Development of WaveLAN®, an ISM Band Wireless LAN

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Wireless voice communications has seen a great many changes in the last few years, including the evolution of cordless telephones, cellular systems, and the development of standards for personal communications services (PCS). Recently, high-speed wireless local area networks (WLANs) have been getting more attention, both in marketing and research. This paper discusses the design philosophy in the development of NCR's WaveLAN®, and the technical tradeoffs.

Introduction

Until recently, WLAN development had been hampered by the relatively large spectrum required, the lack of adequate spectrum allocated for WLAN operations, and a lack of fundamental research to define and overcome perceived channel impairments using consumer-oriented technology.

In 1985, the U.S. Federal Communications Commission (FCC) allocated the Industrial Scientific Medical (ISM) 2.4-GHz band for WLAN use, stimulating practical research and development. This paper discusses the research and development work of NCR's Wireless Communications and Networking Division to develop WaveLAN®, the first high-speed WLAN on the market. The discussion includes:

- The technical requirements that influence spectrum, LAN protocol, and security,
- The processing gain/data rate tradeoffs, and the channel models used during product development,
- The radio architecture, technology, and implementation issues,
- A signal-to-noise ratio (SNR) outage prediction used to estimate link reliability due to external noise, and
- Simulation and measurements of the radio in a multipath channel.

Requirements of a LAN

Until recently, wireless-based data communications systems typically have been low-speed products, affected by limited bandwidth allocation. To be successful, however, WLAN products should have the same capabilities, as well as the same "look and feel" to an end user, as wire LANs.

Spectrum. Three aspects of today's wired LANs are that they are easy to install, they are premises-based products owned by the customer, and there is a range of bandwidths available. Wireless LANs, therefore, should reflect the same conditions. Ease of installation is a solvable engineering issue, and customer ownership is an economic issue decided by each customer. WLAN bandwidth issues, however, are beyond either the engineer's or the customer's ability to solve. Fortunately, the FCC's decision to make available the ISM band for WLAN use is facilitating the development of high-speed, wireless data communications.

Protocol Choice. Most LAN systems are based on IEEE 802 standards or variants that conform to the International Standard Organization (ISO) four-layer communication model. Parameters that characterize LAN protocols include not only the "raw" transmission speed of the physical layer, but throughput and delay characteristics. Each protocol has its own set of advantages and disadvantages, depending upon the system's load and configuration. Advantages of using an already accepted IEEE 802 standard include speeding up software development and adapting existing applications for wireless LANs.

Three LAN protocols were studied for WaveLAN: Token bus, carrier sense multiple access/collision detection (CSMA/CD), and carrier sense multiple access/collision

Panel 1. Acronyms Used in This Paper

ACE — Air channel emulator
BER — Bit error rate
CDMA — Code division multiple access
CMOS — Complementary metal-oxide-semiconductor
CSMA/CA — Carrier sense multiple access/collision avoidance
CSMA/CD — Carrier sense multiple access/collision detection
CW — Continuous wave
dB — Decibel
DPST — Double-pole single-throw
DQPSK — Differential quadrature phase shift key
FCC — Federal Communications Commission
I — In-phase
ISI — Intersymbol interference
ISO — International Standard Organization
ISM — Industrial Scientific Medical band
LAN — Local area network
LOS — Line of sight
NBS-DES — National Bureau of Standards-Data Encryption Standard
NWID — Network identifier
PBX — Private branch exchange
PSK — Phase shift keying
PCS — Personal communications services
PIN — Positive material-intrinsic-negative material
Q — Quadrature phase
RF — Radio frequency
SAW — Surface acoustic wave
SNR — Signal-to-noise ratio
TDMA — Time division multiple access
UHF — Ultra-high frequency
VLSI — Very large scale integrated circuitry
WLAN — Wireless local area network

avoidance (CSMA/CA). *Token bus,* a deterministic token passing scheme, at first seemed a good candidate for a radio physical layer. However, this protocol wasn't pursued by NCR. First, a WLAN using this protocol was not as reliable as cable-based systems, due to the unique properties of the physical radio layer with its fluctuating channel characteristics. Second, a significant portion of the machine state is dedicated to "token management," and a token bus could become unstable or have large delays due to token recovery mechanisms in the radio medium.

Another standard protocol considered was 802.3 *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 implementing collision detection, but the cost in bandwidth seems to exceed the benefits in overall throughput in normal loading conditions.

The third protocol considered was *CSMA/CA*. Due to its random access nature, CSMA/CA is robust with respect to protocol-level, bandwidth-sharing, and radio-channel characteristics. As a result, this protocol was chosen for WaveLAN, and, while it is not yet an IEEE standard, it is being considered actively within the IEEE 802.11 committee.

Security. The transmission of data via radio signals gives many users the perception of a lack of privacy in communicating, due to the openness of the media. To satisfy these concerns, the design of any WLAN must address this issue. NCR's WaveLAN has three levels of security:

- Network Identification (NWID)—Each data package has a NWID code that identifies its WLAN system. Only data with the proper NWID is accepted by the system for upper-level software transport. This also optimizes the bandwidth-sharing facility of the CSMA/CA protocol.
- Spread-Spectrum Modulation— While NCR's implementation is not at the same level as a high-security "military" implementation, the use of spread-spectrum modulation, which will be discussed later in this paper, provides a level of safety from eavesdropping.
- National Bureau of Standards-Data Encryption Standard (NBS-DES)— An optional DES encryption capability is implemented in WaveLAN, which gives a third, and very high level of security.

