A Wireless Network for Wide-Band Indoor Communications

ANTHONY S. ACAMPORA, MEMBER, IEEE, AND JACK H. WINTERS, MEMBER, IEEE

Abstract—**We propose and analyze a wide-band indoor communication system that uses radio as the transmission medium either on a stand-alone basis or to supplement a hard-wired network for those situations where complete portability is desired. One principal impairment to such a system is intersymbol interference caused by frequency-selective fading. A novel media-access scheme is proposed which permits the use of resource sharing, wherein a small pool of time slots is effectively shared among all users to provide added protection against channel impairments on an as-needed basis. Our results show that the use of resource sharing and diversity provide excellent protection against intersymbol interference caused by frequency-selective fading with negligible impact on throughput. Furthermore, resource sharing plus diversity can permit significantly higher data rates without large queueing delays. For example, a wireless network with a 10 Mbit/s data rate in a 10 MHz bandwidth using four antennas at the base station has a less than 10^{-4} outage probability at a 10^{-4} BER in buildings with less than 58 ns rms delay spread. A loading of 75 percent is permitted for a queueing delay of less than 20 packet transmission times all but 0.01 percent of the time.**

I. Introduction

Wide-band communications within a building has emerged as a dominant characteristic of the modern office environment [1], [2]. Shielded and unshielded twisted pair copper wiring, coaxial cable, and lightguide are being used in varying combinations to provide the high-speed backbones needed for private branch exchanges and local area networks. These, in turn, offer the user a vast array of enhanced voice and data services.

In this paper, we propose a wide-band indoor system that uses radio as a transmission medium, either as a supplement to a wired network or on a stand-alone basis. As we show, radio offers not only complete physical portability, but logical portability as well. The users of such a wireless network could enjoy complete freedom from existing building wiring and cross-connect constraints; office rearrangements and physical moves would be handled with minimal disruption of work; remote building locations could readily be served without the need for additional high-speed wiring; equipment which otherwise would require unique wiring could readily be brought online; and temporary service could be provided, for example, to a task force operating in short-term quarters. Also, there would be no need to inform the system administrator or change the physical port or location identifier in software whenever arrangements occur; instant reconnectivity would follow any such rearrangement. Finally, the radio link could serve as a universal interface, avoiding the problem of special purpose terminating equipment for each type of data and telephone device brought on-line.

Indoor radio communication is not without its problems, however. Buildings in general, and office buildings in particular, present a harsh environment for high-speed radio transmission because of numerous reflections from walls, furniture, and even people; the link between a given pair of transmitters and receivers is thereby corrupted by severe multipath distortion arising from the random superimposition of all reflected rays, and by shadow fading caused by the absence of line-of-sight paths. At low data rates, the effects of multipath can be characterized by Raleigh fading; at higher rates, the channel also exhibits dispersion over the communication band. Shadow fading is spectrally flat and characterized by a log-normal distribution. All effects vary dynamically with time as the environment slowly changes. Rayleigh fading produces wide variation in the levels of signals arriving at a particular receiver from different transmitters, thereby precluding the use of standard techniques for multiple access of the radio channel [3]. Dispersion within the channel produces serious intersymbol interference, thereby limiting the maximum data rate of the channel and causing a fraction of users to experience an unacceptably high bit error rate; a link experiencing such conditions is said to have suffered an outage and is temporarily unavailable.

It is a goal of our proposed system to provide arbitrarily high link availability, approaching that of a hard-wired connection. The system affords aggregate capacity in the range of several Mbits/s, to be allocated, upon demand, among the various users. Each user may dynamically communicate at a peak rate less than or equal to the channel capacity.

Functionally, the system topology is that of a star, the central node of which is equipped with diversity transmitters and receivers to offset the effects of multipath [4]. The star topology is compatible with similarly configured wired systems employing a central node with remote concentrators [5]. Each user is provided with a simple nondiversity radio set, and accesses the radio channel via a modified polling scheme which is immune to widely varying signal strength; as a by-product, the media-access scheme accommodates both continuous and bursty data traffic, thereby supporting integrated digital voice–data

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service. The polling scheme admits resource sharing [6], [7], an adaptive coding technique which affords very high bandwidth with arbitrarily high availability by dynamically adjusting the data rate to the prevalent link conditions.

In Section II, we describe the proposed system and discuss the modified polling scheme. The effects of dispersion with regard to frequency-selective fading are studied in Section III which also contains a complete description of the resource-sharing scheme. Typical results show that the use of resource sharing can reduce the number of diversity elements by a factor of two while maintaining the same outage probability, improve the throughput by an order of magnitude for low-order diversity, or achieve arbitrarily high availability with minimal impact upon throughput. In Section IV, we consider the system queueing delay and show that an average load of 75 percent can be maintained with a mean delay of less than 20 packets, all but 0.01 percent of the time. In Section V, we briefly consider the effects of thermal noise with regard to frequency-selective and shadow fading. We apply these results in Section VI to demonstrate the feasibility of a 10 Mbit/s system in most buildings (rms delay spread less than 58 ns). Finally, a summary and conclusions are presented in Section VII.

II. System Description

We begin with a brief description of a hard-wired network, based upon a star topology, and show how radio may be conveniently introduced into such an architecture. A block diagram of the hard-wired network is shown in Fig. 1. Key components are the central node, call processor, and remote concentrators. Devices attach to the network via terminal interface wires (in this context, terminal is used generically to mean a data device, printer, personal computer, host computer, telephone, etc.). Continuous or bursty traffic arriving at a concentrator via interface lines are formed, at the concentrator, into fixed-length packets for time-multiplexed high-speed transmission to the central node; each such packet contains a logical channel number which allows the node to reroute the packet to its target concentrator. The central node contains a contention bus, operating at the speed of each high-speed link, to accomplish this rerouting. All traffic, including that arising at a particular concentrator and destined for that same concentrator, is routed through the central node. The receiving concentrator demultiplexes all arriving packets for distribution to the appropriate interface port. Logical channel numbers are assigned for the entire network at the time a session is established by the call processor. Additional operational details appear in [5].

