Multiple Access in Wireless Digital Networks

NORMAN ABRAMSON, FELLOW, IEEE

Invited Paper

General principles for the design of a multiple-access system for large numbers of terminals transmitting to a single hub station are discussed. The importance of understanding the nature of the traffic to be carried by the network is emphasized. After some discussion of multiple access options for steady traffic and for slowly varying traffic, the use of random-access protocols for rapidly varying traffic is explained.

Two general random-access protocols have been used in a variety of data networks, ALOHA and CDMA. Although these two techniques have different origins and are generally thought of as separate, they are in fact but different ways of looking at the same basic signals. We show that the use of multiple spreading codes in a CDMA network is not necessary in order to achieve multiple access capability. A single code can greatly reduce the complexity of a CDMA system. We introduce a spread-spectrum version of an ALOHA channel (Spread ALOHA) which is equivalent to a CDMA channel with a common spreading code for all users. The equivalence we demonstrate opens the door to a variety of techniques commonly used in ALOHA channels which can significantly increase both the throughput and the efficiency of the spread-spectrum channel.

I. INTRODUCTION

In this paper we discuss the multiple-access problem for digital networks composed of large numbers of packet radio terminals transmitting to a single hub station. These networks include packet data networks (such as RAM Mobile Data and Ardis [1]), cellular and microcellular networks (such as D-AMPS [2], Qualcomm CDMA [3], and the evolving personal communication networks, or PCN's), and mobile satellite networks (such as Iridium [4] and a host of less complex satellite networks [5]).

The evaluation of the competing and yet complementary technologies of FDMA, TDMA, CDMA, and ALOHA for the multiple access problem has sometimes been obscured by a lack of precision in defining the area of application for a particular technology. And the evaluation of the advantages of CDMA in particular has often been obscured by a general misconception relating to the basic mechanism used to separate different transmitters in a CDMA system.

The separation of signals from different transmitters in a CDMA system is frequently explained in terms of the different spreading codes assigned to different users (code division). In fact, the use of multiple codes is not necessary in order to separate one signal from another under almost any set of realistic network assumptions. Distinguishing one transmitter from another is achievable even when all transmitters in a spread-spectrum CDMA network use the same spreading code.

The use of the same spreading code for all transmitters in a CDMA network can result in the decreased complexity of CDMA terminals and hub stations, and in greatly increased flexibility of CDMA networks. This increased flexibility expands the ability of networks employing CDMA to evolve and to develop new services in a seamless manner.

The advantage of using a single code for all transmitters in a CDMA network is greater for the smaller cells of interest in PCN's and for multiple-access mobile satellite applications.

In Section II we describe and analyze the basic network options of fixed capacity assignments, demand access capacity assignments, and random-access capacity allocations for multiple-access digital networks. In Section III we describe the fundamental operation of ALOHA random access and CDMA random access. We also show how these two random access strategies with greatly different origins are in fact related. This relation then leads to the introduction of a spread-spectrum channel using an ALOHA packet separation mechanism—a Spread ALOHA channel. Finally, in Section IV we summarize the significance of these results for network analysis and design.

II. MULTIPLE ACCESS OPTIONS

A. Broadcast Channels and Multiple-Access Channels

The design of a packet radio network with a large number of terminals and a single hub station involves the use of two basically different types of communication channels and channel architectures. One type of channel—a broadcast channel—is used to transmit data from the hub station to the terminals (Fig. 1).
Transmitting data from a single-hub station to a large number of remote terminals (one to many) is a relatively simple problem. This channel architecture is almost always configured in a simple Time-Division Multiplexed (TDM) mode. And although there are differences in data rates, modulation techniques, and transmission formats among different packet data networks, there is general agreement on the use of TDM for multiplexing from the hub to the terminals.

Transmitting data from remote terminals to a single hub (many to one; see Fig. 2) is a much more challenging problem. That multiple access problem [6] is the subject of this paper.

**B. Characterization of the Network Traffic**

There are many solutions to the multiple access problem described in the previous section. The question of which multiple-access solution to use for a given application has recently been the subject of considerable controversy around the world, especially in the area of cellular telephony [7]. In this paper, we examine the various options for multiple access in data networks and the suitability of these options for various types of data networks. Not surprisingly, we find that there is no "best" multiple access solution in all cases. In general, the choice of a multiple-access protocol for a particular application should depend upon two primary factors: 1) the traffic characteristics [8] of the data network of interest and 2) the state of technology development at the time a network is deployed.

