

# System Applications for Wireless Indoor Communications

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Wireless indoor communications can be used in a wide range of applications to provide for user mobility, easy setup, and reconfiguration of terminals, telephones, and so forth. Such applications can be divided into two classes: (1) Narrowband applications, such as paging or wireless PBX systems for voice and low rate data and (2) Wideband applications, such as a wireless local area network capable of handling data rates up to several Megabits per second. Buildings, however, present a hostile environment for radio communications, with in-building radio propagation difficult to predict and continuously changing. Problems include multipath and shadow fading, which reduce the coverage region, and dispersion due to delay spread, which limits the maximum data rate. Furthermore, in buildings with multiple users, interference among users can be a serious problem, and the available spectrum might be much less than that required to handle all potential users.

In this article we describe various antenna diversity techniques, including selection, maximal ratio and optimum combining, and show how diversity, in combination with other techniques, can be used to overcome these problems. One such technique is resource sharing, which recognizes that, at any moment, only a small fraction of all users are experiencing transmission difficulties, and assigns extra system resources (for example, bandwidth or time slots) as needed to protect those users.\* We first briefly describe the indoor radio environment and show why diversity can be effective. We then describe techniques for narrowband applications, such as wireless PBX's, that can be used to increase the coverage region, eliminate interference problems, and permit frequency reuse within the same coverage region, thereby dramatically increasing system capacity. Finally, we describe techniques for wideband applications, such as wireless local area networks, that can be used to increase both the maximum data rate and the coverage region.

## The Indoor Radio Environment

With indoor radio communication, there is rarely a line of sight between the transmitter and receiver, and multiple signal propagation paths exist. The signals from these paths combine both constructively and destructively at the receiver to produce multipath fading. For narrowband transmission, where the propagation delays associated with the various paths are extremely small compared to the inverse of the signal bandwidth, the channel can be considered as a Rayleigh fading channel with frequency flat fading [14]. This Rayleigh fading caused by multipath propagation results in signal strength variation when the receiver is spatially displaced as shown in Fig. 1. A receiver at location

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\*Other techniques not discussed in this paper include infrared [1,2], spread spectrum [1,3-7], and leaky feeders [8,9]. Specific systems utilizing, to some extent, the techniques discussed here include those described in [10-13].

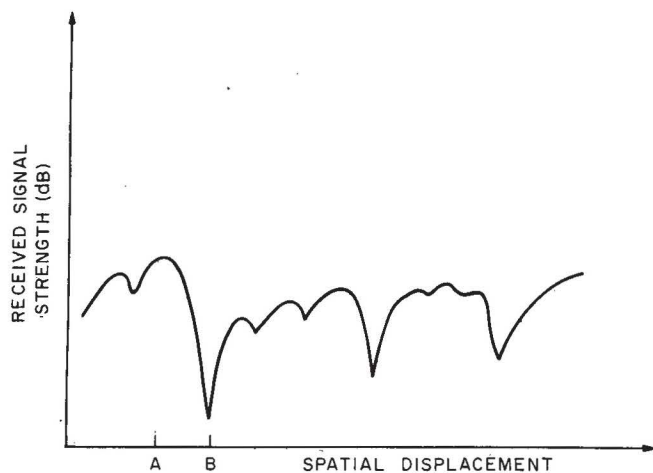


Fig. 1. The Signal Strength Variation of a Rayleigh Fading Signal as a Function of Spatial Displacement.

A receives maximum signal strength, whereas a receiver at location B is in a fade and receives minimum signal strength. These fades generally occur every half wavelength. For example, at 900 MHz, the wavelength is approximately one foot (0.3 m) and many fades can occur over short distances.

In addition to multipath fading, there is also shadow fading [14], caused by blockage and attenuation of the signal by walls, doors, etc. Shadow fading is spectrally flat and characterized by a log-normal distribution, that is, the logarithm of the received signal power has a Gaussian distribution. Shadow fading varies slowly with location, with fades occurring in different portions (for example, rooms) of a building. Numerous studies have been made of shadow and Rayleigh fading in buildings [15-24].

With wideband transmission, the path delays affect the quality of the received signal. This delay spread causes frequency selective fading in the channel. Thus, the received signal strength also varies as a function of frequency, similar to the variation in signal strength with location. Although different models for delay spread exist (for example, [25-31]) the performance of communication systems is mainly dependent on the rms of the delay spread [25,26,28,29]. In a digital system, the dispersion in the channel due to delay spread produces intersymbol interference that increases with the signaling rate, which limits the maximum data rate for acceptable error rate performance. Numerous studies have been made of delay spread in buildings [27,32-34].

In this article, we consider indoor radio communication systems consisting of a base station with numerous remotes as shown in Fig. 2. In this figure, the base station has multiple antennas and the remotes have only one antenna, for reasons that will become clear later. This type of system offers the advantage of a central controller that can ensure that all users receive adequate performance even though the radio environment in buildings is difficult to predict and continuously changing. Note that all users either share a single channel or a set of channels which are assigned to the users. This system configuration is similar to that

used in mobile radio [14]. However, indoor radio differs from mobile radio in two important aspects: the interference environment and the fading rate. First, the interference environment is worse with indoor radio because the attenuation of a signal throughout a building can vary widely and unpredictably. The signal can be greatly attenuated after propagating a few tens of feet through walls, or may still be strong enough for reception after propagating more than a thousand feet along a hallway. Therefore, without a detailed, costly study of each building, interference among users in the same, or even adjacent buildings (and from the same or different systems) can be unpredictable and often severe (as many cordless phone users have realized). Indoor radio also differs from mobile radio in the fading rate. In mobile radio, the receiver experiences many fading events per second. For example, at 60 miles/hour, the fading rate is about 80 Hz at 800 MHz carrier frequency. As a result, studies in mobile radio concentrate on the channel performance averaged over the fading.

