AN ENGINEER'S SUMMARY of an ISM BAND WIRELESS LAN

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The following article is submitted to the IEEE 802.11 committee to be used as reference material. It is not the intention of the author to propose this as a standard. The design trade/offs and the measurements discussed can be useful in facilitating further discussions and contributions, leading to the our future 802.11 protocol layer.

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Invited Paper

Abstract- Activity in the field of wireless voice communications has been enormous in the last years, as has been shown by the evolution of cordless telephones, cellular systems and the various Personal Communications Standard activities. Until recently High Speed Data Communications Cordless Local Area Networks (CLANS) have not been getting much attention both in marketing and research. This paper discusses the design philosophy in the development of WaveLAN, the first high speed ISM band CLAN on the market. The technical trade offs, and standard LAN Benchmark tests are presented.

I. INTRODUCTION

The best word to describe the computer industry is CHANGE. The amount and the rate of change is enormous with enough momentum to keep the race on. Various needs are coming at a cross road: High speed information transfer, powerful portable computers, dynamic office and retail infrastructures and, helped by the Cordless Phone, the end user expectations of cordless care free operation. CLAN development has been hampered by the relatively large, when compared with voice, spectral requirements and lack of fundamental research to define and overcome perceived channel impairments using consumer oriented technology. Without a possible spectral allocation the risk for no return on investment for private research and development is quite high, a typical Catch 22 situation. The allocation of the ISM band using Spread Spectrum technology, by the Federal Communication Commission (FCC) in 1985, has led the way for practical research and development activities with an end product as goal. In chapter II the technical requirements which influence Spectrum, LAN Protocol and security are discussed. In chapter III the Processing Gain/Data Rate trade off is discussed and the channel models used during the product development are shown. Chapter IV covers the radio architecture, technology and implementation issues. A SNR Outage prediction used to estimate link reliability, due to external noise, is given in chapter V. In chapter VI the Simulation and Measurements of the radio in a multipath channel is covered. Standard Benchmark tests results, which measure LAN performance, are given in Chapter VII.

II. REQUIREMENTS of a CLAN

Wireless based data communication systems have been low speed, bandwidth allocation driven products. Since this is a LAN it must "feel" like one, cordless or not. An important axiom in WaveLAN product development has been:
Except for the benefits of cordless operation, the end user should observe the least possible difference with standard installed wired based LAN products.

A. The Spectrum

To facilitate high speed data communications, in the Mega bits/s range, the ISM Spread Spectrum band is used. It is noted that Spread Spectrum Modulation is a FCC requirement, stimulating research for commercial applications in these bands. Protocol based Spread-Spectrum systems using Code Division Multiple Access (CDMA) techniques have been investigated for use with PBX connection oriented applications. Combination of voice statistics together with CDMA has been proposed which predicts spectrally efficient system performance and is under field trial [26]. Data communications is fundamentally different than voice in its statistical properties. There is no user defined pause time which can be used to maximize the system capacity. Also the basic structure of connection oriented fixed bandwidth/user system is different than a shared bandwidth data packet communication network, in which per user throughput is a function of total system load. CDMA systems with dynamic rates as a function of total CLAN load can be envisioned, but the complexity evolved using switched or programmable correlators, compared with more conventional structured time domain multiplex approaches, does not seem promising. Since the cost consequence for a CDMA implementation is not negligible and the lack of "real time" voice statistics in LAN communications, CDMA as a protocol technique has not been chosen. The Spread-Spectrum Modulation method and medium access protocol are two separate entities.

B. The Protocol Choice

The most abundant LAN based systems used today are IEEE 802 based standards or variants which conform to the ISO four layer communication model. The IEEE 802 committee has a charter to support 1 - 20 Mbit/s data rates on the physical medium. Data rates from 1 Mbit/s up to 16 Mbit/s using various wiring structures are available: Shielded and Unshielded twisted pair, coaxial cable and glass fiber. The physical layer "raw" transmission speed is only one of the parameters which characterize different LAN protocols. Further comparison leads one to a more in depth throughput and delay characteristics assessment, with each protocol having its own set of advantages and disadvantages, depending upon the system's load and configuration. In keeping in stride with our development axiom, an already accepted IEEE 802 standard should be used if possible. This is quite important from an end-user marketing perspective when introducing new technology. An advantage in having a standard interface "at the lowest level possible" is in various software development activities; applications already available for existing LAN equipment can easily be adapted, quickening the development cycle. Token Bus, a deterministic token passing scheme, seemed a good candidate for a radio physical layer and the IEEE 802.4L Token Bus working group was investigating this matter. It eventually became apparent that due to the unique properties of the radio physical layer; not as reliable as cable based systems with asymmetric channel characteristics, that the Token Bus Protocol, in which a significant portion of the state machine is dedicated to "Token Management", could become unstable or have large delays due to token recovery mechanisms in the radio medium. Also bandwidth sharing, due to adjacent CLAN usage with electromagnetic overlap, must be solved by having isolated physical channels. This can be implemented [15] with the usual spectrum "break up" into multiple channels. Due to the nature of three dimensional indoor propagation the amount of frequencies needed is strongly dependant on various topological considerations. It is not clear at this point what reuse frequency set is needed and most likely, due to the variation of user topologies and requirements, never will be. Therefore the protocol must not "break down" due to co-frequency adjacent CLAN interference but take on bandwidth sharing responsibility. Another standard protocol is 802.3 Carrier Sense Multiple Access/Collision Detect (CSMA/CD) which has the largest installed base in the LAN market. Due to the large dynamic range of the radio medium, bandwidth efficient collision detection is technically difficult. Various mechanisms exist for collision detection implementations but the cost in bandwidth does not seem to outweigh the benefits of overall throughput in normal loading conditions. Therefore Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) is closest to an IEEE Standard, which, due to its random access nature, is robust with respect to protocol level bandwidth sharing and radio channel characteristics. Standard activity within the IEEE 802 committee for a new Wireless Media Physical Layer Protocol, 802.11, is now under way.

C. Security

Transmission of data via radio signals gives the perception of lack of privacy of communication due to the "open media". The design of any CLAN must address this issue. WaveLAN has three levels of security:

a. Network Identification (NWID).

In each data package a NWID identifying separate CLAN systems. Only data with the proper NWID is accepted for upper level software transport. Besides giving a first level of security, this optimizes the bandwidth sharing facility of the CSMA protocol.

b. Spread Spectrum Modulation.

While not a "military" implementation, it does give a eavesdropping threshold. Another WaveLAN board or equivalent Spread Spectrum Demodulator is needed, not just a amateur radio scanner hooked up to a modem.

c. National Bureau of Standards Data Encryption Standard (NBS-DES).

A DES VLSI option is implemented which gives a very high "standard level" of security.

III. THE PHYSICAL LAYER

A. Processing Gain and Data Rate in the ISM Band.

Within the FCC regulations either Frequency Hopping (FH) or Direct Sequence Spread Spectrum Modulations can be implemented. While Frequency Hopping systems have some interesting diversity and multipath characteristics [29], due to the FCC regulated bandwidth limitation, FH systems are data rate limited to low kB/sec rates.

> *Note: The modulation bandwidth has been recently increased from 25 kHz to 500 kHz which would allow data rates up to 250 kbit/s.*

Attention therefore is focused on Direct Sequence Spread Spectrum. Three bands are available for unlicensed used under part 15 rules and regulations [21]:

902 - 928	MHz
2400 - 2483.5	MHz
5725 - 5850	MHz

First out product development has concentrated on the 902 - 928 MHz band due to the implementation cost trade offs.