Radio links may be introduced via either or both means shown in Fig. 2. In Fig. 2(a), we note that the high-speed links to the central node have been augmented by the appearance of a radio base station which provides a high-speed channel to collect traffic from radio users located throughout the building (henceforth, a channel will imply

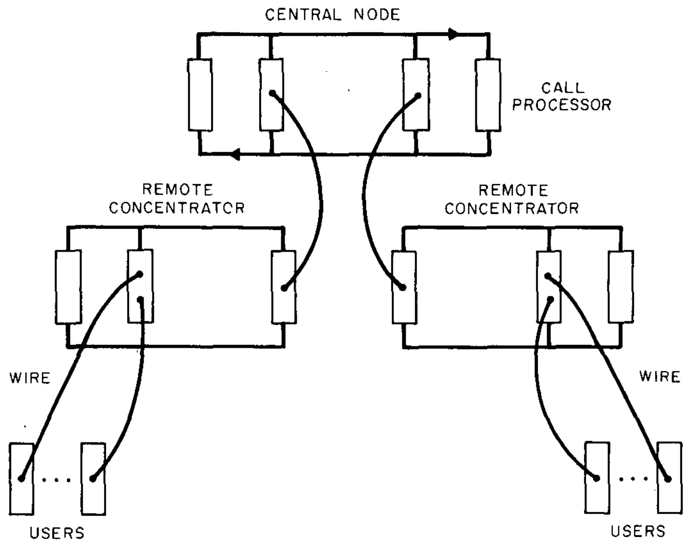

Fig. 1. Architecture of a hard-wired network.

full duplex operation, with separate bands used to transmit to and receive from the radio base station). This radio channel operates at the same rate as the node's contention bus and each of the high-speed links. With an appropriate access protocol, the radio channel may be shared among all radio users and appear, to the node, as a virtual concentrator. Fixed-length packets arriving over this link contend for the nodal bus along with packets arriving from the high-speed wired links; packets arriving from the wired links may be rerouted to the radio link, and vice-versa, according to their destination address. As before, traffic arising from any concentrator (real or virtual), and destined for the same concentrator, must be routed through the node.

In Fig. 2(b), we show a number of radio base stations, each of which establishes a link from its respective remote concentrator to a subset of radio users. Although multiple links are established, these links time-share a single radio channel, that is, at any moment, only one radio user out of all users may access the radio channel. We note that there is no need to provide an aggregate data rate over all radio links in excess of the transmission speed of the central node since all packets must be routed through the node. This observation leads to the conclusion that it is pointless to reuse the radio channel among user subsets, as this increased capacity could not be used. Thus, by sharing a single channel operating at the speed of the node (among all radio users), each user can potentially access the full system bandwidth, and interference among clusters caused by simultaneous use of the channel by users in different clusters is avoided. From the perspective of the central node, the radio link established from each concentrator to its clusters of radio users appears as another wired port on the concentrator. Henceforth, with no loss of generality, we shall consider the radio links only.[1] Each base station employs multiple antennas (diversity) to pro-

[1]Note that the bandwidths of the systems in Fig. 2(a) and (b) are the same, and, thus, the results in this paper apply to both systems.

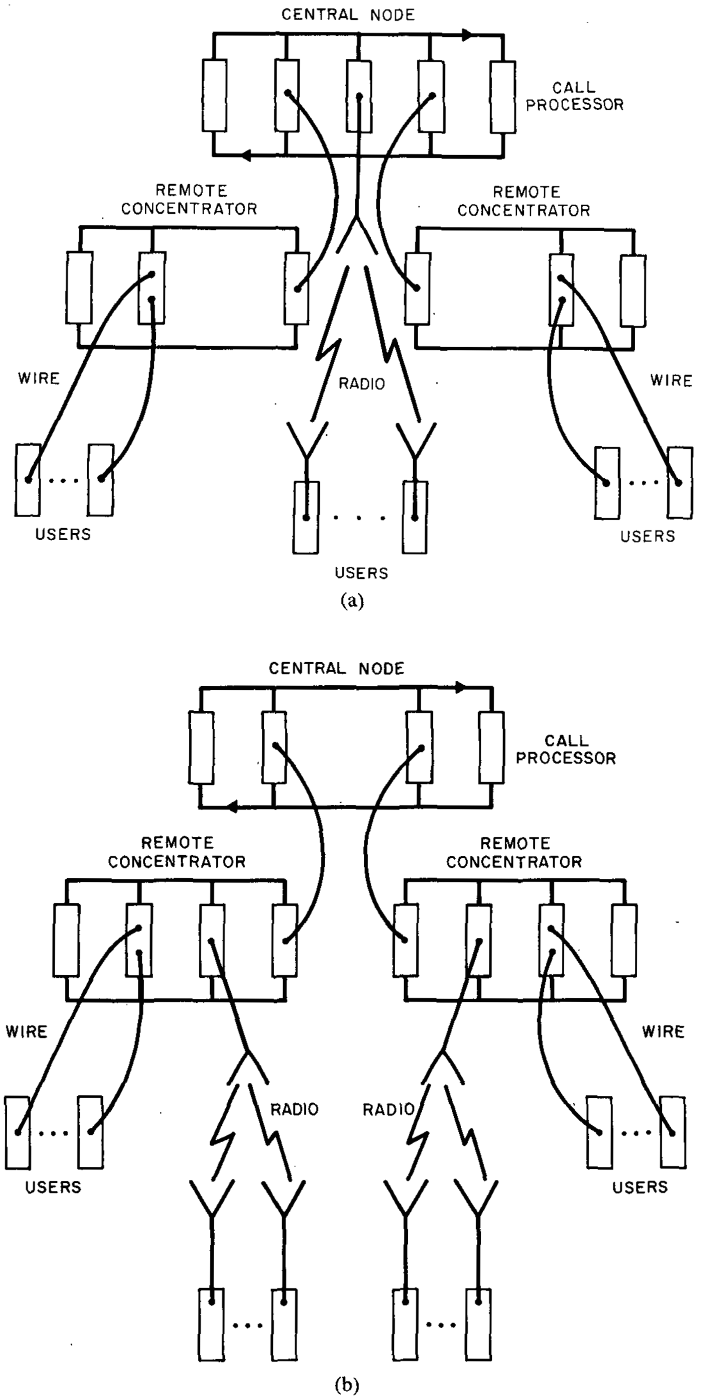

Fig. 2. Radio supplement to a hard-wired network.

tect against multipath fading; each remote radio unit is equipped with a single antenna only. Later, we show how a combination of limited diversity at the base station and resource sharing may be used to provide arbitrarily high availability.