Spread Spectrum in the ISM Band

The name "spread spectrum" is quite literal: the spectrum needed to transmit a modulated signal must be wider than the bandwidth of the information transmitted. This technique is used in military systems, due to its anti-jamming and anti-eavesdropping properties.

The FCC regulations permit either frequency-hopping or direct-sequence, spread-spectrum modulations to be implemented in the ISM band. In frequency hopping systems, the user signal is modulated with the carrier signal in a conventional manner, but the carrier frequency is continually changed. This frequency hopping occurs psuedo-randomly, and only receivers that "hop in step" with the transmitter can receive the carrier signal to extract the user information.

Bandwidth spreading of direct-sequence systems is more subtle. The information-modulated carrier signal does not "hop around" the band in time. Instead, a coded signal is multiplied with the information signal before the carrier is modulated. The transmitted modulated carrier, which contains both user information and the coded "pseudo-noise" carrier, has a much wider spectrum than an information-only modulated carrier. The user information in the spread spectrum is then extracted in the receiver by a correlation process that collapses the received wideband spectrum to just the user information signal.

In a military implementation of spread spectrum, each user bit of information could be represented by up to 100 bits or more of pseudo-random code. The enormous increase in bandwidth required to transmit this encoded user data then makes it more difficult for the "enemy" to monitor the channel. In WaveLAN's spread-spectrum implementation, a single user symbol is represented by an 11-bit code, also called a chip code. Naturally, this encoding requires additional bandwidth, although not as much as a military implementation. WaveLAN's encoding results in a user signal of two Mb/s, based on two bits per symbol, and requires an 11-MHz spread-spectrum bandwidth.

While frequency hopping systems have some interesting diversity and multipath characteristics, the initial FCC regulations, which limited the modulation bandwidth for frequency hopping systems, forced the data rate to the low kbit/s range. Therefore, NCR has focused on direct-sequence spread spectrum. Three bands are available for unlicensed use under the FCC's part 15 rules and regulations[7]: 902–928 MHz, 2400–2483.5 MHz, and 5125–5850 MHz. Initial product development has concentrated on the 902–928 MHz band, due to the tradeoffs in implementation costs.

How Much Bandwidth Spreading?. In military spread-spectrum systems, the processing gain, which is a measure of system robustness—the amount of coding—to jamming and eavesdropping by the "enemy", is of vital importance. One measure of processing gain is the ratio of the spread-spectrum transmit bandwidth (that is, the signal after multiplication of the psuedo-noise code) to the user's information bandwidth before any coding. Various techniques have been developed to allow large processing gains (greater than 25 dB) with minimum receiver code-acquisition times.

The larger the processing gain of a spread-spectrum system, the higher the cost and spectral needs. In some cases, processing gain can even degrade interference immunity with respect to other conventional frequency-assignment techniques.

Considering the fact that the spread spectrum is neither used as a protocol method, nor as the optimal "robust" modulation technique of a given bandwidth, one could ask "Why use this at all?" The answer is that, in the ISM band, a minimum processing gain of 10 dB is required. For a fixed transmit power, the power spectrum density (watts/Hz) decreases in proportion to the processing gain. While other techniques of power reduction and spectrum management are possible, this is not the focus of the FCC's Part 15 rules and regulations.

In terms of maximizing the data rate, without spread-spectrum modulation in the indoor unequalized channel, data rates on the order of only 300 kbits/s can be supported.[1,3] Due to inherent spread-spectrum path resolution properties, a WaveLAN 2-Mb/s data rate, as previously noted, is achieved within an 11-MHz spread-spectrum bandwidth.

In summary, a processing gain is used in WaveLAN that takes into account the tradeoffs in data rate, robust performance, costs, and regulatory considerations.

Channel Echo and Multipath

An important physical limitation in indoor radio communications is caused by multiple signal reflections, which are dispersed in time. This phenomenon is the cause of signal "fading." A common parameter used to characterize the time dispersion of the channel is the delay spread. Initial studies have shown wide variation in the delay spread parameter, ranging from 30 nanoseconds to 250 nanoseconds,[8] depending upon the environment, measurement of the dynamic range, and threshold levels.

For testing WaveLAN's modem, an air channel emulator (ACE) was developed. ACE is a data acquisition unit, which takes a radio frequency modulated signal (within 904 MHz - 926 MHz), down converts it to in-phase (I) and quadrature-phase (Q) components, and stores this converted signal in digital form. It then processes the digital signal, with a programmable impulse response, using a time invariant discrete channel model.[10] Subsequently, the I and Q signals are either up converted for transmission or for further demodulation using the receiver's processing algorithms. The tests concluded that spread-spectrum modulation and demodulation can handle the delay spread.

