Advances in Packet Radio Technology

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Invited Paper

***Abstract*—Packet radio (PR) is a technology that extends the application of packet switching which evolved for networks of point-to-point communication lines to the domain of broadcast radio. It offers a highly efficient way of using a multiple access radio channel with a potentially large number of mobile subscribers to support computer communication and to provide local distribution of information over a wide geographic area. We discuss the basic concepts of packet radio in this paper and present the recent technology and system advances in this field. Various aspects of spread spectrum transmission in the network environment are identified and our experience with a testbed network in the San Francisco Bay area is discussed.**

I. Introduction

AN EXCITING set of developments has taken place during the last few years in the field of digital radio networks. The advantages of multiple access and broadcast radio channels for information distribution and computer communications have been established and several experimental digital radio networks are now in operation. Packet radio is a perfect example of the rapid technological progress which has been achieved. It utilizes packet-switched communications and is particularly important for computer communications in the ground mobile network environment. In this paper, we provide an overview of the basic concepts of packet radio and discuss the recent technology and system advances in this field. We also address the closely related subjects of signaling in the ground mobile radio environment and the advantages of spread spectrum technology in the multiple access network environment. This paper is intended to be tutorial with emphasis on the current state-of-the-art in packet radio.

The rapid growth in packet communications which has taken place during the last decade following the successful development of the ARPANET [1], [2] is directly related to the increasing demand for effective telecommunication service to handle computer communications [3], [4]. Only in this time frame did it become cost effective to utilize minicomputers, and later microprocessors as packet switches in a large scale network [5]. In a packet-switched network, the unit of transmission is called a packet. It contains a number of data bits, and is usually of variable length up to a maximum of a few thousand bits. A packet includes all the addressing and control information necessary to correctly route it to its destination.

Packet switching was originally designed to provide efficient network communications for "bursty" traffic and to facilitate computer network resource sharing. It is well known that the computer traffic generated by a given user is characterized by a very low duty cycle in which a short burst of data is sent or received followed by a longer quiescent interval after which additional traffic will again be present. The use of dedicated circuits for this traffic would normally result in very inefficient usage of the communication channel. A packet of some appropriate size is also a natural unit of communication for computers. Processors store, manipulate, and transfer data in finite length segments, as opposed to indefinite length streams. It is therefore natural that these internal segments correspond to the computer generated packets, although a segment could be sent as a sequence of one or more packets. Computer resource sharing techniques which exploit the capabilities inherent in packet communications are still primarily in the research stage, but significant progress has already been achieved in this area [6].

The packet switching concept incorporates individual per-packet processing by each switch or node in the network such that incremental network capacity can be dynamically allocated by a node immediately after it receives a packet. Each packet wends its way from node to node through the network until eventually it arrives at the final destination and is delivered. The transit time through the network is typically a fraction of a second. Due to the low duty cycle of individual user traffic, allocating a portion of the network capacity for that user in advance (e.g., to provide a dedicated circuit) could also lead to very inefficient use of the network resources even if the allocation is valid over a very short time.

An essential attribute of any network is its ability to provide full connectivity among all network participants. Full connectivity implies that any set of computers can communicate subject only to the overall network performance and administrative limitations. Specific performance parameters or constraints such as throughput, delay, cost and reliability are usually quite important to the critical mass of interconnected subscribers. Within a given network environment, delay, throughput, and cost are intricately related because lower delay usually means higher data rates which, in turn, implies higher throughput and greater cost. Of course, the delay can never be reduced below the speed of light propagation delay.

Packet radio [7] is a technology that extends the original packet switching concepts which evolved for networks of point-to-point communication lines to the domain of broadcast radio networks. The rapid development in this area has been greatly stimulated by the need to provide computer network access to mobile terminals and computer communications in the mobile environment. Packet radio offers a highly efficient way of using a multiple access channel, particularly with mobile subscribers and large numbers of users with

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bursty traffic. During the early 1970's, the ALOHA project at the University of Hawaii demonstrated the feasibility of using packet broadcasting in a single-hop system (see reference [8], [9]). The Hawaii work led to the development of a multihop multiple access packet radio network (PRNET) under the sponsorship of the Advanced Research Projects Agency (ARPA). The PRNET is a fundamental network extension of the basic ALOHA system and broadens the realm of packet communications to permit mobile applications over a wide geographic area. The use of broadcast radio technology for local distribution of information can also provide a degree of flexibility in rapid deployment and reconfiguration not currently possible with most fixed plant installations. Although the original impetus for packet radio development was and still is largely based on tactical military computer communication requirements [10], the basic concept is applicable to an extremely wide range of new and innovative computer communication applications never before possible in any practical way.

In addition to the strong ARPANET and ALOHA system influences, three technical developments in the early 1970's were largely responsible for the evolution of packet switching to the radio environment. The first was the microprocessor and associated memory technology which made it possible to incorporate computer processing at each packet radio network node in a form that was compatible with mobile usage and portable operation. The second was the reduction to practice of surface acoustic wave (SAW) technology which can perform matched filtering (to receive wide-band radio signals) on a very small substrate of quartz or similar piezo-electric material. The third development was purely conceptual and involved an awareness within the computer and communications communities of the importance of "protocols" in the development of network management strategies. It was upon those three pillars that the technical approach to the PRNET was founded.