We now address the issue of accessing the radio channel. The media-access scheme should handle any combination of bursty and continuous traffic with a fair distribution of resources among all users. No direct communication is permitted among users, since users may communicate only with the concentrators (we note that common media-access schemes, such as carrier sense multiple access, are inappropriate in the radio environment because free-space path loss and multipath fading result in too large a variation of signal strength to ensure that all channel usage can be detected). To keep the remote units inexpensive, sophisticated timing requirements should be avoided. Finally, because of problems with delay spread, we want the throughput of the system not to be significantly reduced by the media-access scheme, and separate receive and transmit channels must be provided to allow full duplex operation.

In this regard, we propose use of a modified polling technique with the base station controlling the transmit token. The approach is applicable to both configurations appearing in Fig. 2. For the configuration of Fig. 2(b), polling is performed by a controller situated at the node, with the radio interface units located at the concentrators slaved to this controller such that, at any point in time, only one is allowed to transmit the token to its community of users (remember that the entire collection of remote radio users time share a single radio channel without frequency reuse).

The proposed polling technique is shown in Fig. 3. Time is divided into a sequence of fixed-length intervals called frames, as shown in Fig. 3(a). At the start of each frame appears a polling interval, followed by multiple intervals for transmission of continuous (e.g., voice) and bursty traffic packets. The length of the continuous traffic interval depends on the amount of continuous traffic. This traffic is transmitted periodically (at least once per frame) with the time interval between continuous traffic intervals used for bursty traffic. Transmission of one fixed-length packet per continuous traffic interval constitutes some standard grade service (e.g., 64 kbits/s). Continuous traffic users may request multiples of this basic rate by accessing multiple time slots per continuous traffic interval. The polling details appear in Figure 3(b), which shows transmissions from and to the base station. The following steps are involved.

1) Through the radio interface located at the concentrators, the controller at the node polls each user sequentially (subpackets $P1$–PN).

2) When polled, each user responds whether it has continuous traffic (e.g., voice) or bursty traffic (data) and, if bursty traffic, the number of blocks of data (using subpackets $R1$–RN).

3) The controller then sends a signal (i.e., transmit token TS_I–TS_J) to each continuous traffic user in turn to send one fixed-length packet V_I–V_J (a preset number of data symbols).

4) The controller then sends a signal (i.e., transmit token) to each bursty traffic user in turn to send their first data block (packets D_K–D_L), then the second data block, etc.

5) During steps 3) and 4), while the users are transmitting to the concentrators, the controller, through the radio interface at the concentrators, is transmitting data to the users.

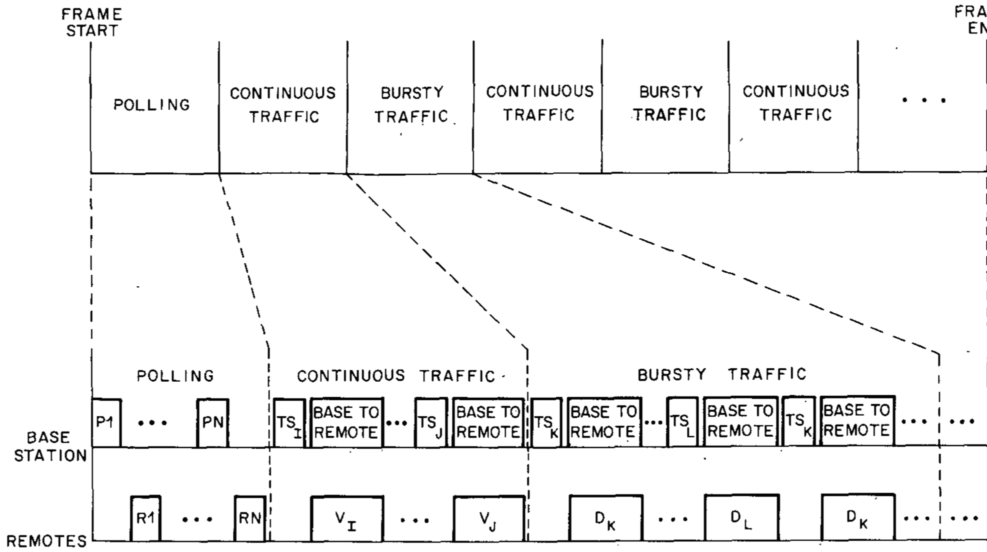

Fig. 3. Diagram of media-access scheme using polling.

6) When it is time again for the continuous traffic to transmit go to step 3).

7) When it is time again for polling (i.e., end of frame) go to step 1).

We note that this technique meets the specifications as described above. First, the technique handles continuous traffic (i.e., periodic data or voice) with priority. Second, the system has the same maximum data rate for each user (i.e., a fair distribution of resources), which depends on the system loading. Third, there are no timing requirements at the remotes. Fourth, the throughput on the channel is not significantly reduced by this technique because the polling has a low duty cycle. This is mainly due to the short propagation delay between the concentrators and the remotes (up to a 10 data symbol delay for a 500 ft range at 10 Mbits/s). Finally, the system has duplex operation.