Large-Scale Power Variation

The macroscopic large-scale signal variation, on the order of meters between rooms and different areas, has been successfully modeled[6] as a log-normal distributed random variable, u(r), as shown in Equation 1:

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

where:

r = the transmitter-to-receiver distance
$m(r)$ = 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 path loss coefficient, n, and the shadow loss deviation, σ. Another parameter that has been found useful in the characterization of different environments is a two-exponent crossover point, that is, the point at which the signal propagation ceases being line of sight (LOS), and becomes dominated by scattering and reflection. For distances close to the antenna, in a line-of-sight path, the path loss coefficient has been found to be close to free space, n = 2, value. At distances in which significant scattering and reflection occur, an increase in the attenuation exponent is found. Work now being done by various researchers shows great promise of being able to accurately predict attenuation in standard office building topologies.

Polarization Diversity

Spacial diversity is a known technique to mitigate Rayleigh fading, which affects the received signal level with small antenna movements. Conventional co-polarized antenna diversity techniques require the separation between antennas to be greater than 1/4 wavelength, minimizing the correlation of the fading events. At 900 MHz, this means the antennas are at least eight centimeters apart to be effective. Studies have shown large cross-polarization coupling in the indoor channel. Therefore, the use of polarization diversity is an attractive method in limiting antenna size. Measurements have been done to determine the correlation between the signal power received by the horizontal and vertical polarized antennas.

Measuring Polarization Density. The vertical dipole transmit antenna, located one meter above the ground, radiates a continuous wave (CW) signal. For reception, vertical and horizontal polarized dipoles of the receiver system are fixed (crossing each other) on an arm, which is mounted on a rotating post. Each antenna is connected, via a double-pole single-throw (DPST) radio frequency semiconductor (PIN) switch, to a spectrum analyzer. The PIN switch, rotating post, and spectrum analyzers are under the control of a personal computer. The receiver system is placed a distance away from the transmitter, which then defines a cell location. During one measurement run, the post is stepped through 35 positions, each separated from the next by 1/4 wavelength. The received signal power is measured during each step on the vertical antenna and then, via the PIN switch, on the 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 one meter distance between the previous receiver system position. In this way, 135 measurement points are obtained per cell location.

Results. Our study measured the signal reception in a typical office building. Without a line-of-sight path between the transmitter and receiver systems, 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 less than .13 in all locations. The correlation coefficient of measurements using the same antenna is greater than .85, due to the channel coherence time, which is affected both by people walking in the office and by unwanted movement of the transmitter or receiver system.

Our measurements show an average of 3 dB cross-polarization coupling. This result was found to be quite common. It shows that, at a significant number of locations, the received signal power is due to reflections that rotate the transmit polarization. Also, the cumulative distributions show excellent Rayleigh fading characteristics (without line of sight) for both horizontal and vertical polarizations, even with negative cross-correlation coupling and a vertically polarized receive antenna.