1. How much Bandwidth Spreading?

Since the spread spectrum modulation is not used as an access technique (CDMA) the trade offs involved are data rate, a robust connection in the presence of interference and the irreducible outage due to multipath intersymbol interference. In military Spread Spectrum systems the Processing Gain, which is a measure of system robustness to jamming and eavesdropping by the "enemy" is of vital importance. Various techniques have been developed to allow large Processing Gains (greater than 25 dB) with minimum receiver code acquisition times [3],[8],[37]. It is vital to realize that the characteristics of an "enemy" and the constraints put upon a system which must deal with this attack are quite different for a commercial communication system. In military systems one must assume that the "jammer" will try to constantly hit the system under attack. This is quite different than, for example, a ISM band interference signal which is quite comfortable staying just where it is. The larger the Processing gain of a Spread Spectrum system the higher the cost and spectral inefficiency. In some cases larger Processing Gain can degrade interference immunity with respect to other conventional frequency assignment techniques. Considering the fact that Spread Spectrum is not used as a protocol method nor is it the optimal "robust" modulation technique using a given bandwidth, one could question why use this at all? The first fact is that in the ISM band a minimum processing gain of 10 dB is a requirement. For a fixed transmit power the power density (watts/Hz) decreases in proportion with the Processing Gain. While other techniques of power reduction and spectrum management are possible, this is not the focus of the Part 15 rules and regulations. (Spread Spectrum does not require a standard "spectrum management protocol" and therefore overlay with already existing systems is possible). In terms of maximizing data rate, without Spread Spectrum modulation in the indoor unequalized channel, data rates on the order 300 Kbps can be supported [1],[7]. Due to inherent Spread Spectrum path resolution properties a 2 Mbit/s data rate is achieved within a 11 MHz Spread Spectrum bandwidth. In summary, a Processing Gain is used which takes into account the trade offs in data rate, robust performance, cost and legal considerations.

B. The Channel Model

1. Channel Echo and Multipath

Recently a wealth of information concerning indoor propagation characteristics has become available. Initial studies have shown wide variation in the delay spread parameter, ranging from 30 ns to 250 ns [9]-[11], [28] depending upon the environment, measurement dynamic range and threshold levels. Correlation Bandwidth measurements performed by NCR [34] of a typical office showed large correlation bandwidths (.5 correlation @ 12 MHz) which support the time domain low delay spread measurement data. For modem testing, an Air Channel Simulator (ACE) was developed. This is a data acquisition unit, which takes a RF modulated signal (within 904 MHz - 926 MHz) down converts into I and Q components, stores this in digital form and process this with a programmable impulse response using a time invariant discrete channel model [35], [19]:

$$h(\tau) = \sum_{i=1}^{L} \beta_i \cdot \delta(\tau-\tau_i) \cdot \exp(j\alpha_i) \qquad (1)$$

Where:

τ_i the ith path delay.

β_i the ith path gain, with a Rayleigh distributed probability density function.

L the number of paths.

α_i the i^{th} path phase, with a uniform pdf within $(0,2\pi]$.

The pdf of the path power gain, $\alpha_i = \beta_i^2$, is found with a change variables [25] giving:

$$p(\alpha_i) = \exp(-\alpha_i) \qquad (2)$$

In which the total channel power gain is normalized to unity: $E[\Sigma\, \alpha_i] = 1$.

Subsequently the impulse response convolved I and Q signals are either upconverted for transmission (hardware modem testing) or further demodulated using the proposed receiver's processing algorithms.

2. Large Scale Power Variation

The channel model of equation (1) gives the microscopic, with respect to distances on the order of wavelengths, properties of the channel. The macroscopic large scale signal variation, on the order of meters between rooms and different areas, is not taken into account. The macroscopic power variation has been successfully modeled [2] as a log-normal distributed random variable, U(r), with pdf:

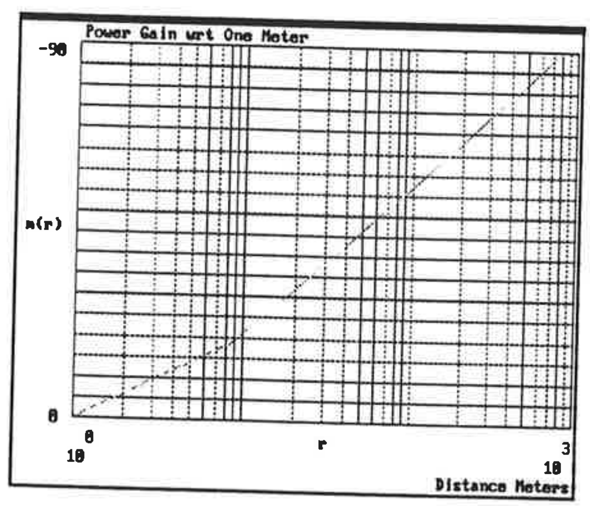
$$p(u) = (1/\sigma \cdot \sqrt{2\pi}) \cdot \exp(-(u-m(r))^2/2 \cdot \sigma^2) \qquad (3)$$

Where:

r the Transmit to Receiver distance

m(r) is the mean power, $n \cdot 10 \cdot \log(r)$ + constant, as a function of distance.

The parameters most often found in the literature are the attenuation exponent, n, and the standard deviation, σ. Another parameter that has been found useful in the characterization of different environments [16] is a two exponent cross over point. For distances "close to" the antenna, in a Line of Sight path (LOS), the attenuation has been found to be close to free space, n=-2, value. At distances in which significant "clutter" occurs an increase in the attenuation exponent is found. Modeling in such a way decreases the standard deviation about the best fit regression lines. Characterization of attenuation of indoor environments is still being done by various researchers [20], [30] with great promise of coupling known building topologies with accurate attenuation predictions.



y = 5 dB/div

Figure 1. Power variation wrt 1 meter with 8.5 m cross point.

C. Polarization Diversity

A known technique to mitigate Rayleigh fading is the use of spacial diversity. Large Cross Polarization Coupling in the indoor channel has been reported [6]. Therefore the use of Polarization Diversity is an attractive method in limiting antenna size. Measurements have been done to determine the correlation between the receiver signal power between horizontal and vertically polarized receiver antennas.

1. Measurement Set-Up and Procedure

The vertical dipole transmit antenna, located 1 meter above the ground, radiates a Continuous Wave (CW), signal. For reception, vertical and horizontal polarized dipoles (RX System) are fixed (crossing each other) on an arm which is mounted on a rotating post. Each antenna is connected via a DPST RF PIN switch to a Spectrum Analyzer. The PIN Switch, Rotating post and Spectrum Analyzer is under Personal Computer control. The RX System is placed a set distance away from the transmitter which defines a cell location. During one measurement run the post is stepped through 35 positions, each separated from each other by 1/4 wavelength. During each step the received signal power is measured on the vertical and then, via the PIN Switch, horizontal antenna. Also the received power from both antennas is measured twice, with the same delay between measurements that occurs when antennas are switched. Three such measurements are done per cell, with 1 meter distance between the previous RX System position. In this way 135 measurement points are obtained per cell location. The calibrated transmit power, taking into account all cable loss, is 8 dBm.