III. Dispersion and Resource Sharing

In this section we begin our performance analysis of the system described in Section II by considering the effects of dispersion due to multipath and by introducing the use of resource sharing and diversity. In a multipath environment, paths of different lengths cause delay spread at the receiver. The delay spread, i.e., the dispersion or frequency-selective fading in the channel, produces intersymbol interference which limits the maximum data rate in a given building. This problem was analyzed in [4] where it was shown that the maximum data rate for a given building depends primarily on the rms delay spread and not the delay spread function. Thus, within the coverage area, there is some probability that the received signal bit error rate (BER) for each user is greater than the required value; we call this the outage probability. Of course, if a remote does not work in one location, the user can move the terminal or antenna. However, the delay spread may vary slowly with time as people and objects move within the building (see [4] for further discussion). Therefore, it is desirable to keep the outage probability (due to delay spread) as low as possible so that the wireless system is almost as reliable as a wired system. In [4] an outage probability of 10^{-4} at a BER of 10^{-4} was considered and is also considered here.

One method for increasing the maximum data rate within buildings is the use of antenna diversity, i.e., multiple transmit and/or receive antennas [8]–[11]. One practical antenna-diversity technique is maximal-ratio combining [8] whereby the signals received by multiple antennas are weighted and combined to maximize the signal-to-thermal-noise ratio at the receiver output. By maximizing the signal-to-thermal-noise ratio, maximal-ratio combining also increases the signal-to-intersymbol-interference (due to dispersion) power ratio at the receiver output [11]. Therefore, maximal-ratio combining increases the maximum data rate for a given building or, alternatively, for a given data rate, substantially decreases the outage probability. Other techniques for increasing the maximum data rate include the use of quadrature phase-shift keying (QPSK) as opposed to binary phase-shift keying (BPSK) [4], [11]. For example, for a 10^{-4} outage probability at a 10^{-4} BER, a system with four-branch maximal-ratio combining and QPSK has almost 150 times the maximum data rate of a BPSK system without diversity with a spectral efficiency of 1 bit/s/Hz [4].

Systems with multiple users in the same bandwidth, such as the system described in Section II, can use resource sharing [6], [7] 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). Unlike the resource sharing treatments of [6], [7], we do not consider the use of coding during the fade events because the channel is dispersive.

With resource sharing, the probability of a user transmitting at rate R_2 is the outage probability for rate R_1, $P_{out}|_1$, and the probability of a user transmitting at rate R_1 is $1 - P_{out}|_1$. Thus, the average symbol duration is $P_{out}|_1 \cdot 1/R_2 + (1 - P_{out}|_1) \cdot 1/R_1$, and the throughput (the inverse of the symbol duration) R_T averaged over all the users (faded and nonfaded) is given by

$$R_T = \frac{R_1}{(1 - P_{out}|_1) + \frac{R_1}{R_2} P_{out}|_1}. \tag{1}$$

Also, note that with this system, the outage probability P_{out} is that for rate R_2 ($P_{out}|_2$).

Implementation of resource sharing with two transmission rates requires modification of the media-access technique described in Section II. With resource sharing, transmission would normally be at the higher rate. If errors are detected at the higher rate via standard error detection techniques, the receiver can request retransmission of the last block (and further blocks) of data at the lower rate. Periodically, the transmitter can retry transmission at the higher rate. The frequency of retries depends on the dynamics of the delay spread in the channel. Unfortunately, published data on the dynamics of the channel are not currently available, although experimental results indicate that the channel varies very slowly with time [12]. Therefore, requests for lower rate transmission and retries at the higher rate need only occur infrequently, and (1) is a good approximation to the throughput of the system.

Fig. 4 shows the throughput versus R_1, both normalized to the rms delay spread τ_0, with resource sharing for an outage probability of 10^{-4} at a BER of 10^{-4} with coherent detection of QPSK with cosine-rolloff signal spectrum with 1 bit/Hz/s efficiency ($\alpha = 1$). Results are shown for a two-path delay spread function (see [4]) with maximal ratio combining with M ($= 1, 2, 4$, and 8) antennas using R_1 and R_2 as calculated from [4]. That is, for given M, P_{out}, and BER, the maximum normalized data rate $\tau_0 R_2$ was determined, and, for given $\tau_0 R_1$, M, and BER, $P_{out}|_1$ was calculated using [4]. From these values for R_1, R_2, and $P_{out}|_1$, the throughput was calculated using (1). Fig. 4 shows that, for each value of M, as R_1 increases, the throughput at first increases, reaches a maximum and then decreases. Thus, for each value of M there is a well-defined optimum rate R_1 which maximizes the throughput.

Table I lists the probability of transmission at the lower rate and the ratio of the higher to lower rate at maximum throughput for the curves of Fig. 4. As M increases, the probability of transmission at the lower rate increases and the ratio of rates decreases. The factor $R_1/R_2 \cdot P_{out}|_1$ is at a minimum with 4 antennas, where it is less than 10 percent.

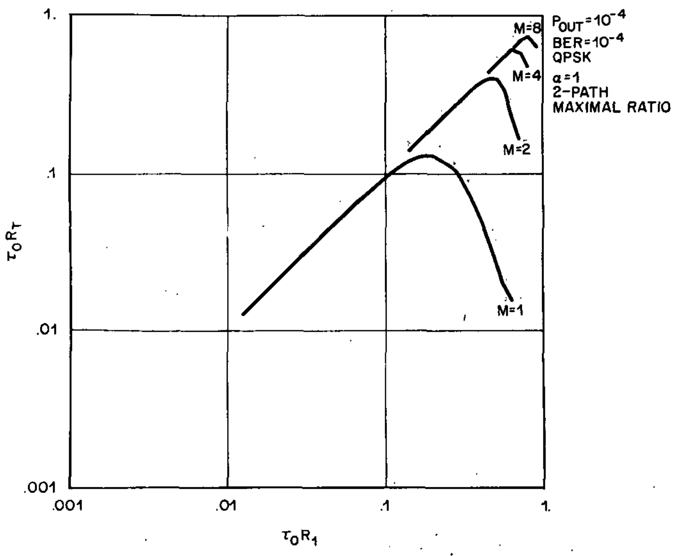

Fig. 4. The throughput versus R_1 (both normalized to the inverse of the rms delay spread) with resource sharing for maximal ratio combining with 1, 2, 4, and 8 antennas.