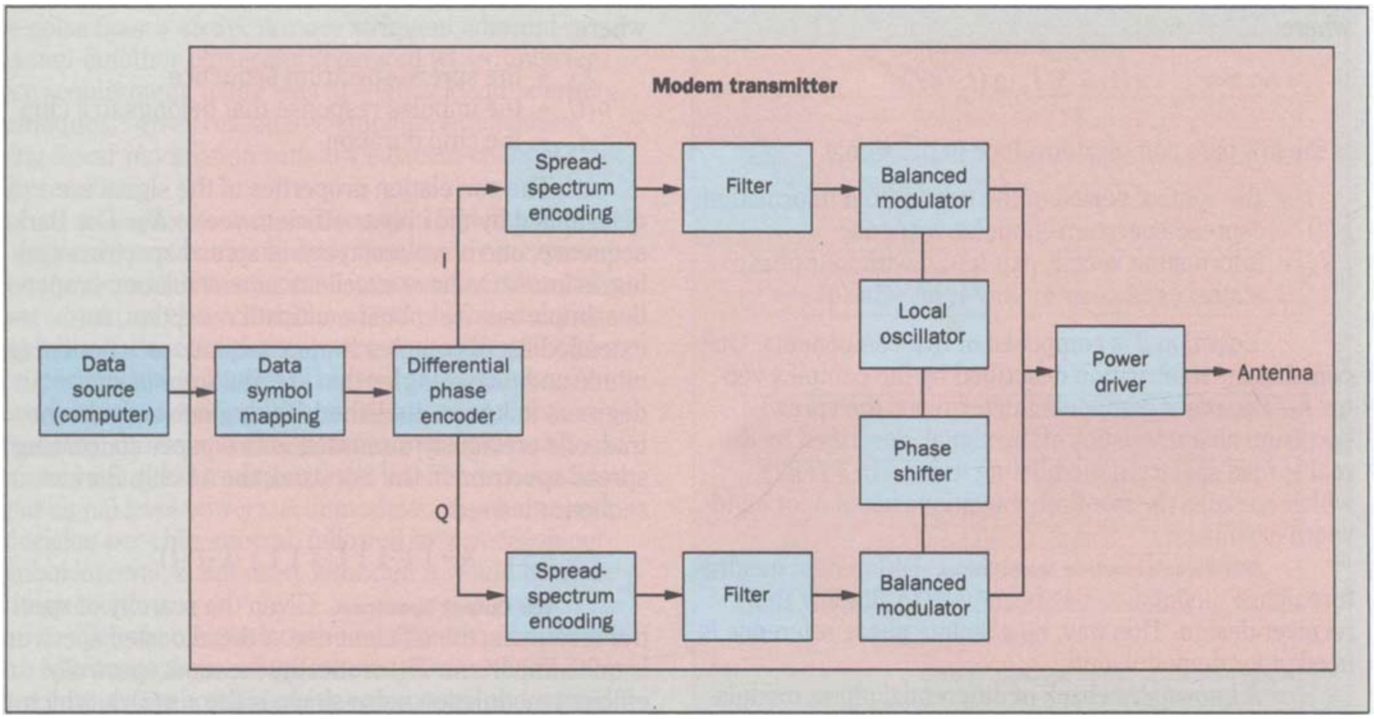

Figure 1. In this transmission block diagram, the data source is the signal from the user's computer. Within the modem, the data symbol mapping function takes the data stream and splits it into two-bit segments. The differential phase encoder transforms the two-bit signals to four different phase states. The two components of the signal, one containing the information (I), the other the spread-spectrum characteristics of the signal (Q), are individually modulated with the spread-spectrum signal, filtered, then combined for transmission by the power driver. A coaxial cable connects the driver to the antenna, which outputs the radio signal on the medium.

Network Topology. Due to the nature of the radio medium, the least number of radio links required to achieve total network connectivity will give the best network performance. The office studied has a typical physical design, a 41-meter-long by 12-meter-wide building with a corridor down the center and offices off either side. The office partitions are 1.5 meters high. The attenuation for signals, from one meter to 41 meters from the WLAN server, ranged from 10 dB to 36 dB at the far end of the corridor. The entrance and conference room walls are floor-to-ceiling reinforced concrete, which gives a significant 25-dB jump in attenuation, to 61dB, from the 34-36 dB in the adjacent cubicles. These results would be different, of course, for buildings with other topologies and interior designs.

There was a problem of bandwidth sharing of co-frequency overlapping signals, that is, signals of other LANs being guided down the hall. One reason CSMA/CA is attractive in this environment is that when a computer is ready to transmit, and senses other traffic on the network, it is required to wait a random amount of time before transmitting. This random wait time reduces to a very low level the probability of a collision on a radio network.

Technology and Radio Architecture

The WaveLAN transmitter is based on a common quadrature modulation scheme and provides spread spectrum by the block in Figure 1.

Modulation/Demodulation. Using complex notation, the transmit signal is represented in Equation 2 by:

$$s(t) = Re[u(t) \cdot \exp(j2\pi f_c t)] \qquad (2)$$

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" impulse response
I_n = information vector, exp $(j\,\theta_n)$, with four phase states: $(\pi/4,\ -\pi/4,\ 3\pi/4,\ or\ -3\pi/4)$

Equation 2 is composed of two components. One contains the information described by the complex vector I_n. The other component determines the spread-spectrum characteristics of the signal, described by the real spread-spectrum modulating waveform $g\ (t\text{-}nT)$, which contains the fast-time transitions needed for bandwidth expansion.

DQPSK Information Modulation. Differential quadrature phase modulation has been used to simplify the receiver design. This way, no absolute phase reference is needed for demodulation.

A known drawback of differential phase modulation is the sensitivity to receiver carrier frequency offset, or how accurate the carrier frequency is in the receiver. This problem was resolved by cost-effective crystals, which are readily available on the market, with accuracies from 25 ppm to 50 ppm. With a 915-MHz carrier, this accuracy translates into a maximum frequency offset of 92 kHz. A one-Mbaud signal, after differential detection, gives an unacceptable phase error between symbols of 33 degrees. Therefore, a frequency offset compensation technique has been implemented in which this constant phase-per-symbol offset is adjusted during the reception of the data frame.

The maximum tolerable frequency offset is related to the sensitivity of the detector of the despread signal for this offset. With a maximum offset of f = 92 kHz, and a symbol interval T = one microsecond, this 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.

Spread-Spectrum Modulation. The spectrum-determining function in Equation 2, $g(t - nT)$, is defined in Equation 3 as:

$$g(t) = \sum_{k=1}^{N} X_k \cdot \mathrm{p}(t - k\tau_C) \qquad (3)$$

where:

X_k = the spread-spectrum sequence
$p(t)$ = the impulse response that belongs to a chip
τ_c = the chip duration

The correlation properties of the signal are determined by the chip coefficient vector X_k. The Barker sequence, one of several types of spread-spectrum coding, is known to have excellent autocorrelation properties, important for robust multipath reception. An extended list of complex Barker sequences[11] (unit magnitude and phase angles that are multiples of six degrees) has been published. Taking into account the tradeoffs previously discussed in this paper concerning spread spectrum in the ISM band, the 11-chip Barker sequence is used:

$$X = [\,1\ \text{-}1\ 1\ 1\ \text{-}1\ 1\ 1\ 1\ \text{-}1\ \text{-}1\ \text{-}1\,\}$$

The Output Spectrum. Given the scarcity of spectral resources, the efficient use of the allocated spectrum is quite important. Theoretically, the 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 that approximates this is the raised cosine. One obstacle in implementing this class of pulse shaping is that the transmit signal has a non-constant envelope and needs linear power amplification. Various forms of spectrally efficient constant envelope modulation containing memory have been developed. One requirement is flexibility in the data symbol sequence that is transmitted.