Indoor communication is quite different in that both the base station and the remote stations are stationary or slowly moving. Therefore, we are not interested in the average performance over the fading, but, rather, in the following question: Given a large number of stations randomly located, what is the probability that a certain number of stations fail to meet a prescribed bit error rate (BER) objective\* The answer may be expressed as "with  $10^{-1}$  probability the communication link can not meet a  $10^{-1}$  BER requirement." The above criterion, based on the outage probability, will charac-

\*Note that in this article we concentrate on digital communication systems. However, most of the techniques considered can also be used in analog systems.

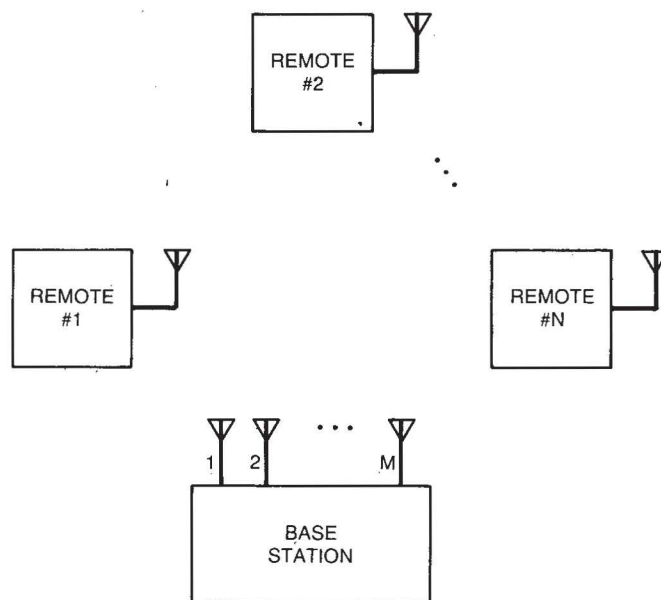


Fig. 2. Radio System Consisting of a Base Station with M Antennas and N Remotes, Each with One Antenna.



terize the following two in-building communication applications.

- 1) *Portable telephone.* The user may hold the phone and move slowly during a conversation. In this case, the user would experience many fades, albeit slowly. We would describe this situation by stating that the user will experience a BER greater than  $10^{-1}$  for no greater than 0.01 percent of the conversation.
- 2) *Stationary terminal.* The above answer allows us to state that no more than 0.01 percent of the randomly located terminals will experience a BER greater than  $10^{-1}$ . However, because of motion within a building (for example, people walking, doors opening, and so forth), the BER for a given terminal may change slowly with time.

An outage can be due to thermal noise (received signal level too low), interference from other users, and/or intersymbol interference caused by delay spread. Thus, for a system with a given outage probability objective, multipath and shadow fading limit the coverage region, interference limits the number of users in a given area, and, in wideband systems, delay spread limits the data rate. We now consider what these limits are in narrowband and wideband systems and show how diversity, in combination with other techniques, can be used to greatly increase those limits.

## Narrowband Systems

### Limits Due to Multipath and Shadow Fading

Let us now consider narrowband systems and the limits on the coverage region due to multipath and shadow fading. With Rayleigh fading, the probability of receiving a signal  $x$  dB below the average received signal power (where the average is taken over the Rayleigh distribution) is approximately  $10^{-x/10}$ . Thus, for a  $10^{-1}$  outage probability at a given BER, the average received signal power must be 40 dB above that required for the given BER without fading. With shadow fading, the decrease in signal strength with distance may vary as the square of the distance for free space propagation, or, in some buildings, as the sixth power of the distance [20]. A power decrease with the fourth power of distance is typical in office buildings. As an example of the coverage region limitations, consider a system that can accommodate an 80 dB dynamic range in received signal power. Then, with a  $10^{-1}$  outage probability, the coverage region could extend from 2 m from the antenna (for example, just outside the room where the base station was located) to about 20 m in a typical building, although the range could be as large as 200 m in buildings with large open areas.

### Antenna Diversity with Fading

Let us now consider the use of antenna diversity to reduce the effects of Rayleigh fading. Figure 3 shows a block diagram of an  $M$  antenna element diversity combiner. The signals received by the  $M$  antennas are weighted (that is, the gain and phase of the received

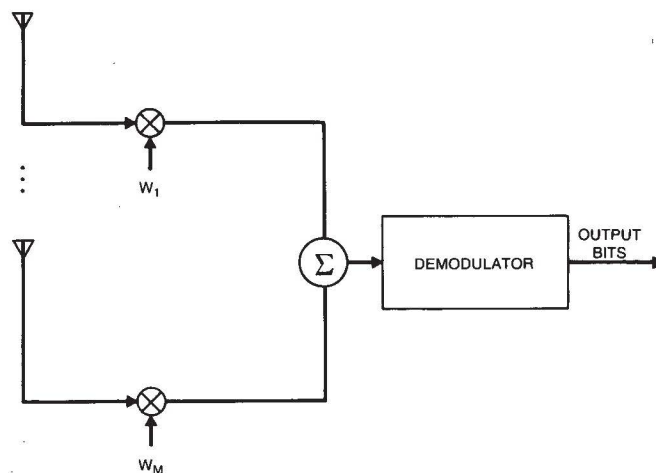


Fig. 3. Block Diagram of an  $M$  Antenna Element Diversity Combiner.

signals are adjusted), combined, and demodulated to generate the output bits. With multipath in buildings, the fading statistics of two antennas are (usually) nearly independent when the antennas are separated by more than a quarter wavelength (for example, 8.3 cm at 900 MHz). Thus, with appropriately spaced antennas\* the probability of multiple antennas all in a fade is much less than with a single antenna.

