Optimum Combining for Indoor Radio Systems with Multiple Users

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Abstract—**This paper studies the use of optimum combining to increase the capacity of narrow-band in-building radio communication systems with multiple users. We consider systems consisting of a base station with numerous remotes in a Rayleigh fading environment and study the problem of more users requiring channels than the number of channels available. A system is described that, with multiple antennas at the base station but only one antenna at each remote, uses optimum combining to suppress interfering signals. We show that this system, with M antennas at the base station, can achieve an M-fold increase in the number of users or tolerate $M - 1$ interferers from other systems. Thus, with optimum combining, radio communications can be used in high-density, multiple-user environments, such as within buildings, even when only limited bandwidth is available.**

I. Introduction

Wireless in-building communication allows the user to be mobile and eliminates wiring and rewiring when adding or moving phones, terminals, etc., and reconfiguring networks. In-building radio propagation [1]–[6] is hard to predict and continuously changing, however, which makes interference management with multiple users difficult. Furthermore, since bandwidth must be shared by all users within the coverage areas (which could overlap), the capacity of a multiple-user system can be much less than that required in many office buildings.

One technique for interference reduction is optimum combining [7]. With optimum combining, the signals received by several antennas are weighted and combined to maximize output signal to interference plus noise ratio (SINR). Thus, interfering signals are suppressed and the desired signal is enhanced. Optimum combining has been shown to substantially reduce interference in mobile radio [7] where multipath fading is present and in systems without fading [8]. For in-building radio communication, there is multipath fading as in mobile radio, but the fading rate is much slower. This makes it possible to use optimum combining in combination with other techniques to further reduce interference. In addition, optimum combining can be implemented as an adaptive technique [7], so that detailed *a priori* knowledge of a building's radio environment is not required and changes in the environment are automatically tracked.

In this paper, we describe a digital in-building radio communication system that allows a large number of users in a small area. We consider a system consisting of a base station with numerous remotes and show how optimum combining, in combination with other techniques, can be used to increase the maximum number of users and eliminate interference from other systems. Computer simulation results are shown for a digital system with phase-shift-keyed (PSK) modulation and coherent detection with Rayleigh and shadow (due to blockage) fading. Narrow-band channels are assumed, i.e., the channel bandwidth is assumed to be much less than the coherence bandwidth [9]. These results show that such a system with one antenna at each remote and M antennas at the base station can achieve either an M-fold increase in capacity (over systems without optimum combining) or tolerate $M - 1$ interferers from other systems.

Section II describes the multiple-user system proposed in this paper and calculates the interference tolerance of the system without optimum combining. In Section III, we describe optimum combining and calculate the increase in capacity and interference tolerance with optimum combining in the system. A summary and conclusions are presented in Section IV.

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II. A Basic System for Multiple Users

Fig. 1 shows the system to be analyzed in this paper for in-building radio communication in a multiple-user environment. Multiple remotes communicate with a base station via radio, with the radio channel characterized by multipath (Rayleigh) and shadow fading. Each user uses a single frequency channel, i.e., frequency-division multiple access (FDMA) is used in multiple channel systems. (As discussed in Section III, the system can also have multiple users per frequency channel by using a form of space-division multiple access, i.e., through the use of optimum combining since the remotes are physically separated.) As described in detail in Section III, the base station has multiple antennas (antenna diversity), while each remote has only one antenna. As discussed below, dynamic channel assignment and transmit power control are also used.

Let us first consider dynamic channel assignment [9] to increase the average number of users in a multiple-user system and transmit power control [9] to reduce adjacent channel interference, and determine the interference tolerance of such a system without optimum combining (i.e., without antenna diversity). For a multiple-user system with multiple channels, dynamic channel assignment [9] is required for efficient channel usage. With this method, before transmission begins, the channels are scanned to find a quiet channel (one with little or no interference) for channel assignment. Furthermore, during transmission, the assigned channel is continuously monitored for interference, 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, the environment changes (e.g., doors are closed or opened), or as other users move or begin transmission. Thus, with dynamic channel assignment, interference does not affect the outage performance of the system as long as there are quiet channels available.

Another technique to reduce interference among users is power control. 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

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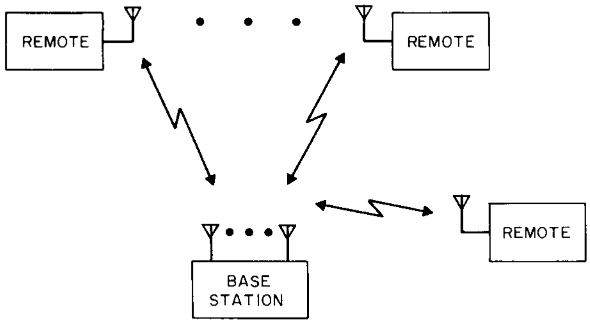

Fig. 1. The multiple-user radio system.

interference problem. The problem can be reduced by adaptively controlling each remote's transmit power 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.

We now consider the effect of interference on a digital communication system using PSK modulation and coherent detection. In general, for voice communications, good voice quality can be maintained at a bit error rate (BER) less than 10^{-2}. In this paper, we conservatively consider a 10^{-3} BER. For data communications, we assume coding could be used to reduce the error rate to a more acceptable value. The BER for coherent detection of a PSK signal in white Gaussian noise is given by [10, p. 381]

$$\mathrm{BER} = \frac{1}{2} \operatorname{erfc}(\sqrt{S/N}) \tag{1}$$

where S/N is the signal-to-noise ratio. Thus, a 6.8 dB S/N is required for a 10^{-3} BER.