2. Results

A typical office building has been measured (Cross over 8.5 m, n= -3.6, σ= 3.7 dB). Without a Line of Sight (LOS) path between TX and RX System a large Cross Coupling has been found with a large variation between receiver sights. Also the Correlation Coefficient, between vertical and horizontal polarized antennas received power levels, was found to be < .13 in all locations. Correlation of measurements using the same antenna, due to the channel coherence time (people walking in the office and unwanted movement of the TX or RX system) is greater than .85. An example correlation plot, between Horizontial and Vertical switched antennas, is shown in Figure 2. In this measurement the average cell power for Horizontial and Vertical antennas is -46.8 dBm and -49.8 dBm respectively giving 3 dB Cross Polariztion Coupling. This was found to be quite common showing, as was found in [6], that at a significant amount of locations, the received signal power is due to reflections which rotate the transmit polarization. Also the Cumulative Distributions show excellent Rayleigh Fading Characteristics (without LOS) for both horizontal and vertical polarizations, even with negative Cross Correlation Coupling and a vertically polarized receive antenna, as shown in Figure 3.

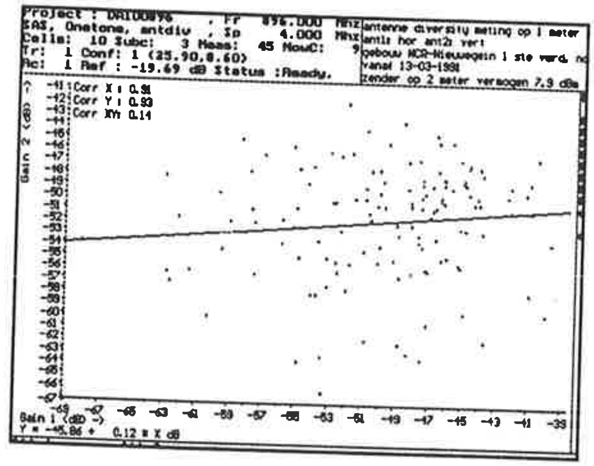


Figure 2. Horizontal vs Vertical Correlation with Cross Correlation Coupling of +3 dB (TX/RX distance of 28 m).

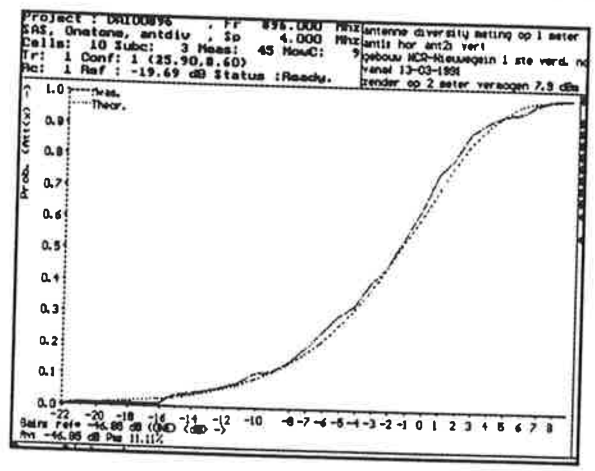


Figure 3. Cumulative Distribution of Vertical Antenna, with respect to cell average power, in a location with -3.7 dB Cross Polarization Coupling (TX/RX distance of 37 meters).

D. Network Topology

Due to the nature of the radio medium, the least number of radio links that achieves total network connectivity will give the best network performance. LAN Operating Systems, Novell being dominant market choice, operate using a central server architecture. Therefore a centralized network topology is implemented by default. While this is a preferred form of operation, it is not required and the implementation of the radio does not prohibit peer to peer configurations. A typical indoor office is shown in Figure 4 with the Mean Power Gain given in Figure 1 (the data in the corridor and conference room has been omitted in this curve). The signal power attenuations, with respect to one meter from the CLAN Server, are underlined, dB. The office is homogeneous, composed of plastic "soft" partitions 1.5 meters tall except for the entrance and conference room. These are floor to ceiling reinforced concrete walls which gives a significant 25 dB jump in attenuation from the adjacent cubicle. Also wave guiding of the signal down the corridor is present which has been found in similar topologies [30], [20]. Benchmark LAN testing has been done with Personnel Computers distributed throughout such an environment.

IV. TECHNOLOGY and THE RADIO ARCHITECTURE

The parameters of the radio modem are listed in Table I and are further clarified in the following discussion.

TABLE I: Radio Parameters

Frequency:	915 MHz
Bandwidth:	11 MHz (peak to null)
Modulation: (Information)	DQPSK
Chip Modulation: (pre filtered)	PSK
Data Rate:	2 Mb/s
Chip Rate: (Chip period, τ_c = 90.9 ns)	11 Mchips/s
Sensitivity: (Including 18 dB Man-Made Noise Factor)	-72 dBm
Output Power	+24 dBm
Antenna Gains (RX/TX)	2 dB

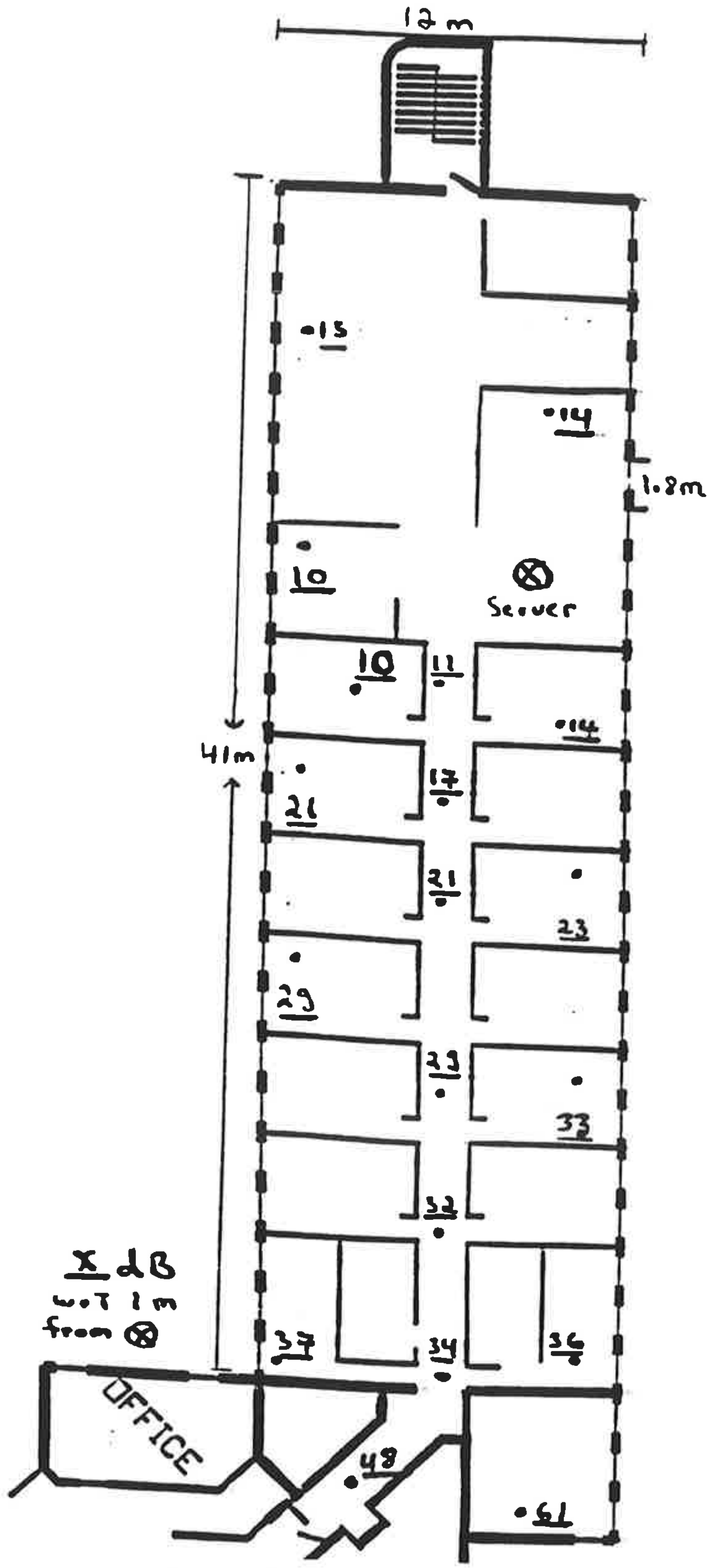


Figure 4. Typical Office Configuration.