Therefore, we first consider selection diversity. With selection diversity, the receiver selects for reception the signal from that antenna with the highest signal power. That is, for the diversity combiner of Fig. 3, one weight is set to 1 and all others are set to 0. Under the assumption of independent fading at each antenna, the outage probability for selection diversity with  $M$  antennas is the outage probability for a single antenna raised to the  $M^{\text{th}}$  power. Thus, for a  $10^{-1}$  outage probability at a given BER, the average received signal power need only be 20 (or 10) dB higher than that required for that BER with 2 (or 4) antennas. Thus, selection diversity increases the range by a factor of 3 (or 6) with 2 (or 4) antennas, for a power decrease in signal strength with the fourth power of distance.

Implementation of selection diversity requires the signal strength at each antenna to be continuously monitored, and, thus,  $M$  receivers are required. However, the outage probability of selection diversity can also be achieved with switched diversity, whereby a single receiver switches from one antenna to another when the antenna is in a fade, as shown in Fig. 4.

We note here that with duplex operation, multiple antennas need only be used at either the remote or the base station (usually just at the base station). Since the propagation characteristics of the indoor radio channel are reciprocal, with selection or switched diversity identical outage performance in both transmission

\*In addition to space diversity, direction [35], polarization [36,37], and field [14] diversity can be used to achieve nearly independent fading at each antenna without increasing the physical size of the antenna array.



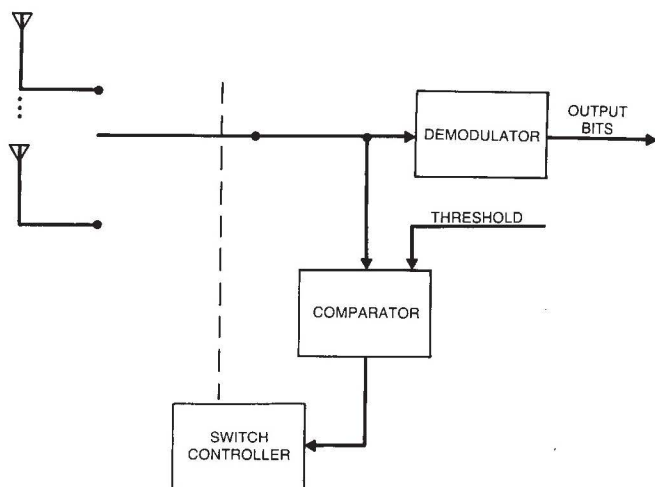


Fig. 4. Block Diagram of an M Antenna Element Switched Diversity Receiver.

directions can be achieved by using the same antenna for transmission as for reception, if the transmit and receive frequencies are close enough so that the fading is the same at both frequencies. For indoor radio communications, this means that the transmit and receive frequencies should be separated by no more than a few hundred kHz. If the transmit and receive frequencies are not close enough, then switched diversity with feedback [14,38] can be used to achieve the same outage probability in both directions. With this technique, the remote tells the base station to switch antennas when the receive signal falls below a threshold. Note that for indoor radio, the switching delay (the time between when the signal falls below threshold and the base station switches the antennas) is much less important than in mobile radio because the fading is much slower.

A somewhat better technique than selection or switched diversity is maximal ratio combining [14]. With this technique, the signals received by multiple antennas are weighted and combined to maximize the output signal-to-noise ratio. Therefore, maximal ratio combining is the diversity combining technique that gives the largest coverage region. With maximal ratio combining, from the analysis of [29] we can show that for a  $10^{-4}$  outage probability, the average received signal power need only be 18 (or 6) dB higher than that required for a given BER without fading, with 2 (or 4) antennas as compared to 20 (or 10) dB with selection diversity. Thus, maximal ratio combining increases the range by a factor of 4 (or 7) with 2 (or 4) antennas, which is only slightly higher than selection diversity.

Again, the improvement of maximal ratio combining can be obtained in both transmission directions with multiple antennas only at the base station. With maximal ratio combining used for signal reception at the base station, the base station can then transmit using adaptive retransmission [14,39,40], whereby the signal is transmitted using the conjugate of the receive weights. That is, if the signal transmitted by each antenna at the base station is amplified before transmission by the magnitude of the receive weight for that

antenna, but phase shifted by the negative of the phase of the receive weight (that is, phase retardation becomes phase advancement), the transmit antenna pattern will be the same as the receive pattern. Thus, because the propagation medium is reciprocal (that is, the same propagation characteristics exist in both transmission directions), these transmit weights will maximize received signal power at the remotes. However, unlike selection diversity, small differences in the channel characteristics at the transmit and receive frequencies cannot be tolerated, and these two frequencies must be the same. Thus, adaptive retransmission must be used with time division, as shown in Fig. 5, whereby a single channel is time shared by both directions of transmission. Thus, with maximal ratio combining, during transmission from the remote to the base station, the antenna element weights are adjusted to maximize the signal-to-noise ratio at the receiver output. During transmission from the base to the remote, the complex conjugate of the receive weights are used so that transmission losses and antenna gains are the same as in the other transmission direction, and, therefore, the signals from the base station combine to maximize the receive signal power at the remotes.

Antenna diversity can also be used to overcome the effects of shadow fading, through the placement of antennas throughout a building (see [14,41,42]). By this method, the coverage region can be made arbitrarily large. Switched diversity is usually considered because it has the least complexity and eliminates the delay spread problems (see the section titled "Wideband Systems.") that can occur when signals received at different locations throughout a building are combined. Using multiple antennas spaced throughout a building can be expensive, however, and here antenna diversity at a single location to overcome Rayleigh fading can help. As shown before, antenna diversity at a single location (for example, antennas spaced a quarter wavelength apart) significantly increases the coverage region for that location and, therefore, also reduces the total number of antennas needed in a building to achieve a given outage probability. For our example, as shown above, selection diversity with 2 (or 4) antennas increases the coverage region by a factor of 9 (or 36). Thus, selection diversity at each antenna location throughout a building can reduce the required number of locations by the same factor and the total number of antennas by a factor of 4.5 (or 9).

