daigle, "Throughput analysis of an asynchronous CDMA system," *ICC '82*, 2F2.1-7.

[23] R. C. Dixon, *Spread Spectrum Systems*, John Wiley and Sons, 1976.

[24] L. R. Welch, "Lower bounds on the maximum cross-correlation of signals," *IEEE Trans. on Inf. Thy.*, pp. 397-399, May 1974.

[25] J. G. Proakis, *Digital Communication*, McGraw-Hill, New York, 1983.

[26] H. E. Rowe, "Bounds on the number of users in spread spectrum systems," *NTC '80*, pp. 69.6.1–6.

[27] R. W. Gibson and R. J. Murray, "Systems organization for multichannel cordless telephones," *International Zurich Seminar on Digital Communication*, pp. 59–61, 1982.

[28] C. L. Weber, G. K. Huth, and B. H. Batson, "Performance considerations of CDMA systems," *IEEE Trans. Veh. Tech.*, pp. 3–9, Feb. 1981.

[29] T. V. Muai, "Receiver design for digital fiber optic transmission systems using Manchester (biphase) coding," *IEEE Trans. on Comm.*, pp. 608–619, May 1983.

[30] H. E. Rowe, "Bounds on the number of signals with restricted cross-correlation," *IEEE Trans. on Comm.*, pp. 966–974, May 1982.
[31] M. B. Pursley, "Performance evaluation for phase-coded spread spectrum multiple-access communication—part I: system analysis," *IEEE Trans. on Comm.*, pp. 795–799, Aug. 1977.

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