Next, consider the effect of a PSK interfering signal with a phase difference θ from the desired signal. The worst case interference occurs when the bit timing for the interfering and desired signals are equal. In this case, the received demodulated signal is modified by the factor $1 + \sqrt{I/S} \cos\theta$ where I/S is the interference to desired signal power ratio,[1] and therefore, the BER is given by

$$\mathrm{BER} = \frac{1}{2} \operatorname{erfc}(\sqrt{z(\theta)}) \tag{2}$$

where

$$z(\theta) = S/N(1 + \sqrt{I/S} \cos\theta)^2. \tag{3}$$

The phase difference θ changes with the modulating bits and varies slowly with time for small frequency offsets between the two signals. We therefore assume that θ has a uniform probability distribution. Thus, the BER averaged over θ is given by

$$\mathrm{BER} = \frac{1}{\pi} \int_0^\pi \frac{1}{2} \operatorname{erfc}(\sqrt{z(\theta)})\, d\theta \tag{4}$$

where $z(\theta)$ is given by (3). Thus, from (4), we can determine the maximum I/S that can be tolerated for a given BER.

Fig. 2 shows I/S versus S/N for a 10^{-3} BER. (Multiple interferer results are discussed in the Appendix.) That is, the figure shows the maximum I/S that can be tolerated for a given S/N and a 10^{-3} BER. For the single interferer case, the maximum I/S increases from -20 to -5 dB with a 5 dB increase in S/N (from 7 to 12 dB). Thus, by increasing transmitter power, we can significantly increase the interference tolerance. However, this works only up to a limit since the single antenna system cannot tolerate an interferer stronger than the desired signal no matter how high the S/N.

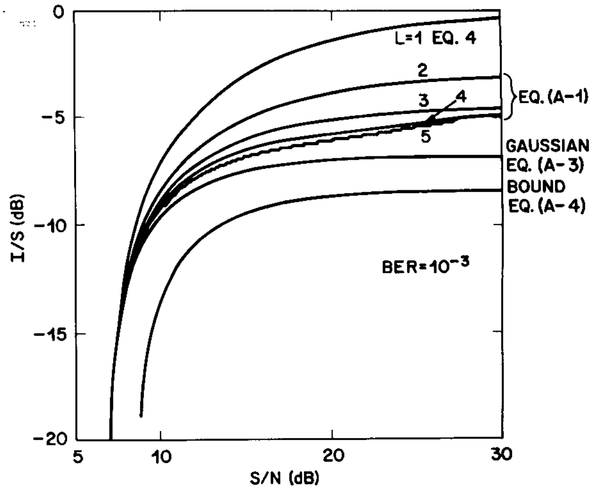

Fig. 2. The interference to desired signal power ratio versus signal-to-noise ratio for a 10^{-3} BER.

Because the signal propagation in buildings varies substantially with position, it is a very real possibility that interfering signals from nearby systems could be stronger than the desired signal. Thus, even if the capacity of a single antenna system were adequate for an office, interference from nearby systems could easily block channels, thereby reducing capacity or abruptly terminating transmissions.

Thus, from both a capacity and interference standpoint, a single antenna system is inadequate for offices.

III. Multiple Antenna Systems

A. Optimum Combining

1) Overview: Interference at the receiver can be reduced with optimum combining. With this technique, the signals received by several antennas are weighted and combined to maximize output signal to interference plus noise ratio. Thus, diversity (e.g., space [9, p. 310], direction [9, p. 311, 11], polarization [9, p. 311, 12], or field [9, p. 148] [see Section III-D]) is used to suppress interfering signals and enhance desired signal reception.

Optimum combining has been shown to substantially reduce interference in systems both with [7] and without [8] signal fading. Our proposed indoor radio system falls somewhere between these two cases because, although there is fading, we compensate for it by adjusting the transmit power (see Section II).

Without fading, optimum combining can null $M - 1$ interferers with M antennas if the angular separation of the desired and interfering signals is large enough. With fading, as in mobile radio, 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 desired signal powers and phases differ somewhat from the received interfering signal powers and phases at more than one antenna. Thus, in a system using several antennas for space, direction, polarization, and/or field diversity, the probability of being unable to suppress an interfering signal is very small. Furthermore, since with dynamic channel assignment the channel can be changed if the interference cannot be suppressed, systems with optimum combining can overcome most interference problems.

As discussed in [7], optimum combining need only be used

[1] Note that we are assuming perfect phase synchronization at the receiver. This is discussed further in Section III-D.

at the base station receiver. Adaptive retransmission with time division [9], [13] can be used to improve reception at the remote without requiring multiple remote antennas. With adaptive retransmission, the base station transmits at the same frequency as it receives, using the complex conjugate of the receiving weights. With time division, a single channel is time shared by both directions of transmission. Thus, with optimum combining, during transmission from the remote to the base station, the antenna element weights are adjusted to maximize the signal to interference plus noise ratio at the receiver output. During transmission from the base to the remote, the complex conjugate of the receiving weights are used so that the signals from the base station antennas combine to enhance reception of the signal at the desired remote and to suppress this signal at other remotes. Thus, we can achieve the advantages of optimum combining at both the remote and the base station with multiple antennas at the base station only.[2]

As discussed above, a system with optimum combining can suppress interfering signals with a high probability even if their power is equal to or greater than that of the desired signal. Therefore, with optimum combining, several signals can use the same channel simultaneously, thus increasing capacity. Also, signals from other systems can be suppressed even if they are stronger than the desired signal. These topics are discussed in detail in Sections III-B and III-C.

2) Description and Weight Equation: Fig. 3 shows a block diagram of an M antenna element diversity combiner. The signal received by the ith element $y_i(t)$ is split with a quadrature hybrid into an in-phase signal $x_{I_i}(t)$ and a quadrature signal $x_{Q_i}(t)$. These signals are then multiplied by a controllable weight $w_{I_i}(t)$ or $w_{Q_i}(t)$. The weighted signals are then summed to form the array output $s_0(t)$.