1) Steady Traffic: When the traffic from each user in a network is steady, or nearly so, it is possible to divide a single high-capacity multiple-access channel into smaller orthogonal channels corresponding to the requirements of individual users. This is ordinarily accomplished either on a frequency basis using Frequency-Division Multiple Access (FDMA) [9] or on a time basis using Time-Division Multiple Access (TDMA) [10]. Various combinations of

FDMA and TDMA can also be used to minimize cost in large networks [11]. As long as the traffic from each user is relatively stable, FDMA and TDMA provide acceptable choices for a multiple access architecture in a packet data network (see Fig. 3).

2) Slowly Varying Traffic: DAMA Networks: In many networks, the traffic from individual terminals in the system will vary as a function of time due to random traffic demands by different users at each terminal. In addition, the set of terminals active in the network can vary from time to time. In such situations it may be desirable to assign channel capacity to users on demand by means of a Demand Assigned Multiple Access (DAMA) architecture. In a DAMA system a separate channel, called the request channel, is used by individual users to request capacity when it is needed. This capacity can then be allocated in response to terminal requests by a central master station or by a common algorithm running in each terminal (see Fig. 4).

A DAMA system will, of course, introduce additional overhead into the multiple access channel due to the process of requesting and (sometimes) assigning capacity. In addition, the demand assignment process introduces a delay which can degrade the performance of the channel under certain conditions. But clearly there is some class of packet data network problems between that of completely static traffic and completely random traffic which is suited to a DAMA architecture.

Finally, we note that the use of a DAMA system does not eliminate the problem of multiple access in the face of varying traffic demands by individual users in a network. The multiple access problem is simply shifted to a higher logical level, in the request channel. For example, in the Intelsat SPADE DAMA system [12], the request channel can be accessed by as many as 50 individual terminals in a fixed allocation TDMA mode using a 50-ms frame length. Since the duration of the TDMA burst from each terminal is 1 ms, the maximum number of terminals which can be supported by the SPADE network is limited to 50.
3) Random Access in a DAMA Request Channel: In some important DAMA networks the total number of potential data terminals sharing the request channel is much larger than the number of terminals active at any given time. In such cases, subdividing a DAMA request channel into small fixed allocation subchannels as done in SPADE becomes impractical. For these cases, it is necessary to design a request channel architecture based upon a random access technique which allows for the possibility of a small subset of active transmitters selected from a much larger set of potential transmitters. Two general classes of random access techniques are available for such applications. These two techniques, ALOHA multiple access and CDMA are described, and the relationship between them is explained, in Section III. Up to now only ALOHA has been employed for random access in a DAMA request channel in a major digital network.

The first commercial implementation of this type of request channel was in the MARISAT (now INMARSAT) maritime satellite communication system [14]. In the INMARSAT system the number of possible ship stations is large and is necessary to utilize a request channel based upon a random access rather than a fixed allocation technique. Request packets in the INMARSAT DAMA system use a pure ALOHA protocol consisting of request packets transmitted from ship terminals with a packet length of 39 ms on a common 4800-bps channel.

The overhead necessary to request a channel allocation, allocate a channel, and de-allocate the channel upon completion of the transmission is not a major consideration when the information to be transmitted is a long file or other type of steady traffic. This is the case in the INMARSAT DAMA system where the request channel is used to allocate telex traffic or uncompressed and therefore constant data rate voice signals.

However, when the data transmitted from the terminals are bursty or when the amount of information to be transmitted from a single terminal is comparable to the amount of overhead required to allocate and de-allocate a channel, the use of DAMA architecture, even with a random access request channel, may not result in an acceptable level of network efficiency. In these circumstances the only practical alternative is to design a data network using a random-access protocol in the primary channel rather than just in the request channel. In Section III we discuss the general principles of random-access protocols and provide several examples of networks built on these principles.

III. RANDOM-ACCESS PROTOCOLS

A. ALOHA Multiple Access

The first data network to be based upon a random-access protocol was the ALOHANET which went into operation throughout the state of Hawaii in 1970 [13]. The ALOHANET provided access to a 9600-bps channel with a range of 400 km throughout the state of Hawaii by means of a $2000$ terminal interface unit using a bandwidth of 30 kHz in the UHF band. The theoretical capacity of that network was well over 600 terminals. The general theory of operation of these networks was worked out in the early 1970's [15], [16].

In an ALOHA multiple-access channel packets are buffered at each terminal and transmitted over a common channel to the hub station. No control is imposed on the channel in order to synchronize transmission from the various users, and therefore the start times of packets from different users in the network can be modeled as a Poisson point process. Under these circumstances, packets from different users will be transmitted with a high probability of success if there is a moderate amount of traffic on the network. As the traffic on the network increases the probability of a collision between packets from different users increases. The pessimistic assumption that a collision results in a loss of two packets is usually made in the analysis of an ALOHA channel. Using this assumption we can derive a relation between the total traffic on the network and the throughput of the network. If we let $G$ be the total traffic expressed as a fraction of the maximum possible data rate and $S$ be the channel throughput expressed as the same fraction, then the throughput will vary as a function of the offered traffic (see Fig. 5).