TABLE I
PROBABILITY OF TRANSMISSION AT THE LOWER RATE AND THE RATIO OF THE HIGHER TO LOWER RATE AT MAXIMUM THROUGHPUT WITH RESOURCE SHARING (FOR THE CURVES OF FIG. 4)

M	$P_{out}\|_1$	R_1/R_2
1	0.035	16.0
2	0.050	3.2
4	0.071	1.4
8	0.22	1.3

Fig. 5 shows the maximum throughput $R_T|_{max}$ (normalized to $1/\tau_0$) versus M with resource sharing. Results are shown for an outage probability of 10^{-4} at a BER of 10^{-4} with coherent detection QPSK with $\alpha = 1$ and maximal-ratio combining. The range in maximum throughput with four different delay spread functions (2-path, Gaussian, uniform, and one-sided exponential) as studied in [4] is shown, i.e., upper and lower bounds for these four delay spread functions are shown. Results with resource sharing are compared to results without resource sharing. This figure shows that resource sharing increases the throughput by an order of magnitude with no diversity, with decreasing improvement as the number of antennas increases. For example, with 4 antennas the maximum throughput is doubled by resource sharing.

Alternatively, we can consider the effect of resource sharing on the outage probability. Fig. 6 shows the outage probability (P_{out}) versus the maximum throughput normalized to $1/\tau_0$ with and without resource sharing. Results are shown for a 10^{-4} BER with coherent detection

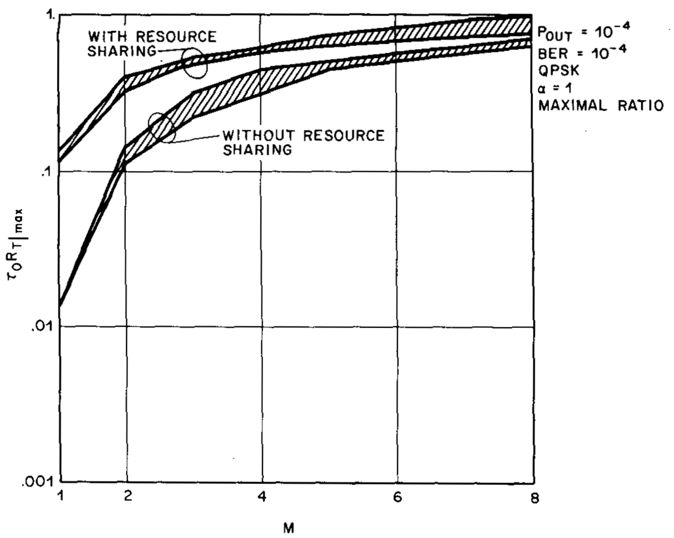

Fig. 5. The maximum throughput (normalized to $1/\tau_0$) versus M with and without resource sharing.

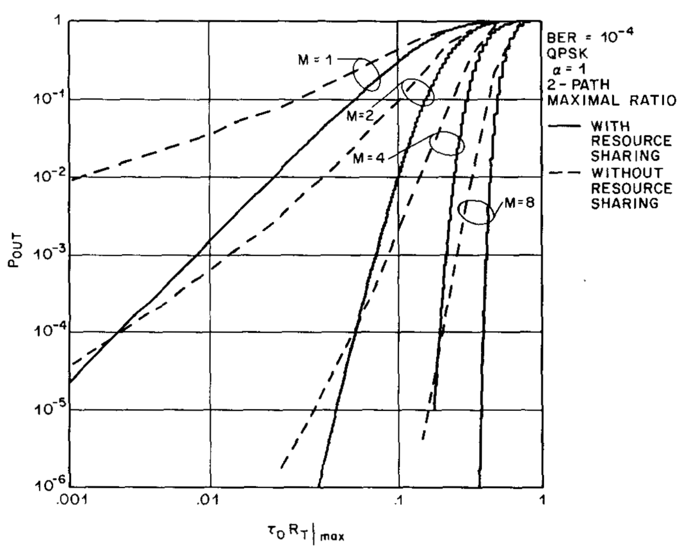

Fig. 6. The outage probability versus throughput (normalized to $1/\tau_0$) with and without resource sharing.

of QPSK with $\alpha = 1$ for a two-path delay spread function with maximal-ratio combining with 1, 2, 4, and 8 antennas. This figure shows that for a 10^{-4} outage probability a system with resource sharing requires half the antennas of a system without resource sharing (for the same throughput). Note also that for $M = 4$ and 8 with resource sharing the outage probability dramatically decreases with throughput. Thus, this figure suggests that with resource sharing and four or more antennas the outage probability can be reduced to an arbitrarily small value with a negligible decrease in throughput.

IV. Queueing Delay

We now consider the delay caused by our media-access technique. The queueing delay in the system increases with the system loading, and, therefore, for given maximum delay specifications, there is a corresponding maximum loading which reduces the maximum throughput for the system with delay spread below that presented in Section III.

Unlike delay spread, which can deny users access to the channel for long periods of time, the media-access scheme delays access for very short periods. However, if the delays are long enough, they can become noticeable to the data user and result in a loss of bits for the continuous traffic (voice) user. Therefore, we want to keep the probability of unacceptable delay for each block of data as small as possible. In our analysis, we present results for a system with a 10^{-4} probability of a queueing delay greater than 20 blocks of data, although the formulas are general.

Of primary concern in the queueing analysis is the use of resource sharing. With resource sharing, some blocks of data have longer transmission times than others. Therefore, although resource sharing increases the maximum throughput without considering delay, it increases the queueing delay for a given loading and thereby decreases the maximum loading for a given delay. Below, we examine the queueing delay with and without resource sharing and determine the increase in maximum throughput with resource sharing when delay is considered.