Let the received interference-plus-noise correlation matrix be given by

$$R_{nn}=\sigma^2 I+\sum_{j=1}^{L} u_j^* u_j^T \tag{5}$$

where σ^2 is the noise power, I is the identity matrix, L is the number of interferers, u_j is the jth interfering signal propagation vector, and the superscripts * and T denote conjugate and transpose, respectively. In (5), the correlation is over a period much less than the reciprocal of the fading rate, i.e., u_j and u_d [in (5)–(10)] are assumed to be reasonably constant over the period in which the bit error rate is calculated. Note that we have assumed the fading rate is much less than the bit rate. The equation for the weights that maximize the output SINR is then (from [14]) (see [7])

$$w=\alpha R_{nn}^{-1} u_d^* \tag{6}$$

where w is the complex weight vector, α is a constant,[3] the superscript -1 denotes the inverse of the matrix, and u_d is the desired signal propagation vector.

3) Preliminary Assumptions and Analysis: In this study, we will assume independent Rayleigh fading (due to multipath) at each antenna with the same shadow or obstruction fading at each antenna for a given signal. Of course, the fading produced by multipath may not be Rayleigh in all locations in all buildings. However, it must be stressed that optimum combining always maximizes the signal to interference plus noise ratio, even if the fading is not Rayleigh.

With independent Rayleigh fading at each antenna and transmit power control as discussed in Section II, the desired

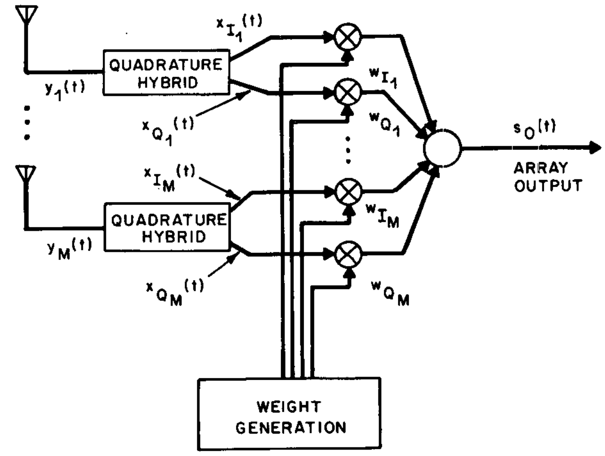

Fig. 3. Block diagram of an M antenna element diversity combiner.

signal propagation vector is given by

$$u_d=\begin{bmatrix} u_{d_1} \\ \vdots \\ u_{d_M} \end{bmatrix}=\begin{bmatrix} \dfrac{P_{rd}}{\sum_{j=1}^{M} |v_{d_j}|^2} \end{bmatrix}^{1/2} \begin{bmatrix} v_{d_1} \\ \vdots \\ v_{d_M} \end{bmatrix} \tag{7}$$

where the v_{d_i} are independent complex Gaussian random variables and $P_{rd}\ (=u_d^T u_d^*)$ is the total received desired signal power. Note that because of transmit power control, the components of u_d are not independent. Although the phases of the components are independent, the amplitudes (and, therefore, the powers) are dependent. The interfering signal propagation vectors (the u_j's) for the interfering users in a multiple users per channel system have the same characteristics as u_d in (7). For interference from other systems, the characteristics of the u_j's can vary widely, however. In Section III-C, we study the system performance with fixed total received power for each interferer, i.e., the u_j's have the same characteristics as u_d in (7), but with a total received power (P_{rd}) that can be different from the desired signal.

4) SINR and BER: We are interested in achieving the lowest possible BER for the digital system. The optimum combiner, however, maximizes the SINR. With Gaussian interference and noise, maximizing the SINR does indeed minimize the BER. However, in our system, the interference is one or more PSK signals. Therefore, maximizing SINR does not necessarily minimize the BER, although it substantially reduces the BER. Thus, since no simple formula currently exists for determining the weights that minimize the BER [from (3), (4), (A-1), and (A-2) note that the BER is a complicated function of S/N and I/S],[4] optimum combining is used.

As discussed above, interference has a different effect from noise on the BER. In fact, the effect of interference depends on the noise and vice versa, as shown in Fig. 2. Thus, in our analysis, we first determined the weights that maximize SINR and then determined the I/S and S/N at the optimum combiner output. The BER can then be determined from (4) for $L = 1$ and (A-1) for multiple interferers.

For the diversity combiner of Fig. 3, it can be shown that the interference to desired signal power ratio I/S and the desired signal-to-noise ratio S/N at the array output are given by

$$I/S=\frac{\sum_{j=1}^{L} |w^\dagger u_j^*|^2}{|w^\dagger u_d^*|^2} \tag{8}$$

[2] Note that for adaptive retransmission to be completely effective, all systems within range must use optimum combining and adaptive retransmission with synchronized time division (see Section III-D).

[3] Note that α does not affect the performance of the optimum combiner, and therefore we will not consider its value.

[4] Note that optimum combining does minimize the upper bound on the BER given in (A-4) and the BER approximation for the interference considered to be the same as Gaussian noise (A-3).

and

$$S/N = \frac{|w^\dagger u_d^*|^2}{\sigma^2 w^\dagger w}, \tag{9}$$

respectively, where w is given by (6) and the superscript † denotes complex conjugate transpose. Note that without interference ($L = 0$), from (5) and (6),

$$w = \frac{\alpha}{\sigma^2} u_d^*, \tag{10}$$

and therefore, noting that $P_{rd} = u_d^T u_d^*$, from (9),

$$S/N = \frac{P_{rd}}{\sigma^2}. \tag{11}$$

With interference, optimum combining causes the S/N to be slightly less than that of (11), while the I/S is substantially less than that received at each antenna.