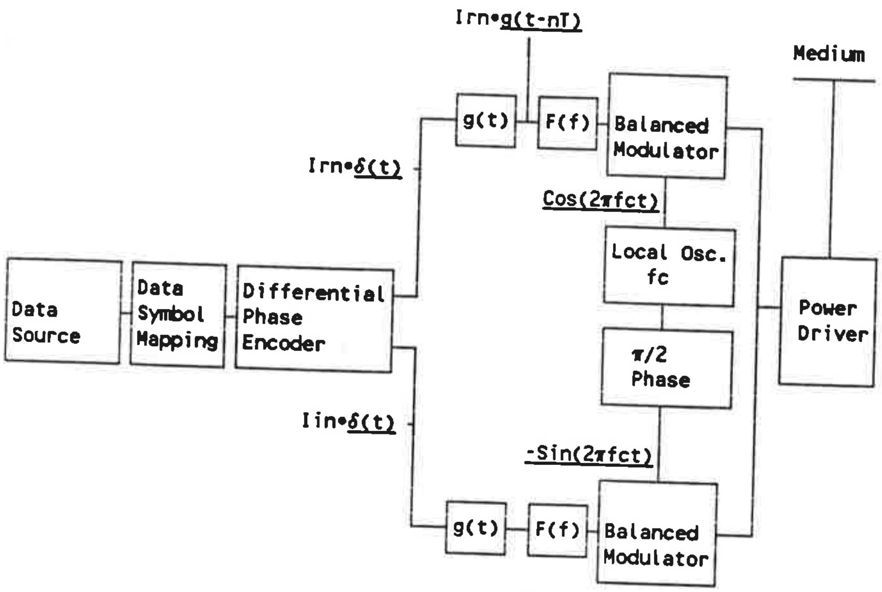


Figure 5. Transmission Block Diagram

A. Modulation/Demodulation

Using complex notation the transmit signal is represented by [27]:

$$S(t) = RE[U(t) \cdot \exp(j2\pi f_c t)] \qquad (4)$$

Where:

$$U(t) = \sum_{n=-\infty}^{\infty} I_n \cdot g(t-nT)$$

Is the low pass complex envelope of the signal.

T the symbol period of the transmitted information.

g(t) "Spread Spectrum" modulating pulse.

I_n Information Vector, $\exp(j\theta_n)$, with four phase states: $\epsilon\{ \pi/4, -\pi/4, 3\pi/4, -3\pi/4 \}$.

Equation (4) is composed of two components. One containing the information, described by the complex vector I_n, the other which determines the spread spectrum characteristics of the signal, described by the real Spread Spectrum modulating waveform g(t-nT).

1. DQPSK Information Modulation

In order to simplify the receiver design differential phase modulation has been implemented. In this way no absolute phase reference is needed for demodulation. In this case the absolute transmitted symbol phase is a function of the previous symbol phase state as follows:

$$\theta_n = d\theta_n + \theta_{n-1} \qquad (5)$$

Where:

$d\theta_n$ the differential symbol phase shift, with Gray phase to dibit encoding.

θ_n the transmitted symbol phase.

θ_{n-1} the previous symbol (T delayed) transmitted symbol phase.

A known drawback of differential phase modulation is the sensitivity to receiver carrier frequency offset. Cost effective crystals are readily available with accuracies from 50 ppm to 25 ppm. With a 915 MHz carrier this translates into a maximum received frequency offset of 92 kHz. A 1 Mbaud signaling, after differential detection, gives an unacceptable phase error between symbols of 33 degrees. Therefore a phase compensation technique has been implemented in which this constant offset is adjusted within the preamble of the data frame. The maximum tolerable frequency offset is now a function of the frequency ambiguity function of the post detected spread spectrum signal [3]:

$$A(df) = | \sin(\pi df \cdot T)/\pi df \cdot T |^2 \qquad (6)$$

Where:

A(df) gives frequency offset signal's power ratio, with respect to zero frequency offset, at the output detector.

df the offset between carrier frequencies.

T the symbol time (1 μs for 1 Mbaud).

Substitution of f = 92 kHz and T = 1 μs into (6) gives a maximum detected signal power degradation of only .5 dB. This allows cost effective frequency synthesis for applications in all the available ISM bands.

2. Spread Spectrum Modulation

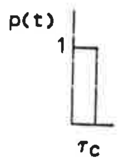
The spectrum determining function in equation (4), g(t-nT), is defined as:

$$g(t) = \sum_{k=1}^{N} X_k \cdot p(t - k\tau_c) \qquad (7)$$

Where:

$g(t)$ the spread spectrum sequence.

$p(t)$ the "chip" pulse:



A unit pulse is given here as an example. Actually pre-filtered pulses are used improving the spectral characteristics of the transmit signal.

τ_c the chip duration such that $N = T/\tau_c$ is an integer.

X_k the kth chip's coefficient $\epsilon\{1,-1\}$

The correlation properties of the signal are determined by the real coefficient vector X_k. The Barker sequence is known to have excellent, bounded by one, odd periodic autocorrelation properties, important for robust multipath reception. An extended list of complex Barker Sequences [38] (unit magnitude and phase angles which are multiples of 6 degrees) has been published. Taking into account the trade-offs (Chap. III Sec.A) the 11 chip Barker sequence is used:

$$\overline{X} = [1\ -1\ 1\ 1\ -1\ 1\ 1\ 1\ -1\ -1\ -1]$$

It is noted, looking at (7) and (4), that a real barker sequence causes the signal to pass through the origin of the complex plane. The carrier is Phase Shift Keyed, PSK, with the Barker chip code. As will be shown the sideband regeneration, after chip pulse filtering, noise floor and power stage efficiency requirements are easily met using this signal structure.

3. The Output Spectrum

Given the scarcity of spectral resources, the efficient use of the spectrum is quite important. The theoretically most spectrally efficient modulation pulse shape is the Sin(x)/x, which gives a "brick wall" rectangular frequency transfer function. One common physically realizable pulse which approximates this is the Raised Cosine. An implementation obstacle with this class of pulse shaping is that the transmit signal has a non constant envelope and the need for linear power amplification. Various forms spectrally efficient constant envelope modulation containing memory, Tame Frequency Modulation as an example, have developed [33]. One requirement is flexibility in the data symbol sequence which is transmitted. Due to the Spread-Spectrum modulation structure, the transmitted Barker chip sequence is fixed, limiting the modulation types that can be used. The output spectrum from a random data stream using equations (4),(7) (unit chip pulse) has been calculated [32]:

$$\Phi uu(f) = T \cdot \mathrm{Sinc}^2(\pi f \tau_c) \cdot \left[11 - 2 \cdot \sum_{k=1}^{5} \mathrm{Cos}(4\pi f \cdot k\tau_c)\right] \qquad (8)$$

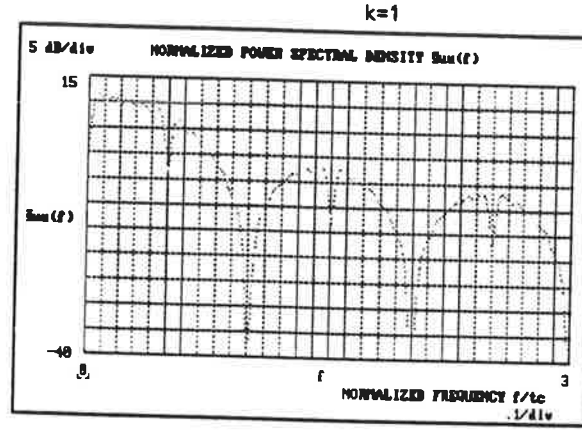


Figure 6. The Base-Band Power Density Spectrum.