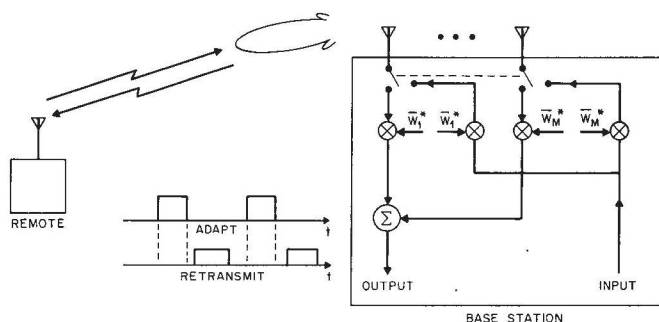


Fig. 5. Radio System with Adaptive Retransmission with Time Division.



## Limits Due to Interference

Because propagation in buildings is difficult to predict and continuously changing, interference from other users can be a serious problem. The interference can come from other users in a multiple user system or from the users of other systems in the same or neighboring buildings, and limits the number of users in the coverage region. Below, we discuss techniques that can be used to reduce interference problems and increase the number of users in a given coverage region.

## Dynamic Channel Assignment and Power Control

In multiple channel systems, the problem of interference from other users can be reduced with dynamic channel assignment. With this method, before each user begins transmission, the channels are scanned to find a quiet channel (one with little or no interference) for channel assignment. Furthermore, while the remote is being used, the assigned channel is continuously monitored for interference (for example, by monitoring the BER with error detection coding), and the channel assignment is changed to a quiet channel when the interference becomes too strong. The latter process must occur because the signal environment is constantly changing as the user moves or as other remotes are used. Thus, with dynamic channel assignment, interference does not affect the outage performance of the system as long as there are quiet channels available. However, since interference eliminates the use of certain channels, interference does reduce the number of available channels and, thereby, the system capacity (number of users). Also, dynamic channel assignment won't work if there is interference in every channel.

Another technique to reduce interference among users is power control. As discussed earlier, within the coverage region, the signal attenuation between the transmitter and receiver can vary widely, by as much as 80 dB or more. Thus, a system with a base station and multiple remotes, all transmitting at the same power level, can have received signals differing in power by as much as 80 dB at the base station, which creates an adjacent channel interference problem. The problem can be reduced by adaptively controlling each remote's transmit power level so that the received power is equal for all signals at the base station. Furthermore, to reduce adjacent channel interference at the remotes, the base station can transmit all signals with equal power. Note that power control also reduces the interference between systems. Although it doesn't reduce the worst case interference (when users transmit at maximum power), it does reduce the outage probability due to interference from randomly located remotes, and increases the average number of users.

## Antenna Diversity with Interference

In addition to dynamic channel assignment and power control to reduce the interference problem, we also consider the use of antenna diversity. In particular, we consider the use of optimum combining at the receiver, whereby the signals received by multiple

antennas are weighted and combined to maximize the signal-to-interference-plus-noise ratio. (Techniques for implementing optimum combining are discussed below.) Thus, diversity is used to suppress interfering signals and enhance desired signal reception.

Optimum combining has been shown to substantially reduce interference in systems both with fading (mobile radio systems [43]) and without fading [44]. Indoor radio systems fall somewhat between these two systems because, although there is fading, with power control we can compensate for it by adjusting the transmit power.

Without fading, optimum combining can suppress  $M-1$  interferers with  $M$  antennas, if the angular separation of the desired and interfering signals is large enough. That is, since an  $M$  element antenna array has  $M-1$  degrees of freedom (that is, the dimensionality of the set of equations describing the combining of the received signals in the array is  $M-1$ ), up to  $M-1$  nulls can be placed in the antenna pattern to null interfering signals. With fading, the angular separation no longer matters because of the multipath. In fact, the receiver can suppress interfering signals and enhance desired signal reception as long as the received power and phase of the desired signal differ somewhat from the received power and phase of the interfering signals at more than one antenna. As discussed earlier, the received signal power and phase from two antennas are usually statistically independent if they are separated by at least a quarter wavelength. Thus, in an indoor radio system using several antennas for diversity, the probability of being unable to suppress an interfering signal is very small, even if two remotes are close together. Furthermore, since with dynamic channel assignment the channel can be changed if the interference cannot be suppressed, indoor radio systems with optimum combining can overcome most interference problems.

As discussed above, since an  $M$  element antenna array has  $M-1$  degrees of freedom,  $M-1$  interfering signals can be suppressed even with fading. However, interference nulling also reduces the output signal-to-noise ratio of the desired signal. Thus, with optimum combining an outage occurs when, although the interference is nulled, the signal-to-noise ratio at the optimum combiner output falls below that required for a given BER\*. Thus, the indoor radio system with optimum combining can achieve a given outage probability with interference at any power level\*\* if the received desired signal power is high enough. In particular, computer simulation studies [45] show that, in

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\*This is analogous to the case with nonfading systems where the angular separation between the interferer and the desired signal is so small that the null in the antenna pattern for the interferer also greatly attenuates the desired signal.

\*\*In a hardware implementation, the maximum interference to desired signal power ratio that can be tolerated is usually limited to 40-80 dB.



a Rayleigh fading environment†, up to  $M-1$  interferers at any power level can be tolerated with optimum combining and  $M$  antennas if the received desired signal power is high enough. For example, at a  $10^{-2}$  outage probability,  $M-1$  interferers at any power level can be tolerated if the received signal-to-noise ratio is about 17 dB higher than that required without interference. That is, for one percent of the possible cases for received interference with  $M-1$  interferers, nulling of the interference also reduces the output desired signal power at least 17 dB below that without interference. The required increase in signal-to-noise ratio is, of course, much less if there are fewer than  $M-1$  interferers, for example, the 17 dB increase is reduced to 6 dB with  $(M/2) - 1$  interferers. Also, for multiple channel systems with dynamic channel assignment, the increase in the required signal-to-noise ratio can be much less, for example, the 17 dB increase is reduced to 8 dB with 8 channels. Thus, with optimum combining, interference can reduce the coverage region (which can be increased by adding more antennas), but cannot decrease the number of users in a system if there is an adequate number of antennas.