Assuming an acceptable channel unless the BER exceeds 10^{-3}, we are interested in the probability that the BER is less than 10^{-3} (and not interested in the average BER). That is, we are interested in the probability that a given channel can be used. This is, of course, the probability that S/N and I/S are below the curves of Fig. 2. In Sections III-B and III-C, we calculate this probability and from it determine capacity and interference tolerance.

B. Multiple Users Per Channel

As discussed previously, because optimum combining can suppress signals even when their power is equal to or greater than that of the desired signals, multiple users per channel are possible. Thus, a much higher capacity than that for single antenna systems can be achieved. In this section, this capacity is determined.

The proposed system with multiple users per frequency channel has one base station with M ($M > 1$) antennas and multiple remotes with one antenna each. The base station has, for every remote's transmitted signal, an optimum combiner 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. All the signals are, of course, desired at the receiver.

The capacity of multiple users per channel systems was calculated by first using Monte Carlo simulation to determine the probability that (for a given received signal-to-noise ratio and number of antennas) a given number of users can use the same frequency channel simultaneously. From this probability, we then calculated the probability that, with a given number of simultaneous users, another user can be added to the channel. Finally, these results were used to determine the capacity of systems with a 0.01 blocking probability (i.e., 99 percent availability was considered in our study).

The analysis uses the following notation. Let K be the number of simultaneous users per channel (all with BER < 10^{-3}). Also, let Γ_d and Γ_j be the average received signal-to-noise ratio per antenna for the desired and jth interfering signals, respectively. Thus, $\Gamma_d = P_{rd}/M\sigma^2$, and for the multiple users per channel system, $\Gamma_j = \Gamma_d$ for $j = 1, L$ and $L = K - 1$. Our results are given as a function of Γ_d. This is because Γ_d determines the required transmit power of the remotes or, alternatively, with fixed maximum transmit power, the maximum range. Note that a 6.8 dB S/N is required for a 10^{-3} BER, and assuming a cubic law of signal strength falloff with distance, a 9 dB increase in required Γ_d with fixed transmit power implies a 50 percent range reduction.

The probability P_K that K users can simultaneously use the same channel was determined by computer simulation. A large number of cases (corresponding to randomly positioned remotes) were generated, and the probability was calculated by determining the proportion of cases in which all signals had a BER less than 10^{-3}. Thus, for each case, the following procedure was employed. First, signal propagation vectors were generated for each signal by

1) generating independent complex Gaussian random numbers, and
2) calculating u_d from (7).

Second, with these signals vectors, it was determined whether the desired signal at the output of every optimum combiner had a BER less than 10^{-3} by, for each signal,

1) designating the signal as the desired signal and all others as interfering signals,
2) calculating the optimum weights (6),
3) calculating S/N and I/S [(8) and (9)], and
4) determining if S/N and I/S were below the appropriate curve of Fig. 2.

Figs. 4–7 show the probability that K users can use the same channel simultaneously versus the average received desired signal-to-noise ratio per antenna with two–nine antennas. Ten thousand cases per data point were used. To conserve computer time, only up to six simultaneous users were considered. The figures show that one user per channel is always possible if Γ_d is greater than 7–10 $\log_{10} M$ dB, and that for $K > 1$, the probability of accommodating K simultaneous users increases with Γ_d. M users per channel with high probability are possible if Γ_d is increased by up to 20 dB, with higher values of K possible only at a much lower probability. Note that as the number of antennas increases, smaller increases in Γ_d are required for multiple users at a high probability. For example, with nine antennas, an increase in Γ_d of only 10 dB is required for a six-fold increase in capacity. For fixed transmit power in a typical building, this represents about a 50 percent reduction in maximum range.

We now consider the probability $P_{K/K-1}$ of being able to add the Kth user (with BER < 10^{-3} for all K users). That is, $P_{K/K-1}$ is the probability that one more user can use the same channel given that $K - 1$ users are using the channel. This probability can be derived from the previous results by noting that the BER for each of the existing $K - 1$ users can only be increased (not decreased) by adding an additional interferer. Thus, the cases where BER < 10^{-3} with K users are a subset of the cases where BER < 10^{-3} with $K - 1$ users, and the probability of adding the Kth user is P_K/P_{K-1}.

Fig. 8 shows the probability that a Kth user can be added to a channel versus the received desired signal-to-noise ratio per antenna for six receive antennas. This probability is similar to the probability for K simultaneous users (Fig. 6) because the probability of adding the Kth user successfully is usually much less than that for the $K - 1$ user. Similar results were obtained for two, four, and nine receive antennas.

The blocking probability for a single channel with capacity K is defined here as the probability that a Kth user cannot be added to the system,[5] i.e., for a one-channel system ($N = 1$),

$$B = 1 - P_{K/K-1}. \tag{12}$$

Thus, the call blocking probability for a single channel can be calculated directly from the above results.

Fig. 9 shows the capacity (maximum number of simultaneous users) versus Γ_d for a single-channel system with a 0.01 blocking probability. The figure shows that the increase in Γ_d required for each additional user becomes smaller as the

[5] This is actually the worst case blocking probability for the capacity K system since the blocking probability is substantially less when there are fewer than $K - 1$ users.

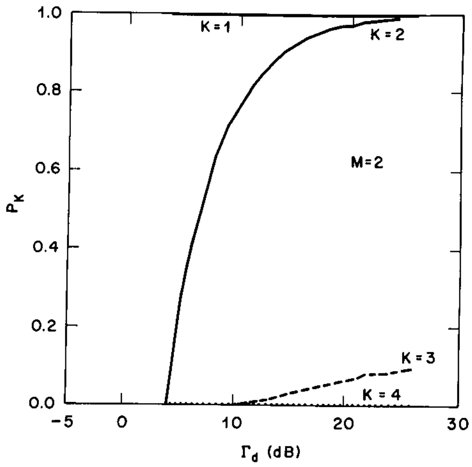

Fig. 4. Probability that K users can simultaneously use the same channel with a BER less than 10^{-3} versus received desired signal-to-noise ratio per antenna for $M = 2$ receive antennas.