Due to the $[Sin(x)/x]^2$ envelope of equation (8) the first sidelobes are only 12 dB down with a $(1/f)^2$ spectral roll-off shown in Figure 6. The main lobe is quite compact, with the first zero at 5.5 MHz. A 3 pole filter, F(f) in Figure 5, with a 7 MHz bandwidth has been implemented, substantially reducing the spectral power outside the main lobe. Since the filtered waveform is not of the constant envelope class, the linearity of the I and Q modulator and power driver stages was a design consideration. Since the out of band spectral requirements are not severe, a class B amplifier end stage operated with 1 dB "backoff" from its compression point gives an efficiency of 60% while keeping the first side-lobe 23 dB down and the noise floor > 45 dB as shown in the actual output spectrum in Figure 7. With a more stringent adjacent channel (another physically separated CLAN) interference requirement, using bias or feedback compensation techniques [31], [36], gives reasonable amplifier efficiencies using linear modulation with low adjacent channel suppression.

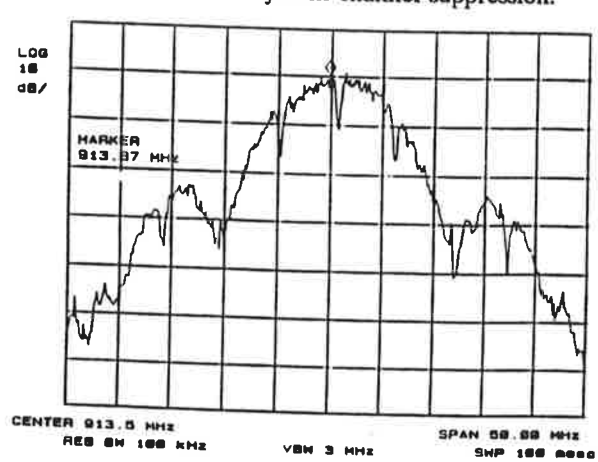


Figure 7. The output spectrum with a 915 MHz carrier.

4. Spread Spectrum Demodulation

Implementation of a Spread Spectrum Modulator is relatively inexpensive. It is the demodulation process which must bear the cost burden. One of the most important characteristics of PSK chip modulation, equation (7), is that it is a linear modulation process and the principle of superimposition applies. This will prove to be quite important when dealing with multipath reception. Therefore the demodulation structures used must maintain the systems linearity (at least up to a specified input signal level power). Demodulation schemes with hard-decision chip decision decoding while simpler to implement, are not used. The despreading process is performed by using a filter matched [19] to g(t) of equation (7).

$$h_{filter}(t) = g(t-T)$$

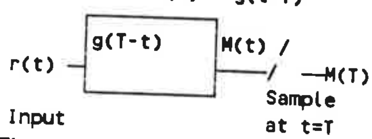


Figure 8. Matched Filter Correlation.

Substitution of the transmit signal (4) into the channels impulse response (1) gives:

$$r(t) = \sum_{n=-\infty}^{\infty} \sum_{i=1}^{L} I_n \cdot \beta_i \cdot \exp(j\alpha_i) \cdot g(t-nT-\tau_i) \qquad (10)$$

Following [18], the received signal (10) for n=0 and n=-1 (present and previous symbol are taken into account) are presented to the matched filter and assuming, without loss of generality, the first path is chosen for detection by the receiver using maximum selection, $\beta_1 > \beta_i$, and this path has zero channel delay, $\tau_1 = 0$, gives:

$$M(T) = I_0 \cdot [T \cdot \beta_1 \cdot \exp(j\alpha 1) + B1 \cdot \tau_c] + I_{-1} \cdot B1 \cdot \tau_c + I_{-1} \cdot [T \cdot \beta_k \cdot \exp(j\alpha k) + B2 \cdot \tau_c] \qquad (11)$$

Where:

$$k \mid [\tau_k = (T + \tau_1) = T]$$

$$B1 = \sum_{\substack{i \mid \tau_i < T \\ i=1}} \beta_i \cdot \exp(-j\alpha_i)$$

$$B2 = \sum_{i \mid \tau_i > T} \beta_i \cdot \exp(-j\alpha_i)$$

In the derivation of (10):

a. The Barker sequence is used having unity bounded odd/even periodic and aperiodic correlation function.
b. The use of superimposition was used due to linear structure of the modulation.

It was important in the system design structure to maintain linearity. Equation (11) shows the robust structure Spread Spectrum modulation has with respect to multipath delay. Two terms, $T \cdot \beta_1$, $T \cdot \beta_k$ are multiplied by a factor T the others by τ_c. The ratio, T/τ_c, being the "Processing Gain" of the system. Since $\tau_k - \tau_1 = T$, only the significantly attenuated path, β_k, at one symbol delay contributes to intersymbol interference (ISI). Without the path delay resolution of spread spectrum, path delays significantly less than the symbol period contribute to ISI [4].

5. Correlation SAW or VLSI?

One the main functional element of a spread spectrum system is the correlator or matched filter. Research has been done using Surface Acoustic Wave Devices for Spread Spectrum demodulation. To determine the cost effective approach, given the spreading requirements, as compared with VLSI technology, NCR in conjunction with the State University of Delft in the Netherlands produced various SAW devices. In this way the production, packaging and performance issues for large quantity production, using standard VLSI production facilities, was ascertained. The major price reduction for a SAW correlator is in the symbol time or length of material. On the other hand, in the VLSI implementation it is the chip rate (processing clock speed) and Bandwidth Symbol Time, BT, product (processing gain) which determine the cost. In our application, T = 1 μs and BT = 11, the VLSI and SAW correlator are cost competitive but the output of the SAW is still in analog form. The necessary processing of these signals must also be taken into account. Since digital processing is the most cost effective for post correlation processing, the addition of correlation in VLSI CMOS technology is the most logical choice.

6. DQPSK Information Demodulation

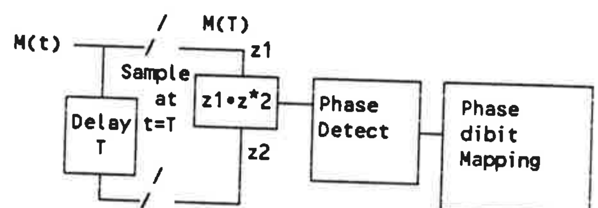


Figure 9. DQPSK Information Demodulator

Performing the complex conjugate multiplication shown in Figure 9 to the matched filter output from (11) gives:

$$M(T) \cdot M^*(0) = (\beta_1 \cdot T)^2 \cdot \exp[j(\theta_0 - \theta_{-1})] + ISI \qquad (12)$$

Taking the phase of the (12) gives the decision variable for Gray dibit decoding. Equation (12), together with the path selection criteria, describes WaveLAN Spread Spectrum demodulation in a multipath channel.