Since optimum combining can suppress interfering signals even when the users are in close proximity, multiple users per channel are possible. Thus, optimum combining can also be used to greatly increase the number of users. Figure 6 shows a block diagram of an optimum combining system with multiple users per channel that has one base station with  $M$  ( $M > 1$ ) antennas and multiple remotes, each with one antenna. The base station has, for each active remote, an optimum combiner ( $OC_1$  to  $OC_N$ ) that uses the signals received by each of the  $M$  antennas. Thus, the designation of the desired and interfering signals depends only on which optimum combiner is being considered. (How to distinguish the desired signals at the base station is discussed below.) All signals are, of course, desired at the base station.

Since with  $M$  antennas up to  $M-1$  interferers can be tolerated at any power level, there can be up to  $M$  users per channel, for an  $M$ -fold increase in the number of users. However, with power control, the interferers to be nulled have power levels equal to that of the desired signal, and all signals must be separated by the receiver with low outage probability. The net result is that, for a given outage probability and  $M$  users, the required receive signal-to-noise ratio is much higher than that required with a single user per channel system, and, therefore, the coverage region is smaller. Fortunately, as with the case of high power level interferers discussed above, the required increase in signal-to-noise ratio can be greatly reduced by having fewer users per channel and by using dynamic channel assignment with multiple channel systems. For example, with only  $M/2$  users per channel, the required receive signal-to-noise ratio is about the same as with a single user [46], that is, an

†Since optimum combining always maximizes the signal-to-interference-plus-noise ratio, we would expect similar results even if the fading environment is not Rayleigh.

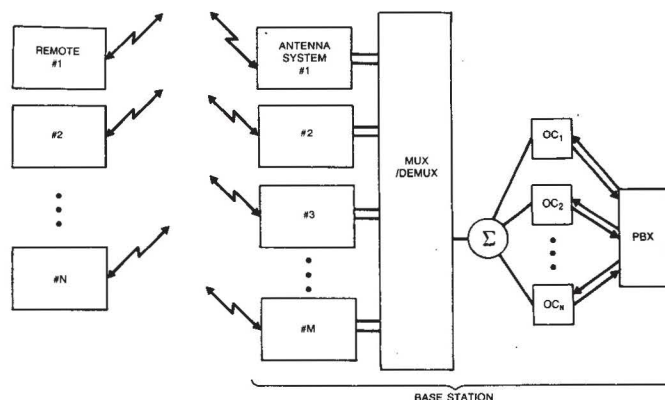


Fig. 6. Wireless PBX with Optimum Combining.

$M/2$  fold increase in the number of users can be obtained in the same coverage region.

Let us now briefly consider implementation of the optimum combining system for indoor radio. We consider the algorithms needed to implement optimum combining and the corresponding performances, the methods to distinguish the signals at the receiver, and base station to remote transmission. Optimum combining can be implemented in indoor radio systems in the same way as in mobile radio [43]. The optimum combiner can be implemented with the LMS [47] algorithm. Although this algorithm takes longer to converge than some other algorithms, it is simple to implement and, for the slow fading of indoor radio, should still be able to track the desired and interfering signals as the propagation characteristics of the channel vary. Signals can then be distinguished at the base station by different pseudo-random codes [48], with these codes added to a biphasic modulated signal via biphasic modulation of the quadrature carrier. These points are discussed in [43]. As discussed earlier for maximal ratio combining (and also in [43] for optimum combining), adaptive time division retransmission can be used to obtain the same performance in both transmission directions with multiple antennas at the base station only. The only difference from the technique used for maximal ratio combining is that the weights are now adjusted to maximize the signal-to-interference-plus-noise ratio in order to achieve the advantages of optimum combining at both the remotes and the base station.

The multiple users per channel system with optimum combining can, of course, still suppress interference from other systems, but at the expense of reduced capacity. We note that adaptive retransmission also reduces the interference from one base station into other systems and, therefore, we can have multiple systems, each with multiple users per channel, in the same building. However, remotes can still receive interference from systems not using adaptive retransmission, although dynamic channel assignment can help reduce the problem.

Thus, through a combination of optimum combining, dynamic channel assignment and power control, indoor radio systems can operate in high-density, multiple user environments.



## Wideband Systems

### Limits Due to Delay Spread

In wideband systems, multipath, shadow fading and interference place limits on the coverage region and on the number of users similar to the limits imposed on narrowband systems. In addition, delay spread, i.e., dispersion or frequency selective fading in the channel, produces intersymbol interference which limits the maximum data (information) rate in a given building\*. It was shown in [29] (and also in the earlier results of [25,26,28]) that the maximum data rate for a given building depends primarily on the rms delay spread and not the shape of the delay spread function. Thus, within the coverage region, there is an outage probability for each user due to delay spread, that is, a probability that the delay spread will cause enough intersymbol interference to increase the BER above the required value. Here, as in the previous section, we consider an outage probability of  $10^{-1}$  at a  $10^{-1}$  BER. We study the maximum data rate for a given rms delay spread with this outage criteria and mention some techniques to increase the maximum data rate.

Measurements of the rms delay spread,  $\tau_0$ , show that it varies widely between buildings. For example, at the AT&T Bell Laboratories Crawford Hill building, the measured  $\tau_0$  was about 30 ns [27], and at the AT&T Bell Laboratories Holmdel building, the maximum measured  $\tau_0$  was about 250 ns [32]. The large  $\tau_0$  of the Holmdel building is partially due to a large center atrium surrounded by metal walls, while Crawford Hill may be a more typical office building. Here, we use these two buildings as examples for the calculation of the maximum data rate in buildings.