The relationship between the throughput $S$ and the traffic $G$ for the ALOHA channel is given by [15]

$$S = Ge^{-2G}.$$  

This relationship is shown in Fig. 6.

From Fig. 6 we see that the ALOHA throughput reaches a maximum value of 0.186 when the value of the traffic is 0.5.

The throughput of the channel, however, is not necessarily the most appropriate figure of merit for a multiple-access channel. The throughput of a channel is simply the fraction of time during which the channel can be used to transmit data. In some cases, such as average-power limited satellite channels or battery-operated transmitters, the average data rate of the channel for a fixed average transmitter power and a fixed bandwidth is a more appropriate figure of merit. We can define a different figure of merit for multiple-access
channels, called the efficiency of the channel, which takes into account the system resources of average power and bandwidth. When these channel resources are taken into account the picture of ALOHA efficiency which emerges is much different from that of ALOHA throughput.

The transmission of packets in a typical ALOHA channel is shown in Fig. 7.

From Fig. 7 we see that the average power in the channel can be much less than the peak power (or the average power during a packet). If the average power in the channel is \( P \), then the peak power is \( P/G \), where \( G \) is the channel traffic. This higher power level during the transmission of a packet can compensate, in part, for the fact that the throughput of the channel is less than one.

We restrict our interest in these arguments to values of channel traffic \( G \) of less than one, so that the terminology “average power” and “peak power” make sense. Although the theoretical results we derive apply equally well for larger values of \( G \), such values of channel traffic seem to have little practical importance. In typical ALOHA networks the channel traffic, \( G \), is usually in the range of 0.10 or less; in these situations there can be more than 10-dB difference between the peak and average powers.

The capacity of the additive white Gaussian noise channel is given by the well-known Shannon equation (2)

\[
C = W \log \left( 1 + \frac{P}{N} \right) \text{ bps} \tag{2}
\]

where \( W \) is the bandwidth of the channel in hertz, and \( P/N \) is the average signal-to-noise power ratio of the channel. For an ALOHA channel transmitting with a throughput of \( S \) we calculate the multiple-access channel capacity \( C_a \) by multiplying the capacity expression in (2) by \( S \) and replacing \( P \) in (2) by \( P/G \), the average power during the transmission of a packet.

\[
C_a = SW \log \left( 1 + \frac{P}{GN} \right) = Ge^{-2G}W \log \left( 1 + \frac{P}{GN} \right). \tag{3}
\]

We can define \( r \), the efficiency of the ALOHA multiple-access channel, as the ratio of the ALOHA channel capacity to the capacity of the continuous channel using the same average power and the same total bandwidth.

\[
\frac{r}{C} = \frac{C_a}{C} = Ge^{-2G} \frac{\log \left( 1 + \frac{P}{N} \right)}{\log \left( 1 + \frac{P}{N} \right)}. \tag{4}
\]

The efficiency is plotted as a function of the channel traffic \( G \) for various values of the average channel signal-to-noise ratio \( P/N \) in Fig. 8.

In the original ALOHANET where the individual transmitters were not average-power-limited the throughput was an appropriate figure of merit for the channel. In a multiple-access channel which is average-power-limited, such as a battery-operated terminal or a satellite transponder, the efficiency of the channel protocol is a more appropriate figure of merit.

From (4) and Fig. 8, we see that the channel efficiency of an ALOHA channel approaches one for the important case of small values of throughput and small values of the signal-to-noise power ratio. In other words, under these conditions it is not possible to find a multiple access protocol which has a higher capacity for a given value of average power and a given bandwidth.

B. Spread-Spectrum Multiple Access

Perhaps the most succinct definition of spread-spectrum communications is due to Viterbi [23].

spreading ... refers to expansion of the bandwidth well beyond what is required to transmit digital data.

Similar but still not entirely precise definitions of spread spectrum can be found in other basic introductory works on spread-spectrum communications [17], [21], [26]. Note that this class of definitions is general enough to include an ALOHA channel. In this section we provide a more precise and restrictive definition of a general spread-spectrum communication channel which will be useful in dealing with the special case of a CDMA spread-spectrum channel.