We now determine the probability that the queueing delay is greater than a given value (i.e., the complementary probability distribution of the delay) for the system with resource sharing. Note that the same formulas can also be used to study the system without resource sharing. To analyze the system, we make the following approximations. We assume that there are an infinite number of users in the system and consider data (bursty traffic) users only.[2] Packets (blocks of data) of N symbols arrive into the system with a Poisson distribution at rate λ, and are transmitted in the order they arrive into the system (first in, first out). The transmission times for packets are N/R_1 and N/R_2 with probability $1 - P_{out}|_1$ and $P_{out}|_1$, respectively. Such a system can be analyzed as an $M/G/1$ queue. Although the standard result for the queue length of an $M/G/1$ queue is in the form of a probability generating function, our system is a special case of an $M/G/1$ queue for which reasonable explicit results are available [13, ex. 5.2]. The complementary probability distribution of the delay[3] can be expressed as the sum over n of the complementary probability distribution of the delay for the nth packet in the queue, times the probability of n packets in the queue, i.e.,

$$P_{DEL}(w/\rho, P_{out}|_1, R_1/R_2) = \sum_{n=1}^{\infty} P_n(w/\rho, P_{out}|_1, R_1/R_2)\, p_n(\rho, P_{out}|_1, R_1/R_2) \tag{2}$$

[2] Since the continuous traffic does not experience queueing delay, the system can operate at up to full loading with continuous traffic. Thus, with a mixture of continuous and bursty traffic, the throughput will be somewhat higher than that shown in this section.

[3] The delay is the time from when the packet arrives in the system until it is received, i.e., the time the packet waits for transmission plus the transmission time.

where w is the delay normalized to the transmission time for a packet at rate $R_1(N/R_1)$, ρ is the loading given by

$$\rho = \lambda N/R_T \tag{3}$$

P_n is the probability that the delay is greater than w (complementary probability distribution of the delay) for the nth packet in the queue, and p_n is the probability of n packets in the queue. From [13, ex. 5.2],

$$p_n(\rho, P_{out}|_1, R_1/R_2) = (1 - \rho)d_n \tag{4}$$

where

$$d_n = \begin{cases} a_n - \sum_{j=1}^{n} b_j d_{n-j} & n = 1, 2, \cdots \\ 1 & n = 0 \end{cases} \tag{5}$$

and

$$a_n = \frac{c_n}{c_0 n!} - \frac{c_{n-1}}{c_0(n-1)!} \tag{6}$$

$$b_j = \begin{cases} \dfrac{c_1 - 1}{c_0} & j = 1 \\ \dfrac{c_j}{c_0 j!} & j = 2, \cdots \end{cases} \tag{7}$$

$$c_i = (1 - P_{out}|_1)e^{-\beta}\beta^i + P_{out}|_1\, e^{-R_1/R_2\beta}\,(R_1/R_2\,\beta)^i \tag{8}$$

and

$$\beta = \lambda N/R_1 = \frac{\rho}{(1 + (R_1/R_2 - 1)P_{out}|_1)}. \tag{9}$$

With n packets in the queue there are $n - 1$ packets waiting to be transmitted while one packet is being transmitted. Therefore, the complementary probability distribution of the delay for the nth packet in the queue is given by

$$P_n(w) = \sum_{i=0}^{n-1} A_i(P_1(w - B_i)) \tag{10}$$

where A_i is the probability of i packets in the queue waiting to be transmitted at rate R_2 (out of $n - 1$ packets), i.e.,

$$A_i = \binom{n-1}{i} P_{out}^i|_1(1 - P_{out}|_1)^{n-1-i} \tag{11}$$

B_i is the transmission time for the $n - 1$ packets, i of which are transmitted at rate R_2, i.e.,

$$B_i = n - 1 + i(R_1/R_2 - 1) \tag{12}$$

and $P_1(w)$ is the complementary probability distribution of the delay for the one packet being transmitted. It can be shown that

$$P_1(w) = \begin{cases} 1 & w \le 0 \\ 1 - w(P_{R_1} + P_{R_2}/(R_1/R_2)) & 0 < w \le 1 \\ 1 - (P_{R_1} + wP_{R_2}/(R_1/R_2)) & 1 < w \le R_1/R_2 \\ 0 & w > R_1/R_2 \end{cases} \tag{13}$$

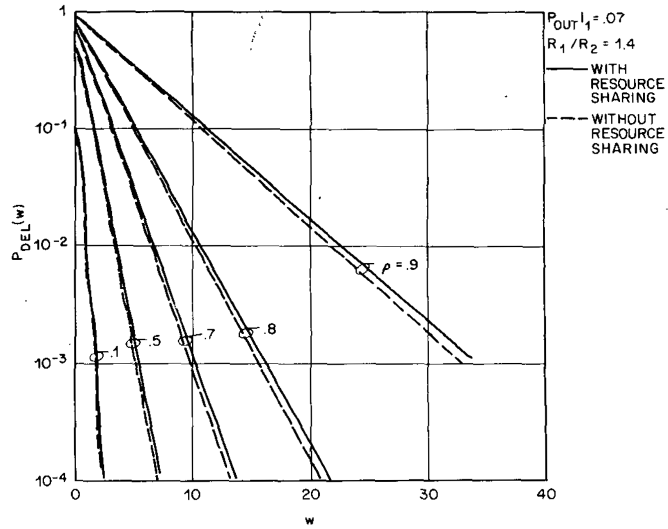

Fig. 7. The complementary probability distribution of the delay (normalized to N/R_1) both with and without resource sharing for the values of $P_{out}|_1$ and R_1/R_2 for $M = 4$ (from Table I) with various system loadings.

where P_{R_2} and P_{R_1} are the probabilities that the packet is being transmitted at rate R_2 and R_1, respectively, and are given by

$$P_{R_1} = \frac{1 - P_{out}|_1}{1 + (R_1/R_2 - 1)\,P_{out}|_1} \tag{14}$$

and

$$P_{R_2} = \frac{R_1/R_2\,P_{out}|_1}{1 + (R_1/R_2 - 1)\,P_{out}|_1}. \tag{15}$$

Thus, the complementary probability distribution of the delay for a system with resource sharing can be calculated from (2)–(15). For a system without resource sharing, the complementary probability distribution of the delay can also be calculated from (2)–(15) with $P_{out}|_1 = 0$ and/or $R_1/R_2 = 1$. For numerical evaluation of (2)–(15), note that (2) contains an infinite sum. However, since

$$\sum_{n=1}^{\infty} p_n(\rho, P_{out}|_1, R_1/R_2) = \rho \tag{16}$$

and

$$P_n(w/\rho, P_{out}|_1, R_1/R_2) \le 1 \tag{17}$$

for all n, the error in the distribution for a finite summation (to N) in (2) is bounded by

$$\sum_{n=N+1}^{\infty} P_n(w/\rho, P_{out}|_1, R_1/R_2)\, p_n(\rho, P_{out}|_1, R_1/R_2) \le \rho - \sum_{n=1}^{N} p_n(\rho, P_{out}|_1, R_1/R_2). \tag{18}$$

In our numerical evaluation, we summed the right-hand side of (2) until the error was less than one percent of the numerical result.