B. The Radio Front End

1. Radio Homodyne Front End Concept

Direct Conversion Radio Design is one of the oldest and forgotten architectures. The main obstacle has been for narrow bandwith voice channels; lumped element baseband filters become quite large and impractical, 1/f noise is quite significant, DC coupling due to impractical blocking capacitors are needed and the need for double (I and Q) RF stage downconversion. For wide bandwidth modulations, especially spread-spectrum, in which low frequency content (In our example < 100 kHz) is not significant, the "narrow band problems are no longer present. Also commercial applications of 1 GHz technology, cellular phones, UHF TV, gives a cost effective implementation; compact with relaxed filtering requirements due to lack of an image frequency and a circuit topology for total integration.

2. Diversity

While the path resolution of Spread Spectrum gives "path diversity", with select largest implemented, a significant amount indoor channels (offices with cubicle dividers) have small delay spreads, < 50 ns. Therefore switched antenna diversity, as measured in Chap.III Sec. C, has been implemented using two cross polarized antennas, etched onto a printed circuit board, at the receiver. The selection criteria is based on a post processed signal quality level. Signal quality is a measure of an averaged correlation peak to side lobe ratio. This ratio decreases as a function of thermal noise, severe multipath and interference. Here we have an excellent method to "probe" the channel's integrity.

V. DISTANCE vs OUTAGE MODEL

Spread-Spectrum modulation is robust with respect to intersymbol interference. Link Outage within indoor office environments will be due to insufficient Signal to Noise ratio as opposed to the irreducible multipath delay. The question that is addressed here is: "What can the distance be, in an environment, characterized by its large scale parameters n, σ and cross over point, between the Terminal and the LAN Server?" From Table I an input power level of -72 dBm is needed in order to achieve 10E-8 BER. For received signals below this value the link is not reliable and a "link outage" has occurred.

Note: The Bit Error Ratio (BER) parameter does not strongly influence the outage of the link, due to the exponential relationship between BER and input power level. Accurate predictions using an on/off channel model [29] is reported.

The Outage can then be expressed as:

P[Pin < -72 dBm]

Where:

P[•] the probability of the event [•]
Pin the received input power of the signal

From the Power Budget of Table I the transmit power is 24 dBm. Therefore a total radio link gain, LG_t, of -96 dB is permissible before outage occurs. The Link Gain is expressed as a sum of random variables:

$$LG\ dB = U\ dB + G_{1meter}\ dB + \Phi\ dB \qquad (13)$$

Where:

U the Large Scale power gain (dB) with respect to one meter, with the pdf of equation (3).

G_{1meter} constant power gain between transmit and receive antennas at one meter.
$G_{1meter} = 20\bullet Log(4\pi/\lambda)$ dB; @ f= 915 MHz (-31.6 dB)

Φ Small scale power gain (dB) of the spread spectrum demodulators selected path delay and diversity antenna. The pdf of this variable is a function of the "diversity level" of the system; The number of delay paths, L, and switchable antennas, A.

The derivation for the probability density functions of LG is given in Appendix I. Numerical techniques are used to solve for the outage using equation (13):

$$\text{Outage}(r) = P[LG\ dB < -96\ dB] \qquad (14)$$

A. Outage Calculations

The "typical office" configuration of Figure 3 is used to estimate the outage.
The Large Scale parameters derived from measurements of a typical office (not including the corridor):

$n = 3.6$
$\sigma = 3.7$ dB
Cross over point (n = -2 to n = - 3.6) = 8.5 m

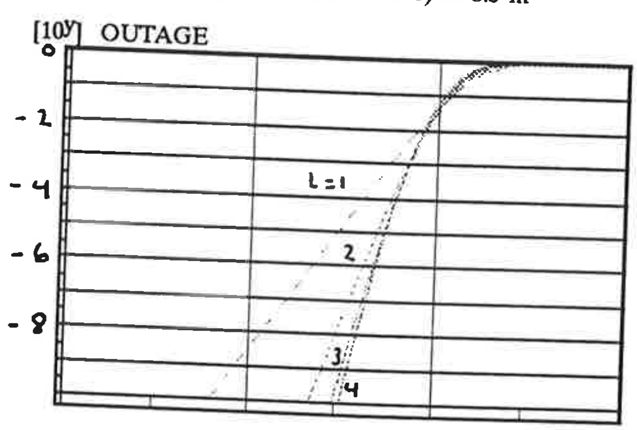


Figure 10. Outage vs Distance in meters [10^x] (L is a parameter).

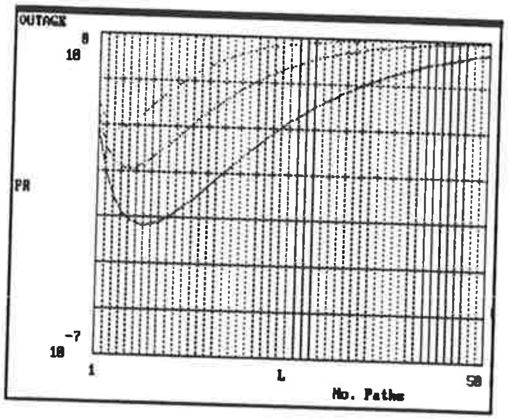


Figure 11. Outage vs L

From Figure 10, which characterizes a typical office, an Outage of .1% (1%) is expected at a Server to Station distance of 50 meters (75 m). In such an environment a one path, L=1, is assumed due to the low delay spread environment [11]. At small Outages, <.1%, a significant improvement is seen with two paths. With greater Outages, increasing the number of paths does not give improvement, as further shown in Figure 11. There is an optimal number of paths as a function of the minimum outage, the larger outage the smaller the optimal number of paths; for an Outage minimum of 1%, L = 3 is optimum. The reason for an optimal number of paths is due to the selection diversity implementation. While more paths help mitigate the Rayleigh fading, the average power of each path is less.

VI. SIMULATION and MEASUREMENTS

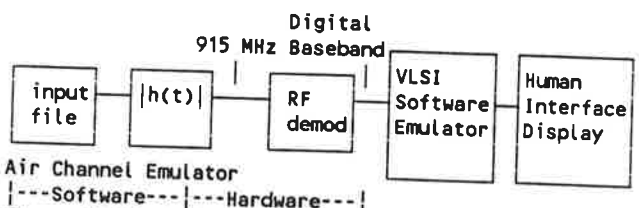
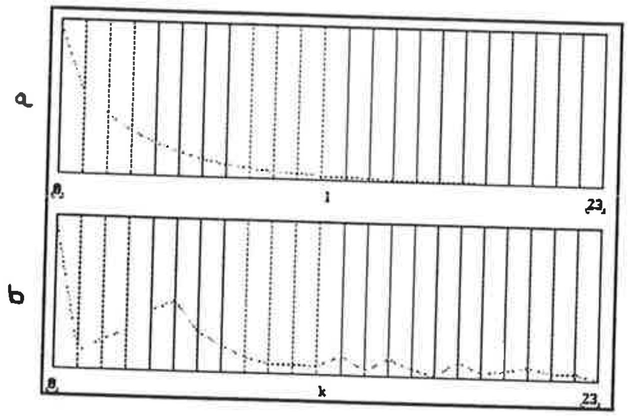


Figure 12. Block Diagram of Receivers simulation Set Up.

The WaveLAN modulation structure and some of the practical reasoning behind the various implementation decisions has been discussed. Software simulation for the modem algorithm development and system testing was extensively used. Since the software simulation structure mapped the VLSI processing exactly, VLSI verification and error detection was accomplished. Replacement of the actual VLSI in the software emulation block of Figure 12, does not alter system performance.