Consider a transmitter in a channel band-limited to \( W \) hertz. Signals in the channel can be sampled at the Nyquist rate of \( 2W \) samples per second. For the case of the additive white Gaussian noise channel the maximum number of bits per sample is obtained from (2).

\[
C_s = \frac{1}{2} \log \left( 1 + \frac{P}{N} \right) \text{ bits/Nyquist sample}. \tag{5}
\]

As the bandwidth \( W \) of the channel is increased, the signal-to-noise ratio \( P/N \) will decrease and the maximum number
of bits per Nyquist sample will decrease. We define a spread-spectrum channel as any channel where $C_s$, the capacity in bits per Nyquist sample, is much less than one.

Under this definition, in a spread-spectrum channel the receiver is charged with the task of combining more than one, usually much more than one, samples for each received bit. This definition is general enough to encompass most systems covered by the definitions referred to at the beginning of this section, but it does exclude conventional ALOHA channels. And this definition has the virtue of emphasizing the point that spread-spectrum communications is concerned with the combination of many low information rate samples into a single (often binary) reliable symbol.

A key consequence of this property of a spread-spectrum channel is that the input signal of a spread-spectrum receiver can be quantized to two levels at the first stage of the receiver with little loss in overall system performance. In [18] we show that the loss in signal-to-noise ratio generated by such a binary decision at the first stage of the receiver is just

$$\pi/2 \text{ or } 1.96 \text{ dB}. \quad (6)$$

The fact that the input can be converted to a binary signal can of course be used to simplify the signal processing function of the receiver.

C. Code-Division Multiple Access (CDMA)

The first commercial application of spread spectrum was the C-100 micro earth station introduced by Equatorial Communications in 1981. That terminal used the spread-spectrum format for one-way satellite data broadcast applications rather than multiple-access applications. In 1984, Equatorial introduced the C-200 micro earth station using a spread-spectrum CDMA format for the first time in a commercial multiple-access data network.

The transmission of a signal from a single user in a multiple-access CDMA channel can be described in terms of a complex signal representation as shown in Fig. 9. The CDMA process is represented [17] as the multiplication of the data input signal $a(t)$ by a different coding signal for each user $b(t)$. The resulting transmitted signal is [18]

$$c(t) = a(t)b(t). \quad (7)$$

If we require that $b(t)$ the CDMA code spreading signal for this user satisfies

$$|b(t)|^2 = 1 \quad (8)$$

then the fundamental operation of the spread-spectrum receiver is to multiply the received signal plus noise, $c(t) + n(t)$, by the complex conjugate of the CDMA code-spread signal, $b^*(t)$, in order to recover the original information in $a(t)$.

$$[c(t) + n(t)]b^*(t) = a(t) + n(t)b^*(t). \quad (9)$$

This representation is general enough to include conventional forms of modulation, when $b(t)$ is a narrow-band carrier. But in the case of CDMA, the modulating carrier $b(t)$ is a different wideband carrier for each possible terminal in the network. This multiplicity of possible transmitter carriers is reflected in a multiplicity of receivers required at a CDMA base station in order to demodulate the received signal. Clearly, if the total number of potential data terminals in the network is much larger than the number of terminals active at any given time this requirement can introduce considerable complexity into the design of a CDMA multiple-access system.

D. Equatorial Communications CDMA

and Qualcomm CDMA

The two significant commercial CDMA data networks which have been built so far (one by Equatorial Communications and one by Qualcomm) have addressed this problem of different carriers used by different terminals in a CDMA system in two distinct ways.

In the Equatorial Communications satellite network composed of large numbers of C-200 micro earth terminals, each terminal was assigned a deterministic CDMA code-spreading sequence to form a different wideband carrier $b(t)$. In order to demodulate a user at the hub station then, it was necessary to install a separate card, called an "ear card," matched to each different spreading sequence, for each user authorized to transmit in the system. With the set of users changing on a daily basis, it was therefore necessary to insert and remove cards at the base station in order to keep current with the existing customer set. The maintenance logistics of such a design for a large network are not easy.

About a year after the introduction of the C-200 system, Equatorial Communications ran into financial difficulties and the company was reorganized and acquired by a larger telecommunications organization. It appears that the development of networks based upon the C-200 CDMA architecture was curtailed at that time.

The Qualcomm CDMA system provides an ambitious network design for use by voice traffic in a cellular-based telephone system. This design has been adopted as the IS-95 standard by the U.S. Telecommunication Industry Association. In the Qualcomm design, the problem of multiple carriers at the terminals and multiple receivers at the base station is handled by software rather than hardware as in the Equatorial system. The process begins by a remote terminal requesting access to the network. Since the terminals do not have a permanently assigned coding sequence, this request is sent via a separate ALOHA channel within the Qualcomm CDMA protocol [19].
Fig. 10. Receiver output with one transmitter in a CDMA channel.