The transmitted Barker chip sequence is fixed, due to the spread-spectrum modulation structure. This limits the modulation types that can be used. Due to the $[sin(x)/x]^2$ frequency spectrum of a unit pulse, the first sidelobes are only 12 dB down with a $(1/f)^2$ spectral roll-off. The main lobe is quite compact, with first zero at 5.5 MHz. A three-pole filter with a seven-MHz bandwidth has been implemented, substantially reducing the spectral power outside the main lobe.

The filtered waveform is not of the constant envelope class, so 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 sidelobe 23 dB down and the noise floor > 45 dB. A more stringent adjacent-channel (another physically separated WLAN) interference requirement, using bias of feedback compensation techniques,[9] gives reasonable amplifier efficiencies using linear modulation with low adjacent-channel suppression.

Spread-Spectrum Demodulation. Implementation of a spread-spectrum modulator is relatively inexpensive; the demodulation process is expensive. One of the most important characteristics of PSK chip modulation 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 system's linearity (at least up to a specified input signal level power). A demodulation scheme with a decision-per-chip interval, followed by a decision-per-symbol interval, is not used, although it would be easier to implement.

To gain insight into the mechanism of the multipath tolerance of spread-spectrum systems, the match filter outputs are compared for non-spread- and spread-spectrum systems. For the non-spread-spectrum case, a signal (using the unit pulse as an example) is transmitted through a simple multipath channel, with one reflection of 273 nanoseconds delay. At the receiver, the output of the match filter, a composite of the direct and reflected signals, is the sum of the match filter output of each signal taken separately, that is, the direct and reflected components. This is due to the fact that the channel and matched filtering operations are linear processes, in which superimposition can be applied.

Figure 2 represents the situation for a non-spread-spectrum. Figure 2a shows the direct-path signal, 2b shows a reflected signal (delay and sign-inverted), and Figure 2c shows the combined path. Significant signal energy of the pulse is present within the symbol time interval of one microsecond. It is obvious that the resulting match filter output is significantly distorted by the presence of the reflected signal. It is this "intersymbol interference" that causes detection errors in the received information.

The exact statistics of the errors depend upon the fading characteristics of the channel and delay spread profile. Analytical and simulation studies show that reliable communication is possible with data rates up to 300 kb/s, without channel equalization techniques,

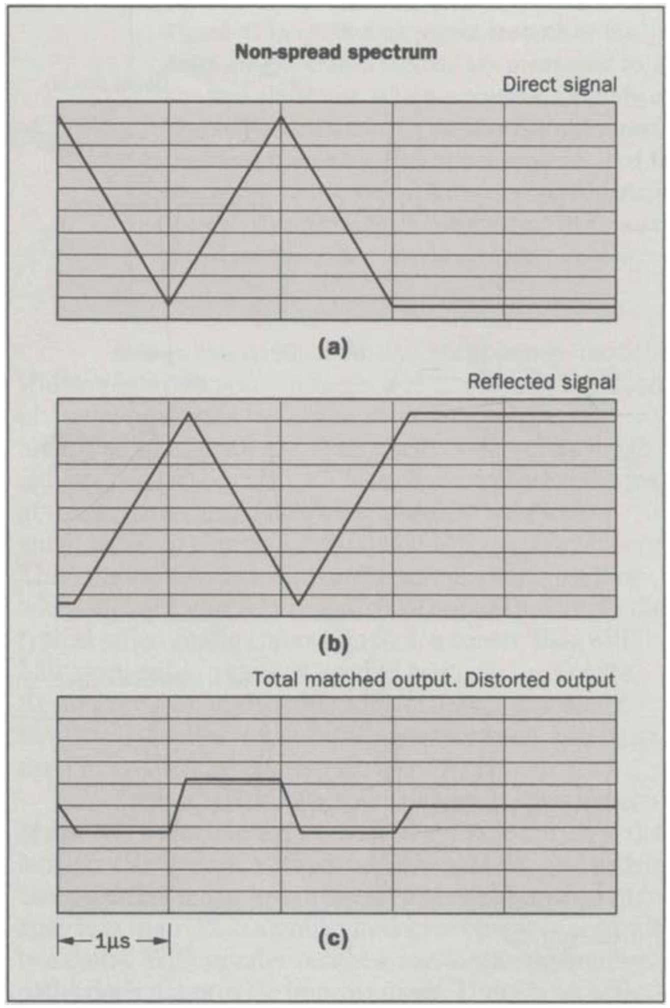

Figure 2. These figures show the situation for non-spread-spectrum signal output. (a) shows the direct-path signal, (b) shows a reflected signal (delay and sign-inverted), and (c) shows the combined path signal.

in common indoor multipath channels.

It is interesting to note that the errors produced by the phenomenon are caused by the signal reflections themselves, and increasing the transmit power does not improve reception. Therefore, these errors are called "irreducible errors."