Fig. 7 shows the effect of resource sharing on the delay distribution with $P_{out}|_1$ and R_1/R_2 chosen from the $M = 4$ results of Table I. The complementary probability dis-

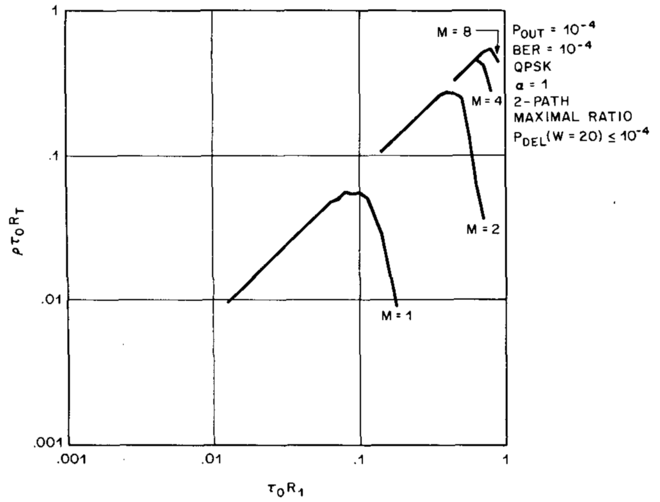

Fig. 8. The throughput versus R_1 (both normalized to $1/\tau_0$) with resource sharing considering loading for less than a 10^{-4} probability of a 20-packet transmission time ($20\ N/R_1$) delay for maximal ratio combining with 1, 2, 4, and 8 antennas.

tribution of the delay is plotted for loadings of 0.1, 0.5, 0.7, 0.8, and 0.9. The increase in delay with resource sharing is only about four percent, i.e., resource sharing has a negligible effect on the delay. Note also that for a 10^{-4} probability of a delay greater than 20-packet transmission times at rate $R_1 (20\ N/R_1)$ the system loading must be slightly less than 0.8 both with and without resource sharing.

The effect of a delay requirement on the throughput is shown in Fig. 8. The throughput is plotted versus R_1 (both normalized to $1/\tau_0$) with resource sharing considering the system loading for less than a 10^{-4} probability of a 20 N/R_1 delay for maximal-ratio combining with 1, 2, 4, and 8 antennas. The figure shows that resource sharing increases the throughput even with delay requirements imposed. Comparing Fig. 8 to Fig. 4 (without delay requirements) we see that with the delay requirement, the increase in throughput with resource sharing is reduced slightly with 1 or 2 antennas, but is about the same for 4 or more antennas. Note that the shape of the curves in Fig. 8 is the same as in Fig. 4, i.e., there is a well-defined maximum throughput for each value of M.

Table II lists $P_{out}|_1$, R_1/R_2, and ρ at maximum throughput with resource sharing and delay requirements. Comparing Table II to Table I (without delay requirements) we see that with delay requirements, for 1 or 2 antennas the higher rate (R_1) and therefore $P_{out}|_1$ are lower at maximum throughput, but for 4 or more antennas, R_1 is unchanged. In all cases, the system loading at maximum throughput is about 75 percent.

Fig. 9 shows the maximum throughput (normalized to $1/\tau_0$) versus M with and without resource sharing considering system loading for less than a 10^{-4} probability of a 20 N/R_1 delay. Comparing Fig. 9 to Fig. 5 (without delay requirements), we again see that for 1 or 2 antennas the increase in throughput with resource sharing is smaller with delay requirements. However, with 4 or more antennas, the increase is unchanged; delay requirements reduce the maximum throughput by about 25 percent (i.e., the system loading is 75 percent) both with and without resource sharing.

TABLE II
PROBABILITY OF TRANSMISSION AT THE LOWER RATE RATIO OF HIGHER TO LOWER RATE AND SYSTEM LOADING AT MAXIMUM THROUGHPUT WITH RESOURCE SHARING AND DELAY REQUIREMENTS (FOR THE CURVES OF FIG. 8)

M	$P_{out}\|_1$	R_1/R_2	ρ
1	0.005	6.3	0.72
2	0.022	2.8	0.73
4	0.071	1.4	0.77
8	0.22	1.3	0.74

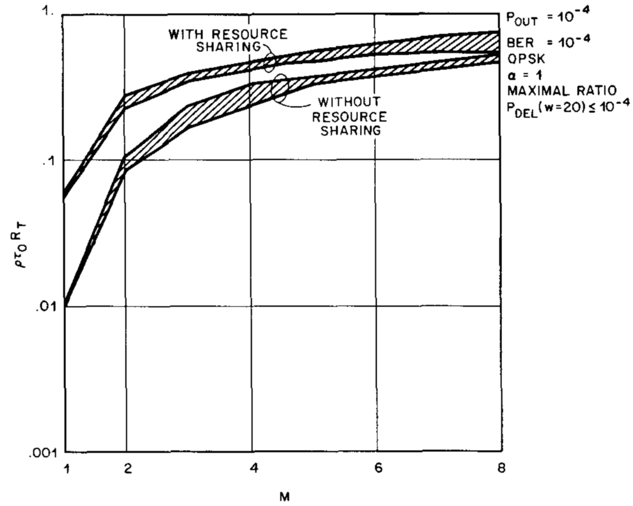

Fig. 9. The maximum throughput (normalized to $1/\tau_0$) versus M with and without resource sharing considering loading for less than a 10^{-4} probability of a 20 N/R_1 delay.