After the ALOHA call request is received at the base station the terminal is assigned a spreading sequence and other setup parameters. These are transmitted to the requesting terminal by means of the broadcast channel from the base station. The spreading sequence is loaded into the terminal and a separate receiver matched to the assigned spreading sequence is assigned at the base station. In the present generation of the Qualcomm design, a maximum of 64 such receivers can be assigned [19].

The Qualcomm CDMA design eliminates the logistical problems associated with installing a separate “ear card” for each different spreading sequence as in the Equatorial Communications CDMA design. But in order to provide a different spreading sequence to each user in a dynamically changing user set, the Qualcomm system must provide a separate ALOHA request channel. In this respect, the Qualcomm design is similar to a DAMA system. As in any DAMA system the request channel introduces a delay and an overhead in the call setup process.

For a network serving only voice traffic it does not appear that this overhead and delay is a serious problem. But in a network which includes a significant amount of transaction traffic, or other digital traffic with less regularity than voice traffic, both the overhead and the delay could limit the network flexibility and the ability of the network to adapt to a more general traffic mix.

Because of the dynamic assignment of different spreading sequences, the Qualcomm base station does not require a separate receiver for each spreading sequence in the network, but it does require a separate receiver for each spreading sequence active in the network. In the present Qualcomm design the maximum number of such receivers in a single cell is fixed at 64. In principle, this number could be increased, but the requirement that a separate receiver be used for each different CDMA spreading sequence is a fundamental limitation on both the simplicity and the flexibility of CDMA operation.

E. Code Division in CDMA

That “code division” is the basic mechanism which allows a CDMA hub station to receive signals from different transmitters seems to be a common assumption in both the technical and the commercial literature of CDMA networks [27]–[29]. There is no doubt that different codes are used by different transmitters in a CDMA network, and there is no doubt that some number of transmitters can share a common channel with only a small probability of mutual interference. However, it does not necessarily follow from these two observations that code division is in fact the mechanism which allows the separation of transmissions from multiple users in a CDMA network. On the contrary, we now show that if we choose the same spreading code for all users in a CDMA system the channel will still have a multiple-access capability. In view of this observation it is not clear in what sense “Code Division” is in fact the multiple-access mechanism operating in a Code-Division Multiple Access channel.

Consider a CDMA channel transmitting chips at the rate of $R_c$ chips per second with a spreading factor of $g$, with $g \gg 1$. Then the bit rate for a single transmitter is

$$R_b = \frac{R_c}{g} \text{ bps.}$$  \hspace{1cm} (10)

A portion of a typical response of a matched filter or correlator detector at the hub station receiver to the signal from a single transmitter with a spreading factor $g$ equal to 128 is shown in Fig. 10. The bits of the received packet are offset from each other by 128 chips at the output of the detector. In this example we see the first three bits of the packet, (101...).

If we now add a second transmitter to the multiple access channel using the identical spreading sequence, and the hub receiver operates in a linear mode, a typical output of the receiver will appear as shown in Fig. 11.

In Fig. 11, the bits of the second packet (110...) are offset from the bits of the first by $d$ chips. In order to simplify the analysis we assume only integer values of $d$ are allowed. We can continue to add users to this multiple-access channel limited only by the self-interference terms of the single-spreading code as long as no user overlaps with any other user. If there are $k$ transmitters sharing the CDMA channel and all the offsets are chosen at random, the probability that a given bit will not overlap with some other bit is given by

$$\left(1 - \frac{1}{g}\right)^k.$$  \hspace{1cm} (11)

We can define $G$, the CDMA traffic in the channel, by $k = Gg$. Then in the limit for large spreading factors $g$, the probability that a given bit will not overlap with some other bit is given by

$$\lim_{g \to \infty} \left(1 - \frac{1}{g}\right)^k = e^{-G}.$$  \hspace{1cm} (12)
Fig. 11. Receiver output with two transmitters in a CDMA channel.

The form of the result in (12) suggests a connection between this view of CDMA and an ALOHA channel. In the next section we explore this connection.

The view of CDMA presented in this section is not a conventional one, so it may be helpful if we summarize here what we have shown and what we have not shown. In a CDMA system, multiple access capabilities exist whether different codes are used or the same code is used for transmitters in the shared channel. The acronym CDMA might just as accurately refer to Contention Division Multiple Access as to Code Division Multiple Access. A large value for the spreading factor, $g$, is necessary for the desired level of division in the channel; different codes are not.