Studies [29] have shown that limits on the maximum data rate due to delay spread and limits on the coverage region due to multipath and shadow fading can be considered separately, and that the maximum data rate cannot be significantly increased by increased signal power. Thus, the results for the coverage region of narrowband systems also apply to wideband systems, and the outage probability due to delay spread is approximately constant over the coverage region.

The outage probability due to delay spread does depend on the modulation technique and pulse shaping used. For example, with phase shift keyed (PSK) modulation and a rectangular signal spectrum of width  $1/T$ , where  $T$  is the bit period, the maximum data rate for a  $10^{-1}$  outage probability at a  $10^{-1}$  BER is only 0.0022 times the inverse of the delay spread. Thus, the maximum data rate for the Holmdel and Crawford Hill buildings are only 8.8 and 75 kb/s, respectively, which are far too low for a local area network. However, by expanding the signal bandwidth relative to the symbol rate, the maximum data rate can be increased. For

\*Note that with spread spectrum very high symbol (chip) rates can be used in buildings, although the information rate is still limited by the dispersion in the channel. Here, we consider a wideband system as one in which the information bandwidth (and not just the signal bandwidth) is wide.

example, with quadrature phase shift keying (QPSK) and raised cosine signal spectrum of the same bandwidth as the PSK signal, the maximum data rate is 6 times higher, 55 and 450 kHz in the Holmdel and Crawford Hill buildings, respectively. However, the data rate is still too low for local area networks, so let us now consider the application of antenna diversity.

### Antenna Diversity with Delay Spread

Figure 7 shows an  $M$ -antenna element diversity combiner for a wideband system. The combiner is the same as for the narrowband system except that the sampling time offset  $\tau_0$  will vary with time and must be tracked as the channel characteristics change. As in the narrowband system, we now consider selection diversity, maximal ratio combining, and optimum combining.

With selection diversity, the receiver selects for detection the received signal with the largest peak amplitude at the output of the matched filter. That is, not only must the appropriate antenna be selected, but the best sampling time offset  $t_0$  must be determined and tracked. Under the assumption of independent fading at each antenna, the outage probability for selection diversity with  $M$  antennas is the outage probability for a single antenna raised to the  $M^{\text{th}}$  power [14]. For a single antenna, the outage probability is approximately proportional to the square of the data rate. Thus, for a  $10^{-1}$  outage probability, the maximum data rate is increased by a factor of 10 (or 32) with 2 (or 4) antennas, and, with selection diversity, data rates in the range of Megabits per second can be achieved in buildings.

As with narrowband systems, the outage performance of selection diversity can also be achieved with switched diversity. Also, diversity need only be implemented at the base station since switched diversity with feedback can be used for base to remote transmission.

Maximal ratio combining can be used to obtain a somewhat higher maximum data rate than selection or switched diversity. With maximal ratio combining, the received signals are weighted and combined to maximize the output signal-to-noise ratio at the sampling time. Since the weights vary with sampling time, the receiver must determine both the best sampling time and the weights for that sampling time, and track both the best sampling time and weights. Thus, maximal ratio combining is more complex in wideband systems. For a  $10^{-1}$  outage probability, maximal ratio combining increases the maximum data rate by a factor of 13 (or 45) with 2 (or 4) antennas, as compared with a nondiversity system, and is slightly better than selection diversity.

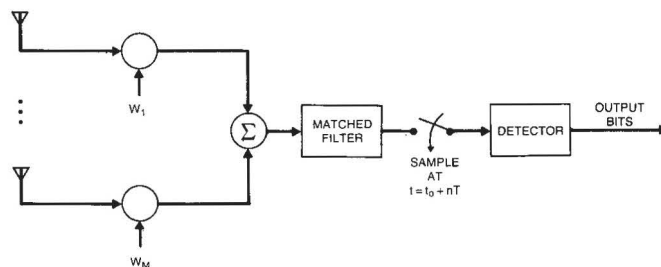


Fig. 7. Block Diagram of an  $M$  Antenna Element Diversity Combiner for Wideband Systems.



Optimum combining can be used to obtain even higher maximum data rates, since optimum combining can also maximize the signal-to-intersymbol-interference-plus-noise ratio (see [49]). However, as with maximal ratio combining, the optimum weights vary with the sampling time, and, therefore, implementation of optimum combining is a multidimensional optimization problem that, for high data rates, may be too complex to be practical. However, the maximum data rate is much higher with optimum combining as compared against other diversity techniques. For example, with 4 antennas, optimum combining permits an order of magnitude higher maximum data rate than selection diversity.

With both maximal ratio combining and optimum combining, advantages can be obtained in both transmission directions with diversity only at the base station, through the use of adaptive time division retransmission. Note, however, that this technique requires a doubling of the transmission rate in the channel, which could offset the advantages of these techniques.

### Resource Sharing

For a wideband local area network, a single high data rate channel may be time shared among the users. This allows for bursty traffic with instantaneous data rates at the data rate of the channel. With multiple users sharing the channel, at any given time a small fraction of users may experience high intersymbol interference due to delay spread, while most will not. Therefore, systems with multiple users in the same bandwidth can use resource sharing [50,51] in addition to the above techniques to increase the maximum data rate and/or decrease the outage probability. With resource sharing, users normally transmit at some high rate  $R_1$ . When channel conditions between the base station and a particular user no longer permit operation at this high rate, the rate is lowered to some value  $R_2$  such that the BER objective can be maintained. Although it takes longer to complete transmission at this lower rate, the number of users simultaneously slowed down is usually a small fraction of the total population, and the overall throughput remains high (a small pooled resource can protect a large community). At a  $10^{-4}$  outage probability, resource sharing increases the throughput (which is about the same as the maximum data rate since few users operate at the slower rate) by about the same factor as does doubling the number of antennas. Thus, if no diversity is used, resource sharing can increase the throughput by a factor of 10. If diversity with 2 (or 4) antennas is used, then resource sharing can increase the throughput by a factor of 3 (or 2). Furthermore, with resource sharing, the outage probability can be reduced to arbitrarily small values with a negligible decrease in throughput.