Figure 3 represents the situation for spread spectrum. Figure 3a shows the direct-path signal, 3b shows a reflected signal (delayed and sign-inverted), and Figure 3c shows the combined path signal. Here, the symbol

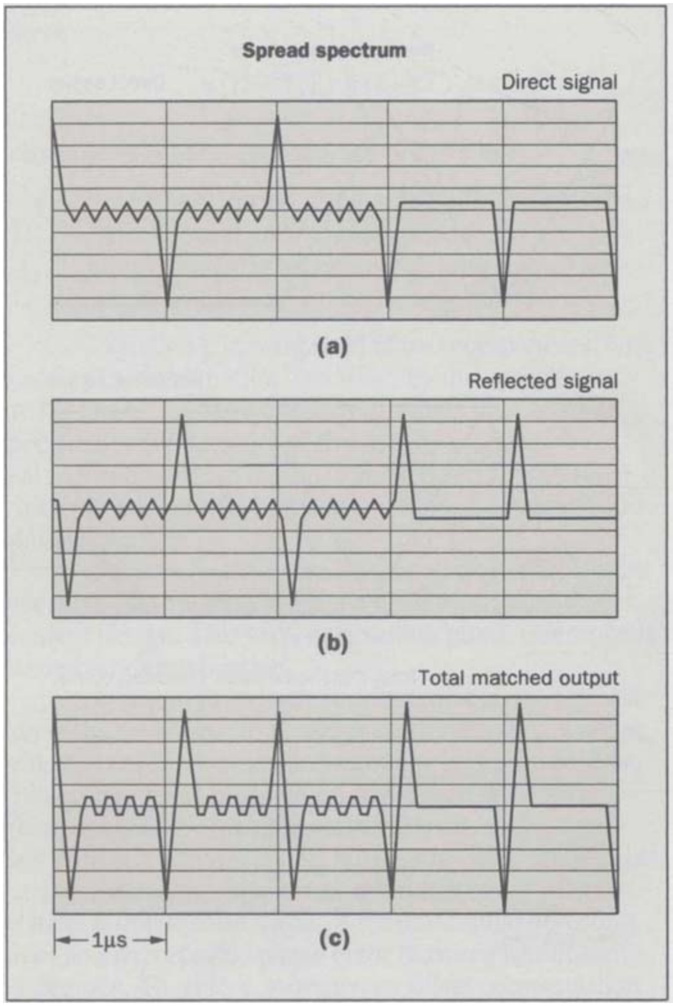

Figure 3. These figures show the situation for spread-spectrum signal output. (a) shows the direct-path signal, (b) shows a reflected signal (delayed and sign-inverted), and (c) shows the combined path signal.

interval of one microsecond is the same, but the energy of the pulse is much more compact in time, compressed around twice "chip interval,"τ_c. In Figure 3c, the orthogonal nature of the direct and reflected signals is shown by their superimposition. Due to the compact nature of the output pulses, they don't have a strong influence on each other. Both output signals, which contain the same information, can be resolved by the receiver and processed, due to the compression in time of the pulse (spectrum spreading).

The WaveLAN receiver will select and track "the largest peak position" of the matched filter output for information extraction. The "ripple" seen in the spread-spectrum output pulse is determined by the correlation properties of the spread-spectrum code used. The Barker sequence has been chosen, since these "sidelobe ripples" are unity bounded, independent from the input information polarity and delay (a unity bounded odd/even periodic, and a periodical correlation function).

Correlation of SAW or VLSI. One the main functional elements of a spread-spectrum system is the correlator, which functions for spread spectrum as a matched filter. Research has been done using surface acoustic wave (SAW) devices for spread spectrum. NCR, in conjunction with Delft University of Technology (The Netherlands), produced various SAW devices in order to determine the most cost-effective approach, given the spreading requirements, as compared with very large scale integrated circuit (VLSI) technology.

The major price reduction for the SAW correlator is due to the symbol time or length of material. In the VLSI implementation, cost is determined by the chip rate, or processing clock speed, and bandwidth symbol time (BT) product, or processing gain. In our application, the VLSI and SAW correlators are cost competitive, but the output of the SAW is still in analog form, requiring additional processing. 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.

DQPSK Information Demodulation. Performing complex conjugate multiplication, and extracting the phase of the sample matched filter output, results in the decision variable for Gray dibit decoding. This detection process, together with path selection criteria, describes WaveLAN spread-spectrum demodulation in a multipath channel.

Radio Homodyne Front End

Direct conversion radio design is one of the oldest and, thus for some, least remembered architectures. The main obstacle to direct conversion has been the narrow bandwidth of the voice channels. The lumped element baseband filters are quite large and impractical, and *1/f* noise is significant. Also, direct conversion requires DC coupling, due to the blocking capacitors, and double (I and Q) radio frequency stage-down conversion.