Even though different codes are not required for multiple access in CDMA channels, the question remains as to whether anything can be achieved by using multiple coding sequences. The answer to this question is a qualified yes. In the case of multiple codes as well as in the case of a single code for all transmitters, the multiple access capability of the channel is a probabilistic one. As long as there are only a few transmitters in the channel both methods will work well and the probability of two transmitters interfering with each other will be small. Under these conditions, if both the multiple-codes system and the single-code system are compared using the protocols designed for the multiple-codes system, the multiple-codes system will have a smaller probability of interference while the single-code system will have a simpler implementation.

However, it is not necessary that a single-code system play by the rules of a multiple-codes system when a network is designed. When all transmitters use the same spreading sequence a number of system simplifications and code design options are available which can make both the throughput and the efficiency of a single-code system superior to that of the multiple-codes system even at low values of throughput.

A number of authors have obtained results which indicate the maximum value of the throughput of a multiple code CDMA system is somewhere between 0.10 and 0.20 [20]-[22]. A single-code system will have the same maximum throughput as an ALOHA channel, or 0.186. In view of these results, a tempting conjecture is that multiple codes do not increase the maximum throughput of a CDMA channel beyond that of a single-code system.

For the case of channel efficiency as defined in Section III-A the comparison of single-code CDMA systems and multiple-code CDMA systems is less equivocal. Single-code systems can achieve the efficiency of an ALOHA channel (Fig. 8). Since this efficiency approaches one for the important case of small values of throughput and small values of the signal-to-noise ratio, multiple codes cannot increase the throughput in such situations.

These results indicate that there is no clear advantage in either efficiency or throughput for the use of multiple codes in a CDMA system. We do not claim that no such advantage exists, but in view of the serious complexity problems of a multiple-codes system, the burden of proof should be on those who propose to use multiple codes for multiple access.

While the use of multiple spreading codes in a CDMA system is difficult to justify on the basis of the multiple-access operation of the channel, there are situations where multiple spreading codes can be of clear value. In the presence of severe multipath the unique code assigned to each terminal allows the use of a Rake receiver [30] tuned to each of these terminals. Since the signal from any given transmitter may arrive at the receiver with different delays, a unique code will simplify the process of sorting out various signal paths from a given transmitter. This advantage of multiple spreading codes is of greatest value for systems with severe multipath problems such as cellular voice networks. In the case of satellite channels and even in the case of a PCN using a microcellular structure the channel is less susceptible to multipath problems and this advantage is decreased.

F. Spread ALOHA Multiple Access

The bandwidth used in a conventional ALOHA multiple-access network is typically orders of magnitude less than that used in a spread-spectrum CDMA network. The bandwidth of the ALOHANET was approximately 30 kHz, while those of the ALOHA request channel in INMARSAT and the ALOHA data channel of the RAM Mobile Data network are roughly the same. The bandwidth of the ALOHA multiple-access channels on the numerous VSAT networks (such as the ATT/ITRON system) are typically much as 100 kHz. But this is still well below the 3 MHz used in the Equatorial CDMA channel, or the 1.25 MHz of the Qualcomm CDMA standard. Because of this great disparity in the typical bandwidths of these two techniques it is useful to ask what we can achieve in an ALOHA...
network if we employ the same frequency resources used in a CDMA network.

The distinction between a narrow-band multiple-access technique, such as ALOHA, and a spread-spectrum technique, such as CDMA, is not simply a matter of using a megahertz channel rather than a kilohertz channel. Rather, this distinction should be understood in terms of the ratio of channel bandwidth to data rate [23] as discussed in Section III-B. In the packet radio networks using ALOHA as well as the INMARSAT system and the various satellite networks using ALOHA multiple access, the burst data rate is close to the bandwidth of the channel. More precisely, the number of Nyquist samples per second required by the signal (2W per second, where W is the signal bandwidth in hertz) is close to the burst data rate measured in bits per second.

The consequence of this correspondence is that in a narrow-band multiple-access channel the received signal is designed to provide close to one bit per Nyquist sample. In a spread-spectrum system in general, and in a CDMA system in particular, much less than one bit of information per sample is provided by the signal. Thus a large number of Nyquist samples per received bit is required in such a channel.

In this section we analyze the operation of a wideband form of ALOHA multiple access. We refer to the operation of such a spread-spectrum wideband ALOHA channel as a Spread ALOHA channel. When we examine the operation of such a wideband ALOHA channel we discover that ALOHA multiple access and CDMA are but two ways of looking at the same multiple-access process. And most importantly, we show the equivalence between a Spread ALOHA channel and the single-code CDMA channel discussed in Section III-E.