A. Channel Perturbations and Decision Region Diagrams

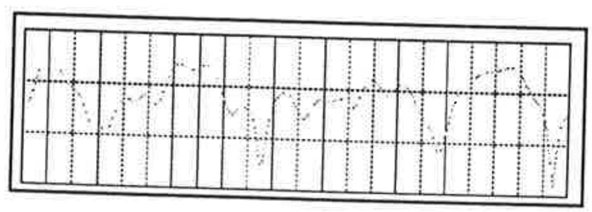
In order to test the spread spectrum's data recovery algorithms, test impulse responses are generated from a given power delay profile $<|h(\tau)|>$ as done in [5]. The sampled value of the delay profile gives the average power of the Rayleigh distributed path's gain. The phase is assumed to have a uniform distribution $(0,2\pi]$.



45 ns/div

Figure 13. (a) Exponential Power Delay Profile, (b) one particular impulse response.

Figure 13(a) shows the exponential profile with rms delay spread τrms = 150 ns. Using this power delay profile and the impulse response model of equation (1), impulse responses are generated with a sample shown in Figure 13(b).



x= 1 MHz/div
y= 10 dB/div

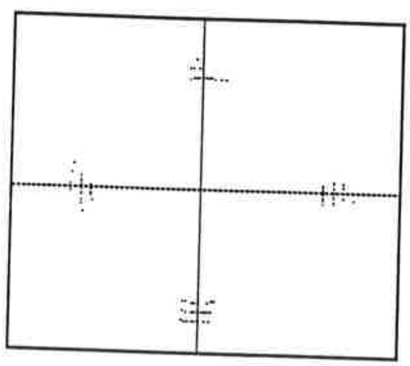
Figure 14. Frequency Transfer Function

Figure 14 shows the frequency domain spectrum of the channels transfer function, $|H(jw)|$. Note that significant "frequency selective" fading is present within the pass band of the modulated signal of Figure 6. A random data sequence is demodulated, using the receiver structure of Figure 9. In Figure 15 the output of the demodulation process is shown.

Figure 15. Post Correlation Signals

Figure 15 (a),(b) shows the I and Q outputs of the digitally correlated data.
In Figure 15(c), the correlated data modulus, a second resolvable path is clearly seen. The first path is chosen for data extraction, due to our switched path implementation. Figure 15 (d) shows the sample and hold of the correlation modulus, variation here is due to bit quantization and clock tracking algorithms.

Figure 16. DQPSK Vector Data Display



The differentially demodulated information vector, Figure 16, with 5,000 random symbols processed, shows clearly defined decision regions and minimal ISI perturbation.

VII. LAN PERFORMANCE

Standard Lan Benchmark testing was performed to compare with standard wired LAN products [14], [17]. Since this is a total system based test, the total system configuration is important. Especially with higher medium data rates a part of the throughput is determined by the Server Speed itself.

A. Test Set-Up

Network
System: Novell SFT Netware version 2.15.

Configuration: Server PC with Intel 80386 processor/16 MHz. Six stations with Intel 80286 processor/8 MHz.

Benchmarks: Novell Perform 3 test and PC Magazine LABS Network Speed Under Load Test rev. 2.

Medium	WaveLAN	Arcnet	Token Ring	Ethernet	StarLAN
Data Rate	2 Mbps	2.5 Mbps	4 Mbps	10 Mbps	1 Mbps
System Throughput (Perform 3)	1 Mbps	1.1 Mbps	2.5 Mbps	3.6 Mbps	.8 Mbps
File Transfer Time (PC Magazine)	580 s	400 s	320 s	300 s	700 s

The effect of multiple electromagnetically overlapping LANS on the throughput and bandwidth sharing has been measured.

#CLANs	#WS	S	S•#CLANs
1	1	.5 Mbps	.5 Mbps
1	3	.7 Mpbs	.7 Mbps
1	6	1 Mpbs	1 Mpbs
2	3	.44 Mpbs	.9 Mpbs
3	3	.3 Mpbs	.9 Mpbs

Where:

S gives the individual LAN system throughput (Novel Perform 3 test).

#CLANs the total number of overlapping LANs.

#WS the number of workstations/LAN.

S•#CLANs gives the total system throughput of all the overlapping CLANs.

As expected the available bandwidth is shared between different overlapping LAN users of the medium.

VIII. CONCLUSION

Various design and implementation issues of the first High Speed CLAN on the market have been discussed. Without channel equalization high data rates are achievable using the existing FCC Spread Spectrum ISM band regulations. WaveLAN, using 11 MHz of bandwidth achieves 2 Mbit/s raw data rate for indoor operation. In the 2.45 GHz and 5.7 GHz ISM bands there is respectively 83.5 MHz and 125 MHz of bandwidth available now. A great opportunity exists to further increase system capacity, helping solve the end-user's LAN connectivity problems of today.

IX. APPENDIX I

OUTAGE CALCULATION USING LARGE AND SMALL SCALE CHANNEL STATISTICS

The pdf of the power gain, in a Rayleigh fading channel, given in (2) is repeated:

$$p(\alpha_i) = \exp(-\alpha_i) \quad \text{(A1)}$$

Normalized such that $E[\Sigma\,\alpha_i] = 1$

The assumption that all path power gains are equal, $\alpha_i = \alpha_k = \alpha$, has proven an accurate modeling technique [19], [23] with the number of paths, L, is given by:

$$L = \mathrm{int}[\tau rms/\tau] + 1$$

Where:

τrms	the channels delay spread.
τc	the chip period (90.9 ns from table I).
$\mathrm{int}[\bullet]$	the closest integer of $[\bullet]$.

Using the equal path criteria, $\Sigma\,\alpha_i = L\bullet\alpha$, and total power normalization, $E[\Sigma\,\alpha_i] = 1$, the average power for a selected path is $E[\alpha] = 1/L$. Substitution into (A1) gives the pdf of one path's power gain:

$$p(\alpha) = 1/L\bullet\exp(-\alpha\bullet L) \quad \text{(A2)}$$

The cumulative distribution, $P(\alpha o) = P[\alpha < \alpha o]$, is found using (A2):

$$P(\alpha o) = \int_{-\infty}^{\alpha o} p(\alpha)\bullet d\alpha = (1-\exp(-\alpha\bullet L)) \quad \text{(A3)}$$

Equation (A3) gives the cumulative distribution function of one out of L received paths in which the spread spectrum receiver will choose the largest. The probability that all the L statistically independent paths are less than αo is expressed as [15] :

$$P[\alpha 1,\alpha 2,\ldots\alpha L < \alpha o] = P(\alpha o)^L \quad \text{(A4)}$$

With antenna diversity different polarizations and physical separations can be used; the received paths from each switched antenna are uncorrelated and statistically independent. Therefore the spread spectrum receiver signals from L paths and A antennas or L•A diversity variables. Using the same argument in used for (A4) gives the cumulative distribution function of path power gain, with antenna and path selection diversity, $Psel(\alpha o)$:

$$Psel(\alpha o) = P(\alpha o)^{L\bullet A} = (1 - \exp(-\alpha\bullet L)^{L\bullet A} \quad \text{(A5)}$$

Expressing this in path gain, Φ (dB), is found by a change of variables giving:

$$Psel(\Phi) = (1 - \exp(-L\bullet 10^{(\Phi/10)})^{L\bullet A} \quad \text{(A6)}$$

Defining a new random variable, PGain dB such that:

$$PGain\ dB = LG\ dB - G_{1meter} = U\ dB + \Phi\ dB$$

Since the pdf of the sum of two random variables is the convolution of the individual pdf's [25], the Link Gain distribution is expressed as:

$$p(pgain) = psel(\Phi)\bullet p(u) \quad \text{(A7)}$$

Where:

$psel(\Phi)$	$d(Psel(\Phi))/d\Phi$ of equation (A6)
$p(u)$	the large scale pdf of (3)
$\bullet$	the convolution operator

Substitution in the outage as defined in (14), using $G_{1meter} = -31.6$ dB, gives:

$$P[Pgain < 68.4\ dB] = P_{Pgain}(68.4\ dB)$$

Where:

$P_{Pgain}(pgain)$ is the cumulative distribution of the pdf, $p(pgain)$ of equation (A7) and is a function of L, A and r.