V. THERMAL NOISE

In addition to dispersion due to frequency-selective fading, another principal impairment to wideband indoor radio communication systems is received signal power variation caused by frequency-selective and shadow fading. Frequency-selective fading is caused by multipath with paths of different lengths, while shadow fading is caused by blockage and attenuation by walls, doors, etc. Frequency-selective and shadow fading each contribute variations in signal level that are location-dependent and, for movement within a building, time-dependent. Thus, from these causes, there will be a range of probabilities at remote locations from the base station (or concentrator) that the signal-to-noise ratio will be below that required for specified BER (the "outage probability"). Primarily, shadowing increases the incidence of such outages with increasing distance, thus delimiting the coverage area in a given system. On the other hand, dispersion and the consequent intersymbol interference affects all receivers in the coverage area, and so may be the outage determinant well within the coverage area.

We note here that the techniques discussed in this paper, antenna diversity and resource sharing, can also be used to decrease the signal variations from these two causes, and expand the coverage area (for the same system gain). Detailed calculation of these effects will be presented in a forthcoming paper.

VI. Example System

We now present a specific example of a wireless network that operates at a rate of 10 Mbits/s. We consider a 10 MHz bandwidth channel for each transmission direction (20 MHz total bandwidth). The system specifications call for a 10^{-4} outage probability from intersymbol interference (due to delay spread) at a 10^{-4} BER (uncoded) and a 10^{-4} probability of a queueing delay of greater than 20 packet transmission times.

From the previous analysis [4], such a system with BPSK modulation and no diversity could operate within specifications in buildings that had rms delay spreads less than 0.23 ns.[4] Such an rms delay spread is too low to be practical. However with QPSK and four-branch maximal-ratio combining the system could operate in buildings that had rms delay spreads up to 32 ns. In addition, with resource sharing the maximum rms delay spread is increased to 58 ns.[5] With resource sharing 7.1 percent of the users transmit at 7.2 Mbits/s while the rest transmit at 10 Mbits/s. With the media-access scheme of Section II, the system could operate within the queueing delay specifications up to a loading of 77 percent (7.5 Mbits/s).

VII. Summary and Conclusions

In this paper we proposed and analyzed a wideband indoor communication system that uses radio as the transmission medium. The primary impairments to such a system are frequency-selective and shadow fading. Our analysis shows that wide bandwidth service can be readily provided through the combined use of resource sharing and diversity. Overall, the outage probability can be reduced to arbitrarily small values. The queueing delay with the modified polling media-access scheme was shown to be small for system loadings less than 75 percent and does not significantly increase with resource sharing. As an example, a wireless network was considered with a 10 Mbit/s data rate in a 10 MHz bandwidth channel. Such a network could operate with less than a 10^{-4} outage probability at a 10^{-4} BER (with four antennas at the base station) in buildings with an rms delay spread less than 58 ns (most buildings), while maintaining very low queueing delay.

[4]Note that the maximum rms delay spread is much smaller than the bit period because of the low outage probability and BER specifications for BPSK with severe band limiting (for a 10 Mbit/s signal in a 10 MHz bandwidth). Relaxing these specifications will result in much larger maximum rms delay spread. For the QPSK system with diversity described in this section, the maximum rms delay spread is not as strongly affected by these specifications.

[5]Alternatively, these results show that for given rms delay spread in a building, the maximum data rate is $580/\tau_0$ (in ns) Mbits/s. Thus, as examples, for the building in [12] where the measured τ_0 was 30 ns and the building in [14] where it was 250 ns, the maximum data rate is 19 and 2.3 Mbits/s, respectively.

Glossary

R_1	Higher transmission rate with resource sharing.
R_2	Lower transmission rate with resource sharing.
$P_{out}\|_1$	Outage probability at higher transmission rate.
$P_{out}\|_2$	Outage probability at lower transmission rate.
ρ	System loading.
τ_0	rms delay spread.
M	Number of antennas at base station.

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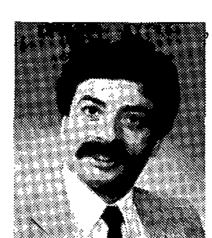
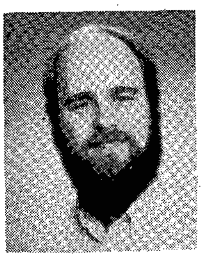


Anthony S. Acampora (M'75) was born in Brooklyn, NY, on December 20, 1946. He received the B.S.E.E., M.S.E.E., and the Ph.D. degrees from the Polytechnic Institute of New York, Brooklyn, in 1968, 1970, and 1973, respectively.

From 1968 through 1981, he was a member of the Technical Staff at Bell Laboratories, Holmdel, NJ, initially working in the fields of high-power microwave transmitters, radar system studies, and signal processing. From 1974 to 1981, he was involved in high-capacity digital satellite systems research, including modulation and coding theory, time-division multiple-access methods, and efficient frequency reuse techniques. In 1981, he became Supervisor of the Data Theory Group at Bell Laboratories working in the field of computer communications and local area networks. In January 1983, he transferred with his group to AT&T Information Systems to continue work on local area networks. In November 1983, he was appointed Head of the Department of Radio Communications Research, AT&T Bell Laboratories, Holmdel, NJ, where his responsibilities included management of research in the areas of antennas, microwave, and millimeter wavelength propagation, terrestrial radio and satellite communication systems, and multiuser radio communications. Since May 1984, he has been Head of the Department of Network Systems Resarch responsible for research in the areas of communication systems, switching systems, and local lightwave networks.



Jack H. Winters (S'77-M'82) received the B.S.E.E. degree from the University of Cincinnati, Cincinnati, OH, in 1977 and the M.S. and Ph.D. degrees in electrical engineering from Ohio State University, Columbus, in 1978 and 1981, respectively.

From 1973 to 1976 he was with the Communications Satellite Corporation, Washington, DC, and from 1977 to 1981, the ElectroScience Laboratory, Ohio State University, Columbus. He is presently with the Department of Network Systems Research, AT&T Bell Laboratories, Holmdel, NJ, where he is studying indoor radio, lightwave, and neural networks.

Dr. Winters is a member of Sigma Xi.