1) High-Bandwidth ALOHA Multiple Access: Increasing the bandwidth of an ALOHA channel does not introduce anything new into the analysis of the multiple-access ALOHA channel. If the bandwidth of an ALOHA channel is increased by a factor of g, we can scale up the traffic in the channel by the same factor g. The same throughput versus traffic relation described in (1) and Fig. 6 will apply; and the same expression for efficiency given in (4) and Fig. 8 will also apply. We refer to such a channel simply as a high-bandwidth ALOHA channel as distinct from the Spread ALOHA channel, mentioned in the previous paragraph. In Fig. 12 we sketch the result of simply increasing the bandwidth in this manner.

From Fig. 12 we see that increasing the bandwidth by a factor g allows us to transmit each packet in a shorter time, thus increasing the channel throughput by the same factor g. In order to maintain the efficiency results of (4) and Fig. 8, we keep the energy per bit in the channel unchanged. This means that the power during a packet burst must increase by the same factor g in order to compensate for the decreased time per bit. Under these conditions the average power in the channel is unchanged.

2) Wideband ALOHA Multiple Access/Spread ALOHA: There is, however, a practical limitation which assumes importance in the implementation of a high-bandwidth ALOHA channel. Since the power transmitted during a packet burst must increase by a factor g, the instantaneous power required by a terminal in the network can be quite high. Values of g on the order of 100 to 1000 are of interest here if we are to use a bandwidth in an ALOHA channel comparable to that of a typical CDMA channel.

In order to decrease the burst power requirements of the terminals in the system then, we must spread the packet transmissions from each terminal in time. In other words, we start with the packets as shown in Fig. 12(b) and spread these packets so that the time duration of the packets is close to (or even greater than) the packets shown in Fig. 12(a). The spread packets which result from this operation, however, differ from those in Fig. 12(a) since the bandwidth of the resulting time-spread packets is the same as the bandwidth of the packets in Fig. 12(b). In other words, these time-spread packets use a large number of Nyquist samples per bit, while the packets of Fig. 12(a) typically require one sample per bit. The time spreading of the packets allows us to decrease the average power of the bursts from each terminal while still retaining the original value of the average power in the channel and retaining the high bandwidth of the channel. And since the number of Nyquist samples per bit is large, this channel qualifies as a spread-spectrum channel under the definition provided in Section III-B.

There are several ways to achieve the time spreading we want in this process [24], but perhaps the simplest is illustrated (for the case of a packet composed of only 6 bits, using a spreading sequence of 7 bits) in Fig. 13. Realistic values of the number of bits in a packet and the length of a spreading sequence are of course much greater.

The same expression for the efficiency of the ALOHA channel given in (4) and Fig. 8 will apply to the Spread ALOHA packets since neither the energy per bit nor the
average power in the channel is affected by the spreading process. In the case of Spread ALOHA, however, it might appear that the increased packet length will result in many more packet collisions in the ALOHA channel and therefore a greatly decreased channel throughput as given in (1) and Fig. 6.

Although it is true that the Spread ALOHA process we have described will result in a large number of packet overlaps in the multiple-access channel, it is not true that these overlaps will result in an overall lower value of packet throughput as would be the case in a narrow-band ALOHA channel. The reason for this difference in the Spread ALOHA channel can be seen by considering the process of signal detection in a wideband channel.

In a conventional narrow-band ALOHA channel where the Nyquist rate and the bit rate are roughly equal it is reasonable to assume that two packets which overlap in time in the channel will both be lost. For the case of a wideband channel such as used in Spread ALOHA however, two packets from different transmitters which overlap in the channel may still be received correctly if the packets do not overlap at the output of the hub receiver. This distinction will be significant when the hub receiver can compress the packets received from different transmitters in the multiple-access channel. This kind of compression can take place when the number of Nyquist samples per bit in the packet is large; that is, in the case of a CDMA packet or the case of a Spread ALOHA packet. This kind of packet reception is illustrated with two overlapping packets in Fig. 15. The bit samples of the two packets at the output of the receiver will in general be interlaced so that the two packets, or even a larger number of packets, may be correctly interpreted by the receiver.

In order for such compression of a Spread ALOHA packet to occur we must choose the spreading sequence so that it has the proper autocorrelation sequence with low sidelobes. But only one sequence with these properties is required in a Spread ALOHA channel. Of course it may happen that two packets overlap in precisely the worst possible way, so that the compressed bits from one packet align precisely with at least some of the compressed bits from another packet. In these cases we must repeat the packets just as is done in a conventional ALOHA channel. But the probability of such destructive contention in the channel is identical to that of a conventional ALOHA channel, so that we can use the throughput versus traffic results of (1) which apply without change to the Spread ALOHA channel.