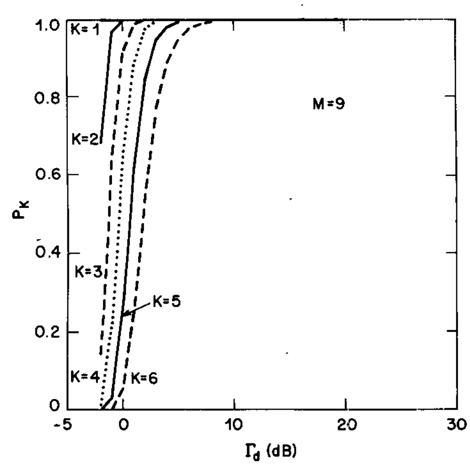

Fig. 7. Probability that K users can simultaneously use the same channel with a BER less than 10^{-3} versus received desired signal-to-noise ratio per antenna for $M = 9$ receive antennas.

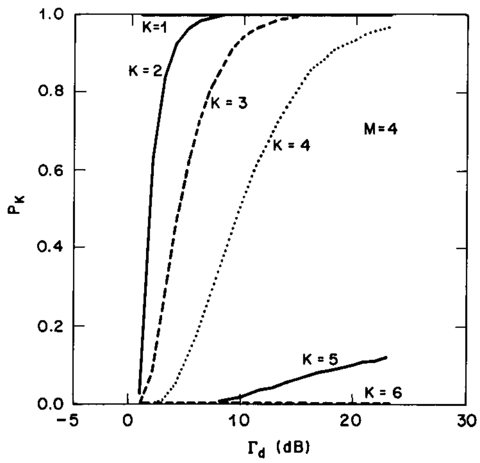

Fig. 5. Probability that K users can simultaneously use the same channel with a BER less than 10^{-3} versus received desired signal-to-noise ratio per antenna for $M = 4$ receive antennas.

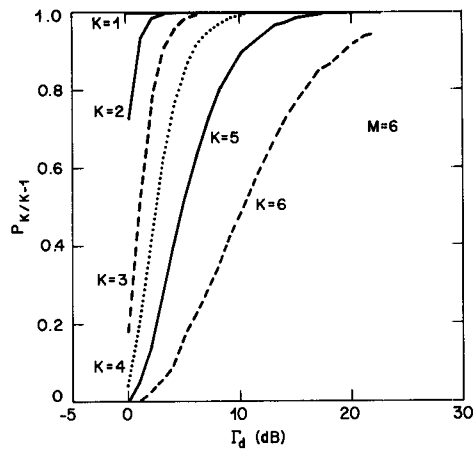

Fig. 8. Probability that a Kth user can be added to a channel that already has $K - 1$ users with the BER less than 10^{-3} for all K users versus received desired signal-to-noise ratio per antenna for $M = 6$ receive antennas.

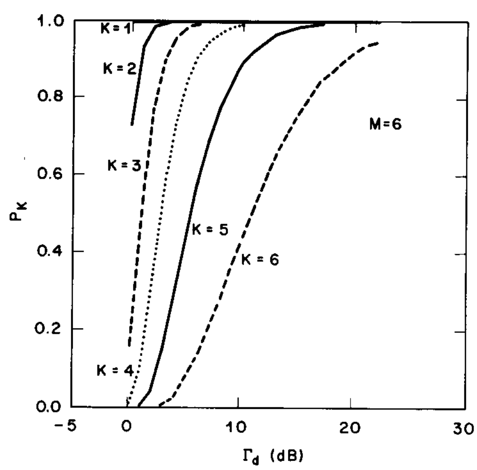

Fig. 6. Probability that K users can simultaneously use the same channel with a BER less than 10^{-3} versus received desired signal-to-noise ratio per antenna for $M = 6$ receive antennas.

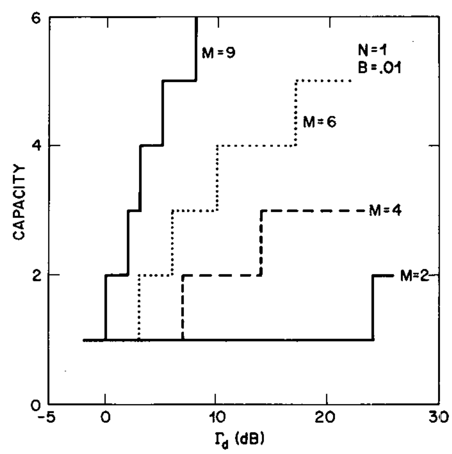

Fig. 9. The capacity (maximum number of simultaneous users) versus Γ_d for a single-channel system with a 0.01 blocking probability for several values of M.

number of antennas increases. For example, five users with six antennas require $\Gamma_d = 17$ dB, while with nine antennas, only 5 dB is required. Also, the results show that close to M users are possible, but only with a substantial increase in Γ_d as compared to the single-user system. However, multiple users with a small Γ_d penalty are possible if the capacity is much less than M.

We now study the capacity of multiple channel systems ($N > 1$) where N is the number of channels. Because of dynamic channel assignment, the capacity for a given blocking probability is greater than just N times the capacity of a single-channel system. In fact, with dynamic channel assignment, there may be many users in one channel and only a few in another. However, to simplify the analysis, we will assume that all channels have K users before any have $K + 1$ users. This is a worst case model since the capacity is greater if the number of users in each channel is more unevenly distributed. Our results are, therefore, somewhat pessimistic.