For wide bandwidth modulations, especially

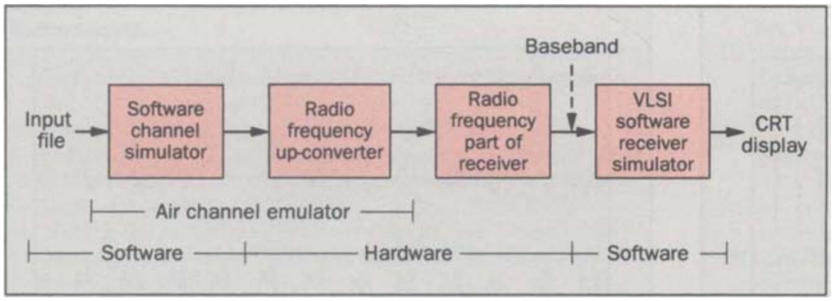

Figure 4. In simulating signal reception, the software-generated signals are presented to a channel simulator, which emulates a variety of channel conditions. The signals are converted in the radio frequency part of the receiver, and then presented to the VLSI software, which emulates a variety of radio receiver conditions. The results of the simulations are shown on a CRT screen.

spread spectrum in which low frequency content (in our example < 100 kHz) is not significant, the "narrow band" problems are no longer present. Therefore, due to available filter technology, WaveLAN uses a direct conversion radio design.

Diversity. The path resolution of a spread-spectrum system provides "path diversity" by selecting and tracking the "largest peak position" of the correlator output. Also, in a typical office, a significant number of indoor channels experience small delay spreads (less than 50 nanoseconds). Therefore, switched antenna diversity, as discussed previously under "Polarization Diversity," has been implemented using two cross-polarized antennas etched onto a printed circuit board at the receiver. This selection is based on a post-processed signal quality level, a measure of an average correlation peak-to-side lobe ratio. This ratio decreases as a function of thermal noise, severe multipath distortion, and interference from other signals.

Distance vs. Outage Model

Spread-spectrum modulation is robust with respect to intersymbol interference from other frequency signals. Link outages for WLANs, running at 2 Mb/s in an office environment, usually are due to an insufficient signal-to-noise ratio (SNR), rather than to the irreducible multipath delay. The question addressed is: "What can the distance be, in an environment characterized by its large-scale parameters n, α and cross-over point, between the terminal and the LAN server?" We found an input power level of -72 dBm is needed to achieve a bit error rate (BER) of 10^{-8}, which includes a 18 dB "man-made" noise/margin. For received signals below this value, the link is not reliable, and a "link outage" has occurred. Note that the BER parameter does not strongly influence the outage of the link, due to the exponential relationship between the BER and input power level.

Outage Calculations. An analytical outage model, which takes into account large- and small-scale multipath phenomenon, has been used to predict the coverage area. The small-scale behavior corresponds to Rayleigh fading. The large-scale path loss characteristizes the loss at a certain distance, after averaging the losses over small areas, to eliminate the Rayleigh fading fluctuations. The random effects of the multi-path phenomenon are taken into account by the analytical outage model. In the typical office configuration studied, a center aisle with offices on either side was used to estimate the outage. An analytical outage model, which takes into account large- and small-scale multipath phenomenon, has been used to predict the coverage area.

From a typical office, an outage of .1% is expected at a server-to-station distance of 50 meters, and 1% at distances of 75 meters. In such an environment, one path is assumed due to the low-delay spread environment. At outages less than .1%, a significant improvement is seen with two paths. With greater outages, increasing the number of paths does not provide improvement. There is an optimal number of paths as a function of the minimum outage. The larger the outage, the smaller the optimal number of paths. For an outage minimum of 1%, the use of three paths is optimum. The need for determining an optimal number of paths is due to the implementation of selection diversity. While more paths help mitigate the Rayleigh fading, the average power of each path is less.

Simulation and Measurements

The WaveLAN modulation structure and some of the practical reasoning behind the various implementation decisions has been discussed. Software simulation was extensively used for the modem algorithm development and system testing. Since the software simulation structure was mapped to the VLSI processing exactly, VLSI verification and error detection also was possible. The

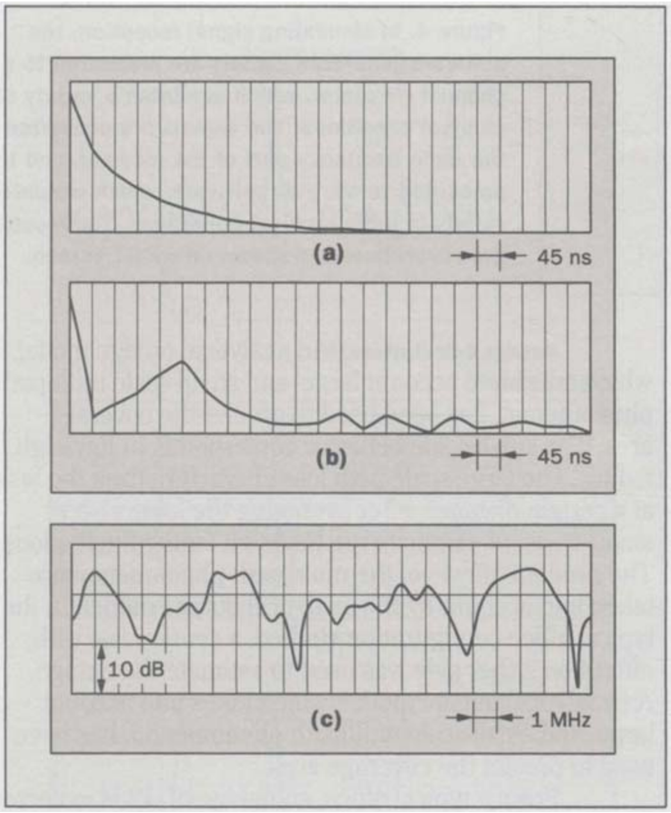

Figure 5. In this illustration, (a) shows an exponential profile with a root mean squared (rms) delay spread of 150 nanoseconds. (b) shows one particular impulse response, and (c) shows the frequency-transfer function.

replacement of the actual VLSI in the software emulation block, as shown in Figure 4, does not alter system performance.