In order for such compression of a CDMA packet to occur it is necessary to choose a set of spreading sequences with low sidelobes and also with low cross correlation properties among all of the different spreading sequences used in the network. If there are \( n \) such terminals in the network there are \( n(n - 1)/2 \) different cross correlation sequences to be taken into account. It is not clear how successful the effort to find such a family of sequences was in the Equatorial Communications CDMA system. In the Qualcomm CDMA system these sequences are chosen at random, and the statistical properties of random sequences are relied upon to provide acceptable isolation of one transmitter from another. This statistical approach has been criticized by some authors [25] and as a theoretical point of view this criticism is justified. Nevertheless, the Qualcomm statistical approach to the analysis of this interference problem seems appropriate as a practical guide to systems design as long as the spreading sequences are long enough.

IV. SUMMARY
The choice of a multiple access architecture for a data network should begin with an understanding of the statistics of the traffic to be transmitted on the multiple-access channel. Of particular importance here is the regularity of the traffic from a single terminal and the size and stability of the set of users transmitting on the network. When network traffic is composed of analog voice signals generated by a fixed set of transmitters, there is little alternative to the use of simple FDMA. When these signals are digitized to provide continuous and constant rate digital signals the option of a TDMA structure can be considered.

If the set of transmitters on the network changes rapidly enough, a DAMA architecture to assign capacity on demand will be called for. Capacity within a DAMA system can be allocated on the basis of frequency, on the basis of time, or on the basis of both frequency and time. The design of the request channel for a DAMA system presents a new level of multiple access choices. When the set of possible transmitters is small, say less than 100, a fixed-allocation architecture (such as TDMA) in the request channel is a possibility. However, for many of the networks of interest today, the set of possible users is much greater than this. In these circumstances the only alternative appears to be an ALOHA architecture in the request channel as used in both the Inmarsat DAMA system and in the Qualcomm CDMA system.

During the past few years, considerable activity in the analysis of multiple-access channels has been generated by the need to replace the existing analog cellular telephone network with a digital system providing much higher capacity. A variety of TDMA-based standards and a single CDMA standard for this upgrade have been proposed around the world [7]. The throughput of both the existing analog system (AMPS in the United States) and the various TDMA systems proposed is limited by the fundamental in-
ability of these systems to reuse frequency or time resources in contiguous cells. The throughput of a random-access channel, such as CDMA or ALOHA, does not suffer from such a geometric limitation and therefore these multiple access architectures have the potential for considerably greater throughput.

This potential for higher throughput of a random access architecture is enhanced by a number of secondary features of these architectures which are not properly part of the multiple access system itself. Among these secondary features are voice packetization and compression, advanced power control, and soft hand-off. Each of these features can be integrated within a total system design more easily using the quasi-orthogonal signal approach of a random access architecture (either ALOHA or CDMA) rather than the orthogonal signal approach of conventional FDMA and TDMA architectures.

Existing multiple-access networks which employ a random access architecture tend to be of two different types—narrow-band systems such as RAM Mobile Data and a variety of VSAT networks using variations of an ALOHA protocol; and wideband systems such as the Equatorial Communications C-200 micro earth station and the Qualcomm cellular network using two different implementations of CDMA. The use of multiple spreading codes in each of these CDMA systems results in an undesirable level of system complexity. And in the Qualcomm system, the call setup procedure seems to limit the flexibility of the system to serve a wider variety of traffic than that generated by voice terminals.

In Sections III-E and -F we show that the use of multiple codes in a CDMA network is not necessary in order to achieve multiple access capability. A single code can greatly reduce the complexity of a CDMA system. We introduce a spread-spectrum version of an ALOHA channel (Spread ALOHA) which is equivalent to a CDMA channel with a common spreading code for all users. The equivalence we demonstrate opens the door to a variety of techniques used in conventional ALOHA channels [6] which can significantly increase both the throughput and the efficiency of the channel.

REFERENCES

Engineering and Professor of Information Sciences at the University of Hawaii. At the University of Hawaii he served as a Chairman of the Information and Computer Sciences Department and as a Director of THE ALOHA SYSTEM—a university research project concerned with new forms of computer communication networks. He was a founder of Database Associates in 1984, and in 1994 he assumed the position of Vice President, DBA/Wireless Systems. He has taught communication theory, computer networks, and satellite communication courses at Berkeley, Harvard, and MIT, while on visiting appointments. He has served as a Consultant in data networks and satellite communications to government and industrial laboratories in the United States. He has also served as an expert in computer networks for the ITU/Geneva and for the United Nations in Asia and in Europe. In 1993 he edited Multiple Access Communications: Foundations for Emerging Technologies for the IEEE Press. This work provides a view of multiple-access technology for use in LAN’s, packet radio networks, satellite networks, and PCN’s.