Finally, if the rms delay spread in a building is less than that for which a wireless system has been designed, then resource sharing can be used to partially offset the effects of multipath, thereby increasing the coverage region. In a typical building, resource sharing may thereby be able to increase the coverage region several times with only a few percent decrease in throughput. Therefore, in multiple user systems, resource sharing

can significantly reduce the required number of antennas.

Thus, through the use of well-chosen modulation and pulse shaping techniques, diversity, and resource sharing, indoor radio systems with Mbps data rates and high reliability can be practical. For our example, with a  $10^{-4}$  outage probability, 4 antenna selection diversity, and resource sharing, the maximum data rates are 3.5 and 29 Mb/s in the Holmdel and Crawford Hill buildings, respectively.

### Conclusions

Buildings present a hostile environment for radio communications, with in-building radio propagation difficult to predict and continuously changing. Problems include multipath fading, shadow fading, dispersion due to delay spread, and interference among users. We have shown that various antenna diversity techniques, in combination with other techniques, can be used to overcome these problems. For narrowband systems, antenna diversity can greatly increase the coverage region, and optimum combining with  $M$  antennas, dynamic channel assignment, and power control can eliminate interference from up to  $M-1$  interferers and/or permit up to an  $M$ -fold increase in the number of users via frequency reuse within the same coverage region. For wideband systems, a combination of well-chosen modulation and pulse shaping techniques, antenna diversity, and resource sharing permits Mbps data rates with high reliability.

### References

- [1] K. Pahlavan, "Wireless communications for office information networks," *IEEE Communications Magazine*, June 1985.
- [2] F. R. Gfeller and U. Bapst, "Wireless in-house data communication via diffuse infrared radiation," *Proc. IEEE*, vol. 67, pp. 1474-1486, Nov. 1979.
- [3] R. Eschenbach, "Applications of spread spectrum radio to indoor data communication," *Proc. Milcom '82*, pp. 34.5-1, Oct. 1982.
- [4] M. Kavehrad and P. J. McLane, "Performance of direct sequence spread spectrum for indoor wireless digital communication," *Proc. Globecom '85*, pp. 32.2.1-6, Dec. 1985.
- [5] M. Kavehrad and B. Ramamurthi, "Direct-sequence spread spectrum with DPSK modulation and diversity for indoor wireless communications," *Proc. ICC '86*, pp. 27.6.1-5, June 1986, and *IEEE Trans. on Commun.*, Feb. 1987.
- [6] M. Kavehrad, "Performance of nondiversity receivers for spread spectrum in indoor wireless communications," *AT&T Technical Journal*, vol. 64, pp. 1181-1210, July-Aug. 1985.
- [7] M. Kavehrad and P. J. McLane, "Performance of low-complexity channel coding and diversity for spread spectrum in indoor, wireless communication," *AT&T Technical Journal*, vol. 64, pp. 1927-1966, Oct. 1985.
- [8] K. F. Treen and Q. V. Davis, "The role of leaky feeders in spectrum conservation," *IEE International Conference on Radio Spectrum Conservation Techniques*, pp. 43-47, 1980.
- [9] A. J. Motley and D. A. Palmer, "Reduced long-range signal reception with leaky feeders," *Electronic Letters*, vol. 19, pp. 714-715, Sept. 1, 1983.