REFERENCES

[1] A. S. Acampora and J.H. Winters, "System Applications for Wireless Indoor Communications", IEEE Communications Magazine Vol. 25, No. 8, August 1987.

[2] S.E. Alexander, "Characterizing Buildings for Propagation at 900 MHz", Electron Lett. Vol. 19 No. 20 Sep. 1983.

[3] Charles R. Cahn, "Spread Spectrum Applications and State of the Art Equipments", NATO, AGARD Lecture Series No. 58, July, 1973.

[4] Justin C-I Chuang, "The Effects of Delay Spread on 2-PSK, 4-PSK and 16-QAM In a Portable Radio Environment", Globecom 1987.

[5] Justin C-I Chuang, "The Effects of Time Delay Spread on Portable Radio Communications Channels with Digital Modulation", IEEE Journ. on Selected Areas in Communications, SAC-5, June 1987.

[6] Donald C. Cox, Roy R. Murray, Hamilton W. Arnold, A. William Norris, and Marvin F. Wazowicz, "Cross-Polariztion Coupling Measured for 800 MHz Radio Transmissions In and Around Houses and Large Buildings", IEEE Trans. on Ant. and Prop. Vol. Ap-34 No. 1, Jan. 1986.

[7] Donald C. Cox, "Universal Digital Portable Radio Communications", Proc. of The IEEE, Vol. 75. No. 4, April, 1987.

[8] Klaus Dostert, "Ein Neues Spread-Spectrum Empfängerkonzept Auf Der Basis Angeapfter Verogerungsleitungen Für Akustische Oberflächenwellen", Universität Kaiserslautern, Dissertation 1980.

[9] D.M.J. Devasirvatham, "A Comparison of Time Delay Spread Measurments within Two Dissimilar Office Buildings", ICC'86, June 23-25, 1986.

[10] D. M. J. Devasirvatham, "Time Delay Spread Spectrum Measurments of Wideband Radio Signals Within a Building", Electronic Letters, Vol. 20, Nov. 1984.

[11] D.M.J. Devasirvatham, R.R. Murrayand C. Banerjee, "Time Delay Spread Measurements at 850 MHz and 1.7 GHz Inside a Metropolitan Office Building", Electron Lett. Vol. 25 No. 3, Feb. 1989.

[12] Datapro Reports on PC & LAN Communications: LAN Hardware evaluation 800-101 Token Ring Network Adapters, NSTL reports;, June 1990.

[13] Grand Prix, comparision between various Arcnet, Ehternet and Token Ring boards, LAN Magazine, January 1990.

[14] W. Diepstraten and H.J.M. Stevens, "WaveLAN System Test Report", NCR Corporation TR No. 407-0023871 rev A.

[15] William C. Jakes, Jr., "Microwave Mobile Communications", John Wiley & Sons, 1974.

[16] Donald Johnson, "Indoor Coverage Area Modeling", NCR Research and Development, 1988.

[17] A. Kamerman, "Perfomance of WaveLAN and other LANs", NCR Systems Engineering Design Document.

[18] M. Kavehrad, "Direct-Sequence Spread Spectrum with DPSK Modulation and Diversity for Indoor, Wirless Communciations", IEEE Trans. Commun., vol. Com-35, Feb. 1987.

[19] M. Kavehrad and G. E. Bodeep, "Design and Experimental Results for a Direct Sequence Spread-Spectrum Radio Using Differential Phase-Shift Keying Modulation for Indoor, Wireless Communications", IEEE Journal on Sel. Areas in Communications, Vol. SAC-5, No.5, June 1987.

[20] Jean-Francois Lafortune and Michel Lecours, "Measurements and Modeling of Propagation Losses in a building at 900 MHz", IEEE Tran. Vehicular Tech, Vol. 39, No. 2, May 1990.

[21] Michael J. Marcus, "Regulatory Policy Considerations for Radio Local Area Networks", IEEE Communications Magazine, Col. 25, No. 7, July 1987.

[22] Novell: LAN Evaluation Report, Novell Advanced Netware, 1986.

[23] K. Pahlavan,"Spread Spectrum For Wireless Local Networks", Proc. IEEE PCCC, Febuary 1987.

[24] K. Pahlavan, "Wireless communications for office information networks", IEEE Commun. Magazine, June 1985.

[25] A. Papoulis, Probability, Random Variables, and Stochastic Processes", McGraw Hill, New York, 1965.

[26] PCN America, Inc., "For Authorization in the Experimental Radio Service of a Spread Spectrum Personal Communications Network, to Serve the Washington, D.C., Metropolitan Area", FCC File No. 1343-E-PC-90, January 1990.

[27] J.G. Proakis, Digital Communications, New York: McGraw-Hill, 1983.

[28] Adel A. M. Saleh and Reinaldo A. Valenauela, "A Statistical Model for Indoor Multipath Propatation", IEEE Journal SAC Vol. SAC-5 No. 2, Feb. 1987.

[29] Adel A. M. Saleh and Leonard J. Cimini, JR., "Indoor Radio Communciations Using Time-Division Multiple Access with Cyclical Slow Frequency Hopping and Coding", IEEE Journal on Selected Areas in Communications, Vl. 7, No. 1, January 1989.

[30] Scott Y. Seidel and Theodore S. Rappaport, "900 MHz Path Loss Measurements and Prediction Techniques for In-Building Communication System Design", Vehicular Technology Conference, St. Louis, MO, May 1991 (Future presentation).

[31] Sirikiat Ariyavisitakul and Ting-Ping Liu, "Characterizing the Effects of Nonlinear Amplifiers on Linear Modulation for Digital Portable Radio Communciations", IEEE Trans. on Vehicular Technology, Vol. 39, No. 4, November 1990.

[32] Carl-Erik Sundberg and Nils Rydbeck, "Recent Results on Spectrally Effecient Constant Envelope Digital Modualtion Methods", CH1435-7/79/0000-0227 IEEE 1979.

[33] Kiwi Smit "Spectrum of 11 chip Barker Sequence", NCR Systems Engineering Design Report.

[34] Bruce Tuch, "Radio Propagation Measurement Report", NCR Systems Engineering, 1987.

[35] George L. Turin, "Introduction to Spread-Spectrum Antimultipath Techniques and Their Application to Urban Digital Radio", Proc. of the IEEE, Vol. 68, No. 3, March 1980.

[36] Yoshihiko Akaiwa and Yoshinori Nagata, "Highlty Efficient Digital Mobile Communications with a Linear Modulation Method", IEEE Journal on Selected Areas in Communiations, Vol. SAC 5, No. 5, June 1987.

[37] Shen Yunchun and C.P. Tou, "A Scheme for Further Strengthening Interference Protections of Spread Spectrum Communication Systems", IEEE EMC Symposium 1990, Washington.

[38] Ning Zhang and S.W. Golomb, "Sixty-Phase Generalized Barker Sequences", IEEE Trans. on Information Theory, Vol. 35, No. 4, July, 1989.

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