Consider an N-channel system with $N - (l - 1)$ channels with K users per channel and $l - 1$ channels with $K + 1$ users per channel ($0 < l \leq N$). Then the total number of users is $NK + (l - 1)$, and the blocking probability for the next user is given by

$$B = (1 - P_{K+1/K})^{N-(l-1)}(1 - P_{K+2/K+1})^{l-1}. \quad (13)$$

That is, (13) is the call blocking probability for a system with capacity $NK + l$. Thus, from the previous results in this section and (13), the capacity (maximum number of users) for a given blocking probability can be determined.

As an example, consider an eight-channel system. Fig. 10 shows the capacity versus Γ_d with a 0.01 blocking probability for several values of M. This figure shows that an M-fold increase in capacity can be achieved with M antennas if Γ_d is increased by as much as 20 dB (for $M = 2$). However, the required increase in Γ_d decreases with more antennas. Furthermore, for less than an M-fold capacity increase, the Γ_d penalty is significantly less. For example, with nine antennas, a five-fold increase in capacity is possible with only a 3 dB increase in Γ_d. Note that as the number of channels increases, for the same blocking probability, the required Γ_d decreases.

The results can be generalized as follows. In systems with Rayleigh fading, an M-fold capacity increase is obtained because $M - 1$ signals are nulled by each optimum combiner. Thus, the number of signals that can be nulled is the same as that in a nonfading environment ($M - 1$). We might therefore expect that our results would be valid even if the fading were not Rayleigh and/or there were more than nine antennas. However, such results need to be verified in a practical system.

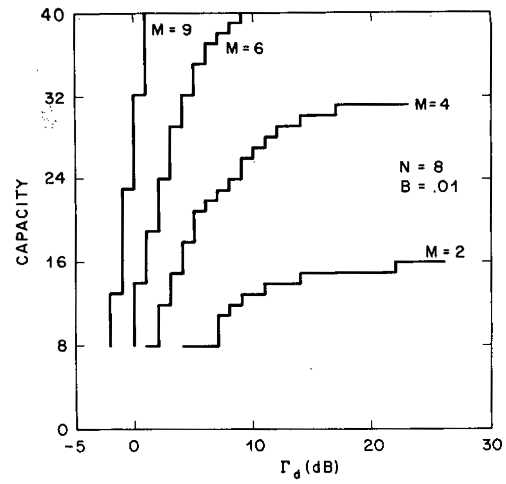

Fig. 10. The capacity (maximum number of simultaneous users) versus Γ_d for an eight-channel system with a 0.01 blocking probability for several values of M.

C. Interference

In this section, we determine the number and power of interfering signals that can be tolerated by the optimum combiner. We first describe how the results were generated and discuss the effect of interference on the optimum combiner. Next, results are shown for the maximum level of interference for a 0.01 blocking probability with L equal power interferers and M antennas. Finally, we determine the maximum number of interferers at any power that can be tolerated.

The probability that L interferers of equal average received power (Γ_j) block a channel for the desired signal was determined by computer simulation. A large number of cases (corresponding to randomly positioned remotes) were generated, and the probability was calculated by determining the proportion of cases in which the single desired signal had a BER greater than 10^{-3}. The method used was the same as that described in Section III-B, except that there is only one desired signal and the power of the interferers is not necessarily equal to the desired signal power. Results for the maximum interference power for a given blocking probability were obtained by increasing the interference power (in 1 dB steps) until the blocking probability exceeded the given value.

The weights are affected by the power of the interference as shown in (5) and (6). If $\Gamma_j < 1$ (i.e., the power of the interference is less than that of the noise), the interference has little effect on the weights, and the interference-to-noise ratio at the optimum combiner output is close to that at the input. However, when $\Gamma_j > 1$, the weights are adjusted to suppress the interference in the output to a level far below the noise. In this case, increasing the received interference power decreases the interference-to-noise ratio at the optimum combiner output.

The optimum combiner can greatly suppress (far below the noise level) interferers and not greatly suppress the desired signal if the received desired signal phases differ somewhat from the received interference signal phases at more than one antenna. With multiple antennas and multipath, it is very unlikely that the phases will be the same. Therefore, the probability of the optimum combiner being unable to null the interference is negligible. However, interference nulling does reduce the output desired signal-to-noise ratio. Thus, call blocking occurs when S/N is reduced to less than 7 dB (i.e., BER $> 10^{-3}$) with high received interference power. The optimum combiner can therefore tolerate interference at any power[6] with high probability if Γ_d is large enough.

These points are illustrated in Fig. 11 for $M = 4$. This figure shows the maximum Γ_j/Γ_d versus Γ_d for a blocking probability of 0.01 with eight channels. Thus, the probability of call blocking in one channel is 0.56 [$(0.56)^8 \approx 0.01$]. Results show that the system can tolerate $M - 1$ ($=3$) interferers at any power if Γ_d is 7 dB greater than that required without interference. With M or more interferers, the optimum combiner can only tolerate interference that has power approximately equal to that of the desired signal even with very high Γ_d. Similar results were obtained for $M = 2$ and 4 with $N = 1$ and 8.

From the above results, the Γ_d required for the system to tolerate L interferers at any power can be determined. Fig. 12 shows the maximum number of interferers at any power versus Γ_d for a blocking probability of 0.01 with one channel. The figure shows that close to $M - 1$ interferers can be tolerated with large increases in Γ_d.

[6] In a hardware implementation, the maximum interference power that can be tolerated is usually limited to 40–80 dB.

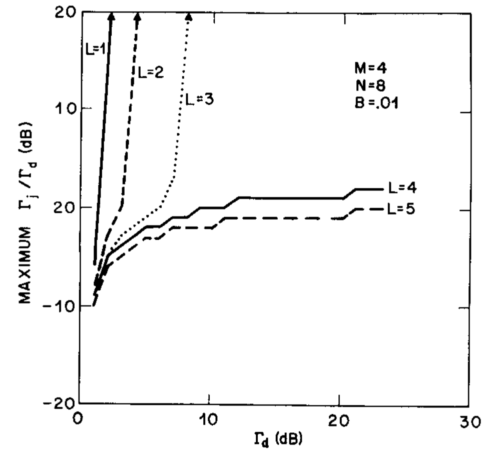

Fig. 11. The maximum Γ_j/Γ_d versus Γ_d for a blocking probability of 0.01 with eight channels and four antennas.