Channel Perturbations. To test the spread spectrum's data recovery algorithms, test impulse responses are generated from a given power delay profile $h(\tau)$. 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 $(0,2\pi)$. Figure 5a shows an exponential profile with root mean squared (rms) delay spread of 150 nanoseconds. Figure 5b shows one particular impulse response, and Figure 5c shows the frequency transfer function.

Figure 6 shows the output of the correlator process. Figures 6a and 6b show the I and Q outputs of the digitally correlated signals. In Figure 6c, the modulus of the correlated signals, a second path is clearly seen. The first path is chosen for data extraction, due to our switched-path implementation.

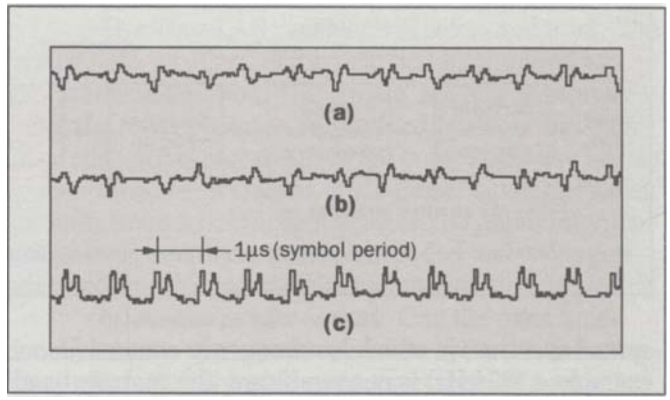

Figure 6. This illustration shows the output of the correlator process. Figures (a) and (b) show the I and Q outputs of the digitally correlated signals. In (c), the modulus of the correlated signals is presented, and a second path is clearly seen. The first path is chosen for data extraction, due to our switched path implementation.

LAN Performance

Standard LAN benchmark testing was performed to compare NCR's WaveLAN with standard wired LAN products. Test results of WaveLAN showed similar performance between it and other LANs, such as Starlan®, Ethernet, or token ring. (Ethernet is a registered trademark of the Xerox Corporation.)

Conclusions

Various design and implementation issues related to the first high-speed wireless LAN on the market, NCR's WaveLAN, have been discussed. High data rates are achievable without channel equalization, following the existing FCC spread-spectrum ISM band regulations. WaveLAN, using 11 MHz of bandwidth, achieves a 2-Mb/s raw data rate for indoor operation. The ISM spread-spectrum communication band now has a unique global presence. Also, services on the 1.9-GHz band, in the U.S., and the European HIPERLAN 5.2 GHz and 17.1 GHz bands are beginning to evolve. A great opportunity to solve the end-user's WLAN connectivity problems now exists, leading the way to an exciting future for high-performance wireless data communications.

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. Justin C-I Chuang, "The Effects of Delay Spread on 2-PSK, 4-PSK and 16-QAM In a Portable Radio Environment", Globecom 1987.
3. Donald C. Cox, "Universal Digital Portable Radio Communications", *Proceedings of the IEEE*, Vol. 75. No. 4, April 1987.
4. D. M. J. Devasirvatham, "A Comparison of Time Delay Spread Measurements within Two Dissimilar Office Buildings", ICC '86, June 23–25, 1986.
5. D. M. J. Devasirvatham, R. R. Murray and C. Banerjee, "Time Delay Spread Measurements at 850 MHz and 1.7 GHz Inside a Metropolitan Office Building", *Electronic Letters*, Vol. 25, No. 3, February 1989.
6. William C. Jakes, Jr., *Microwave Mobile Communications*, John Wiley & Sons, 1974.
7. Michael J. Marcus, "Regulatory Policy Considerations for Radio Local Area Networks", *IEEE Communications Magazine*, Col. 25, No. 7, July 1987.
8. Adel A. M. Saleh and Reinaldo A. Valenzuela, "A Statistical Model for Indoor Multipath Propation", *IEEE Journal on Selected Areas in Communications*, Vol. SAC-5 No. 2, February 1987.
9. Sirikiat Aryavisitakul and Ting-Ping Liu, "Characterizing the Effects of Nonlinear Amplifiers on Linear Modulation for Digital Portable Radio Communications", *IEEE Transactions on Vehicular Technology*, Vol. 39, No. 4, November 1990.
10. George L. Turin, "Introduction to Spread-Spectrum Antimultipath Techniques and Their Application to Urban Digital Radio", *Proceedings of the IEEE*, Vol. 68, No. 3, March 1980.
11. Ning Zhang and S. W. Golomb, "Sixty-Phase Generalized Barker Sequences", *IEEE Transactions on Information Theory*, Vol. 35, No. 4, July, 1989.

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