- [10] R. W. Gibson and R. J. Murray, "Systems organization for multichannel cordless telephones," *International Zurich Seminar on Digital Communication*, pp. 59-61, 1982.
- [11] P. D. White and T. W. F. Whiter, "A high capacity cordless telephone system," *Philips Research Laboratories Annual Review 1983*.
- [12] J. Krebs, "Portable computer and host talk over radio-frequency link," *Electronics*, pp. 142-145, August 25, 1983.
- [13] D. C. Cox, "Universal portable radio communications," *IEEE Trans. Veh. Tech.*, vol. VT-34, pp. 117-121, August 1985.
- [14] W. C. Jakes, Jr. (Ed), *Microwave Mobile Communications*, Wiley, New York, 1974.
- [15] Paul S. Wells, "The attenuation of UHF radio signals by houses," *IEEE Trans. Veh. Tech.*, vol. VT-26, pp. 358-362, Nov. 1977.
- [16] K. Tsujimura and M. Kuwabara, "Cordless telephone system and its propagation characteristics," *IEEE Trans. Veh. Tech.*, vol. VT-26, pp. 367-371, Nov. 1977.
- [17] H. H. Hoffman and D. C. Cox, "Attenuation of 900 MHz radio waves propagating into a metal building," *IEEE Trans. Antennas Propagat.*, vol. AP-30, pp. 808-811, July 1982.
- [18] D. C. Cox, R. R. Murray, and A. W. Norris, "800-MHz attenuation measured in and around houses," *B.S.T.J.*, vol. 63, pp. 921-954, July-Aug. 1984.
- [19] D. C. Cox, R. R. Murray, and A. W. Norris, "Measurements of 800-MHz radio transmission into buildings with metallic walls," *B.S.T.J.*, vol. 62, pp. 2695-2717, Nov. 1983.
- [20] S. E. Alexander, "Radio propagation within buildings at 900 MHz," *Electronic Letters*, vol. 18, pp. 913-914, Oct. 14, 1982.
- [21] S. E. Alexander and G. Pugliese, "Cordless communication within buildings: results of measurements at 900 MHz and 60 GHz," *Br. Telecom. Technol. J.*, vol. 1, pp. 99-105, July 1983.
- [22] S. E. Alexander, "900 MHz propagation within buildings," *IEE Second International Conference on Radio Spectrum Conservation Techniques*, pp. 51-55, Sept. 1983.
- [23] A. J. Motley and D. A. Palmer, "Directed radio coverage within buildings," *IEE Second International Conference on Radio Spectrum Conservation Techniques*, pp. 56-60, Sept. 1983.
- [24] R. J. Pillmeier, "In-building signal correlation for an urban environment," *Proc. Veh. Tech. Conf.*, pp. 156-161, May 1984.
- [25] P. A. Bello and B. D. Nelin, "The effect of frequency selective fading on the binary error probabilities of incoherent and differentially coherent matched filter receivers," *IEEE Trans. Commun. Syst.*, vol. CS-11, pp. 170-186, June 1963.
- [26] C. C. Bailey and J. C. Lindenlaub, "Further results concerning the effect of frequency-selective fading on differentially coherent matched filter receivers," *IEEE Trans. Commun. Technol.*, vol. COM-16, pp. 749-751, Oct. 1968.
- [27] A. A. M. Saleh and R. Valenzuela, "A statistical model for indoor multipath propagation," *IEEE Journal on Selected Areas in Communications*, vol. SAC-5, Feb. 1987.
- [28] B. Glance and L. J. Greenstein, "Frequency-selective fading effects in digital mobile radio with diversity combining," *IEEE Trans. Commun.*, vol. COM-31, pp. 1085-1094, Sept. 1983.
- [29] J. H. Winters and Y. S. Yeh, "On the performance of wideband digital radio transmission within buildings using diversity," *Proc. Globecom '85*, pp. 991-996, Dec. 2-5, 1985.
- [30] J. C-I. Chuang, "Modeling and analysis of a digital portable communications channel with time delay spread," *Proc. Veh. Tech. Conf.*, May 1986.
- [31] J. C-I. Chuang, "Simulation of digital modulation on portable radio communications channels with frequency-selective fading," *Proc. Globecom '86*, pp. 31.6.1-7, Dec. 1986.
- [32] D. M. J. Devasirvatham, "Time delay spread measurements of wideband radio signals within a building," *Electronic Letters*, vol. 20, pp. 950-951, Nov. 8, 1984.
- [33] D. M. J. Devasirvatham, "Time delay spread measurements of 850 MHz radio waves in building environments," *Proc. Globecom '85*, pp. 32.1.1-4, Dec. 1985.
- [34] D. M. J. Devasirvatham, "A comparison of time delay spread measurements within two dissimilar office buildings," *Proc. ICC '86*, June 1986.
- [35] K. H. Awadalla, "Direction diversity in mobile communications," *IEEE Trans. Veh. Tech.*, vol. VT-30, pp. 121-123, Aug. 1981.
- [36] R. T. Compton, Jr., "On the performance of a polarization sensitive adaptive array," *IEEE Trans. on Antennas and Propagation*, vol. AP-29, pp. 718-725, Sept. 1981.
- [37] D. C. Cox, "Antenna diversity performance in mitigating the effects of portable radiotelephone orientation and multipath propagation," *IEEE Trans. Commun.*, vol. COM-31, pp. 620-628, May 1983.
- [38] J. H. Winters, "Switched diversity with feedback for DPSK mobile radio systems," *IEEE Trans. Veh. Tech.*, vol. VT-32, pp. 134-150, Feb. 1983.
- [39] P. S. Henry and B. Glance, "A new approach to high capacity digital mobile radio," *B.S.T.J.*, vol. 60, pp. 1891-1904, Oct. 1981.
- [40] D. C. Cox, "Time division adaptive retransmission for reducing signal impairments in portable radiotelephones," *IEEE Trans. Veh. Tech.*, vol. VT-32, pp. 230-238, Aug. 1983.
- [41] R. C. Bernhardt and P. T. Porter, "Cost comparisons of macroscopic diversity architectures for universal digital portable communications," *Proc. Globecom '85* pp. 32.8.1-5, Dec. 1985.
- [42] R. C. Bernhardt, "RF performance of macroscopic diversity in universal digital portable radio communications," *Proc. Globecom '85*, pp. 32.7.1-6, Dec. 1985.
- [43] J. H. Winters, "Optimum combining in digital mobile radio with co-channel interference," *IEEE Journal on Selected Areas in Communications*, vol. SAC-2, pp. 528-539, July 1984 (also *IEEE Trans. Veh. Tech.*, vol. VT-33, pp. 144-155, Aug. 1984).
- [44] R. A. Monzingo and T. W. Miller, *Introduction to Adaptive Arrays*, John Wiley and Sons, New York, 1980.
- [45] J. H. Winters, "Optimum combining for indoor radio systems with multiple users," submitted to *IEEE Trans. Commun.* (also *ICC '87*).
- [46] J. H. Winters, "On the capacity of radio communications systems with diversity in a Rayleigh fading environment," *IEEE Jour. on Selected Areas in Communications* SAC-5, pp. 871-878, June, 1987.
- [47] B. Widrow, P. E. Mantey, L. J. Griffiths, and B. B. Goode, "Adaptive antenna systems," *Proc. IEEE*, vol. 55, p. 2143, Dec. 1967.
- [48] S. W. Golomb, *Shift Register Sequences*, Holden-Day, Inc., San Francisco, CA, 1967.
- [49] Y. S. Yeh and L. J. Greenstein, "A new approach to space diversity combining in microwave digital radio," *AT&T Technical Journal*, vol. 64, pp. 885-905, April 1985.
- [50] A. S. Acampora, "A shared resource TDMA approach to

influence the rain margin of 12/14 GHz satellite systems," *B.S.T.J.*, vol. 58, Nov. 1979.

- [51] A. S. Acampora, "The use of resource sharing and coding to increase the capacity of digital satellite," *IEEE Jour. on Selected Areas in Communications*, vol. SAC-1, pp. 133-142, Jan. 1983.

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