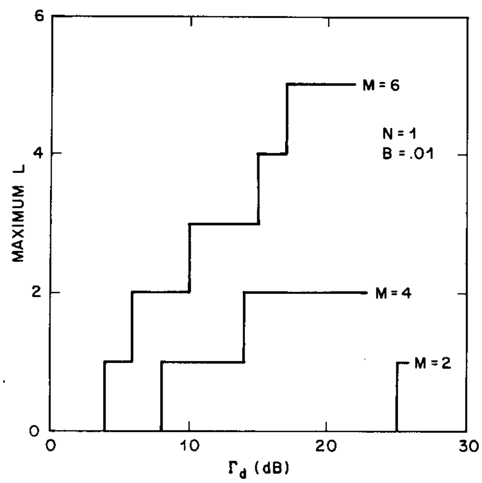

Fig. 12. The maximum number of interferers at any power versus Γ_d for a blocking probability of 0.01 with one channel and M = six, four, and two antennas.

Fig. 13 shows the maximum number of interferers at any power versus Γ_d for a blocking probability of 0.01 with eight channels. $M - 1$ interferers can be tolerated with $M = 2$, 4, and 6 and increases in Γ_d of only 3, 7, and 8 dB, respectively.

Thus, the results in this section show that $M - 1$ interferers at any power can be tolerated with a several dB increase in Γ_d if $M \leq 6$. Since these results are similar to those for a nonfading environment (where up to $M - 1$ interferers can be nulled), we might again expect that our results would be valid, even if the fading were not Rayleigh and/or there were more than six antennas.

D. Implementation

For the system with optimum combining to be practical, the antenna array at the base station must not require a large area. The separation for (nearly) independent fading at each antenna is one-quarter wavelength ($\lambda/4$, e.g., 8 cm at 900 MHz and 1.5 m at 50 MHz). Thus, with space diversity [9, p. 310], an array of M antennas requires a $\lambda/4(\sqrt{M} - 1)$ by $\lambda/4(\sqrt{M} - 1)$ area. Furthermore, direction [9, p. 311, 11], polarization [9, p. 311, 12], or field diversity [9, p. 148] can also be used. With these diversity schemes, antennas can be added without increasing the physical size of the antennas array. For example, with polarization diversity in addition to space diversity, the number of antennas can be tripled (three orthogonally polarized antennas for each space diversity antenna) without any change in the area of the array. Thus,

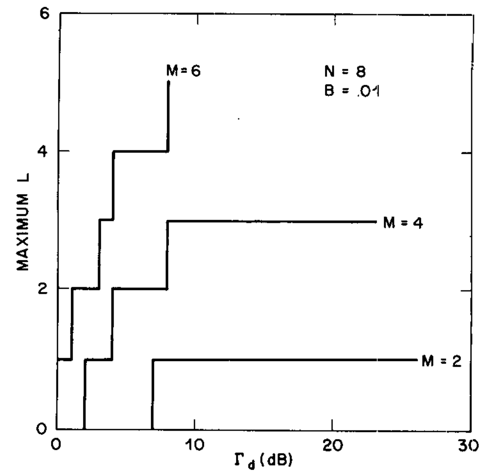

Fig. 13. The maximum number of interferers at any power versus Γ_d for a blocking probability of 0.01 with eight channels and M = six, four, and two antennas.

with a mixture of diversity techniques, a large number of antennas can be placed in a relatively small area.

Optimum combining can be implemented for in-building systems in the same way as in mobile radio [7]. The optimum combiner can be implemented with an LMS [15], [16] adaptive array. Signals can then be distinguished at the base station by different pseudonoise codes, with these codes added to the biphase PSK signal with an orthogonal biphase PSK signal (see [17]).

The pseudonoise codes that are used to distinguish signals are also useful for carrier recovery. The received signal can be mixed with the code to generate a narrow-band signal for carrier recovery. Because of the processing gain with the code, the narrow-band signal will have a high signal to interference plus noise ratio, even when I/S at the receiver output is high. Therefore, the receiver can track the signal phase with little phase jitter even when I/S at the receiver output is close to 1.

A major difference between in-building systems and mobile radio is the fading rate. In mobile radio, the fading rate is about 70 Hz. Thus, the weights must adapt in a few milliseconds. In buildings, however, the fading rate is much less. For example, a 1.5 m/s velocity (i.e., walking with the remote) produces a 4.5 Hz fading rate at 900 MHz and a 0.25 Hz fading rate at 50 MHz. Thus, the weights can be adapted much more slowly, making implementation of the LMS algorithm on a chip much easier. Furthermore, because the fading rate is less, the dynamic range of the LMS adaptive array is greater. That is, the receiver can operate with higher interference to desired signal power ratios. Using the analysis of [7], we can show that the maximum interference to desired signal power ratio is on the order of 30 dB for a 4.5 Hz fading rate as compared to 20 dB for mobile radio. If greater dynamic range is required, other (more complicated) techniques [8] may be used because rapid adaptation is not required.

As noted in Section III-A1), for adaptive retransmission to be completely effective (i.e., same BER at the remote as at the base station), two requirements are placed on the systems. First, all transmissions must be synchronized. That is, all remotes must transmit at the same time, and all base stations must transmit at the same time. With one base station and multiple remotes, synchronization is not a problem. However, with multiple base stations, there should be synchronization between systems within the same building. A second requirement is that all base stations use optimum combining with adaptive retransmission. If another system did not use this technique, it could interfere with the base-to-remote transmissions[7] of other systems on a channel. However, the system without optimum combining could suffer interference on both transmission paths. Therefore, in high-density multiple-user environments, systems could not operate without optimum combining, and would be required to use optimum combining with adaptive retransmission.

In this paper, we have studied only the steady-state performance of the optimum combiner. In an actual system, the base station receiver must track both the desired and interfering signals. Although the dynamics of in-building radio communications are slow, the movement of the remotes will affect the performance of the LMS adaptive array (or any other implementation of the optimum combiner). Thus, the transient performance of the system should also be studied.

Finally, in this paper, we have studied the performance of the base station receiver only. A brief analysis (not presented in this paper) shows that the BER at the remote should be similar to that at the base station (for adaptive retransmission with time division). Computer simulation is needed, however, to verify that when the BER is less than 10^{-3} at the base station, it is also less than 10^{-3} at the remote.

IV. Summary and Conclusions

In this paper, we have studied multiple-user in-building radio communication systems. We described a multiple-user system and showed that optimum combining can be used to increase the capacity and interference tolerance of the system. Computer simulation results showed that with optimum combining, a system with one antenna at each remote and M antennas at the base station can achieve either an M-fold increase in capacity or tolerate $M - 1$ interferers. Finally, we discussed implementation of the system and showed that the system was practical for the office environment.

Appendix

Extending the results of Section II, we can see that with L interferers, the BER is

$$\text{BER} = \frac{1}{\pi^L} \int_0^\pi \cdots \int_0^\pi \frac{1}{2} \operatorname{erfc}\left(\sqrt{z(\theta_1, \cdots, \theta_L)}\right) d\theta_1 \cdots d\theta_L \quad \text{(A-1)}$$

where

$$z(\theta_1, \cdots, \theta_L) = S/N\left(1 + \sqrt{I_1/S}\cos\theta_1 + \cdots + \sqrt{I_L/S}\cos\theta_L\right)^2 \quad \text{(A-2)}$$

and I_i/S is the interference to desired signal power ratio of the ith interferer. Note that the total interference to signal power ratio I/S is $\Sigma_{i=1}^{L} I_i/S$. There are two problems with (A-1) and (A-2), however. First, the BER depends not only on the total interference to signal power ratio, but on the individual interference powers as well. However, it was concluded (although not proved) in [18] and [19] that for fixed total interference power, the highest BER is achieved with equal power interferers, i.e., $I_i/S = (1/L)I/S$ for $i = 1, L$. Therefore, we considered equal power interferers as a worst case and generated an approximate lower bound for maximum I/S versus S/N for a 10^{-3} BER.

A second problem is that for numerical evaluation of (A-1), computer time grows exponentially with L, and therefore, calculations are only practical for small values of L. Another formula for the BER is given in [18], which uses a series rather than integration. Unfortunately, the series has convergence problems (on a digital computer) for most of the cases of interest in this paper. Thus, (A-1) was used to calculate the BER, but only for $L \leq 5$. Fig. 2 shows the results. Note that for large S/N with $L = 5$, there appears to be some error in the curve. (For $L = 5$, the error could not be determined because of the extensive computer time required.) However, this error does not affect our results for the reasons discussed below. We also considered two other BER equations. First, for large L, the interference can be considered to be the same as Gaussian noise [18], and therefore, the BER is given by

$$\text{BER} = \frac{1}{2} \operatorname{erfc}\left(\sqrt{\frac{1}{(S/N)^{-1} + I/S}}\right) \quad \text{(A-3)}$$

Results using this approximation are given in Fig. 2. Second, an upper bound on the BER with interference for any number of interferers is given by [20]

$$\text{BER} \leq \exp\left[-\frac{1}{(S/N)^{-1} + I/S}\right] \quad \text{(A-4)}$$

Results using this upper bound are also shown in Fig. 2. Note that this bound is not very tight for small I/S; from this bound, the S/N is 8.4 dB at a 10^{-3} BER (without interference, $I/S = 0$), while the actual S/N required [from (1)] is 1.6 dB less.

Fig. 2 shows that the maximum I/S varies significantly with the BER equation used. (Equations (A-1) and (A-2) with equal power interferers were used for the results presented in Figs. 4–13.) However, our results for the optimum combining system (with M antennas and L interferers) for $L < M$ in Figs. 4–13 and our conclusions do not depend on the BER equation used. This is because, for $L < M$, the number of degrees of freedom in the adaptive array using optimum combining is greater than or equal to the number of interferers, and therefore, the array can usually greatly suppress the interferers without affecting the desired signal. Therefore, the I/S at the array output is small, and, if the S/N is large enough, the BER is less than 10^{-3}. Thus, the array usually operates in the small I/S region where the required S/N is about the same for all the BER equations (except for the upper bound (A-4) where the required S/N is 1.6 dB higher). We verified that our results for $L \leq M$ in Figs. 4–13 were not significantly changed by the I/S curve used, except that the S/N was 1.6 dB higher for the I/S curve from (A-4).

For $L \geq M$, the number of degrees of freedom in the array is less than the number of interferers, and therefore, the array cannot greatly suppress all the interferers in most cases. Thus, the variation in maximum I/S at high S/N has a dramatic effect on the results. As noted above, the results in this paper are based on (A-1) with equal power interferers, and thus, our results should be conservative for $L \geq M$. However, our conclusions (an M-fold increase in capacity and suppression of $M - 1$ interferers) are based on the $L < M$ case, and therefore, do not depend on which BER equation is used.

[7] It would not interfere with remote-to-base transmissions of systems with optimum combining, however, as optimum combining suppresses any interference.

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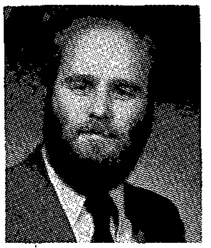

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