Packet radio network technology will be essential for military and other governmental needs as terminals and computer systems become pervasive throughout essentially all aspects of their operations. Initially, the needs for radio-based computer communications are expected to be prevalent in training, on or near the battlefield, and for crisis situations. The first operational systems, even if of limited availability, are most likely to be deployed for use in one of these areas where a higher relative cost of providing the advanced capability can be tolerated. Within the civilian sector, there is also a strong need for terminal access to information in the mobile environment, but the cost of service to the user (e.g., personal terminal, tariffs) will dictate when such capabilities should be publicly provided. We expect to see a considerable increase in the usage of civilian terminals and microcomputers "on the move" during the early 1980's but, in contrast to the military environment, these applications are expected to involve relatively simple equipment, reduced capabilities and lower costs.

All users in a packet radio network are assumed to share a common radio channel, access to which is controlled by microprocessors in the packet radios. In contrast to a CB radio channel in which contention for the channel is directly controlled by the users (who at best can do a poor job of scheduling the channel), the packet radio system decouples direct access to the channel from user requests for channel access. Within a fraction of a second, the microprocessors can dynamically schedule and control the channel to minimize or avoid conflicts (overlapping transmissions) particularly when the transmissions are very short. The use of computer control for channel access can lead to very efficient system operation relative to other more conventional manual methods of access control [11].

In recent years, the subject of efficient spectrum utilization has received increasing attention. A special issue of *IEEE Transactions on Electromagnetic Compatibility* on spectrum management [12] addresses this topic in considerable detail. This subject is not addressed further in this paper, other than to note that because of its capability for dynamic allocation of the spectrum, packet radio is a particularly good choice to obtain efficient utilization for bursty traffic. The ability to achieve effective usage of the spectrum will be a central factor along with cost in determining the ultimate viability of radio based networks for local distribution of information.

In this paper, we discuss the basic concepts of packet radio and present the recent technology and system advances. In Section II, we indicate various capabilities and services which a packet radio network might provide. In Section III, we consider the problem of signaling over a ground radio channel with all its attendant environmental factors. In Section IV, we discuss the basic operation of a packet radio network with underlying emphasis on the network elements and system protocols. In Section V, we discuss several advanced system capabilities for operation and control of the packet radio system. In Section VI, we separate out a subject of particular interest, namely spread spectrum transmission in the network environment. Although a packet radio system need not employ spread spectrum, there are several noteworthy attributes arising from its use. The experimental packet radio network (PRNET) under development by the ARPA is discussed in Section VII. The final section contains conclusions.

II. Capabilities and Services of a PR Network

A primary objective of a packet radio network is to support real-time interactive communications between computer resources (hosts) connected to the network and user terminals (e.g., terminal–host, host–host, and terminal–terminal interactions). In order to satisfy this objective, the network should provide certain basic capabilities and services which can be grouped roughly into two categories: those which are always or automatically provided by the network and those which a user may select based on his application. The former category includes such capabilities as network transparency, area coverage/connectivity, mobile operation, internetting, coexistence, throughput with low delay, and rapid deployment. The last category includes error control options, routing options, addressing options, and services for various tactical applications.

We identify here a few of these basic packet radio network services and capabilities. While the list is not intended to be exhaustive, those items on it are all major factors of interest.

We assume that computer resources (hosts) need to be connected with each other and with individual users who might access data bases, manipulate files, run programs or write and execute programs to run on remote hosts. The packet radio network merely provides a high throughput, low delay means of interconnection for the (potentially mobile) community of users. Many of these operations will be interactive, with a computer response to a remote user entry being desired in real-time. Although the primary objective of the net is to provide service to computer communication traffic, other types of service, such as might be required for real-time speech, can be accommodated along with the capability for end-to-end security based on packet encryption techniques.

A. Transparency

The basic internal operation of the network should be transparent to the user. We use this term to mean that all user data presented to the net should be delivered to the destination without modification of the information content in any way. Only the data to be delivered, and the necessary control and addressing information should be required of the user as input. All other aspects of routing, reliable delivery, protocols and network operation should be handled by the network itself. Only in the case of communication difficulties should the user or user process be advised of internal network status. Transparency is desirable in order to allow the network to regulate and optimize its internal flow of traffic in a global manner without unnecessary constraints applied by users. The users, in turn, need not be concerned with the activities taking place in the net or their effect on network operations, but need only specify the services desired.

B. Area Coverage and Connectivity

Area coverage with full connectivity should be provided. For ground mobile radio, network diameters on the order of 100 miles are appropriate, but the system architecture should allow the geographic area of coverage to be expanded at the expense of increased end-to-end delay across the network. All valid traffic originators within the net must be provided connectivity with all other valid receivers subject only to the overall reliability and performance of the system. The network need have no prior knowledge of which users may wish to connect to which other users or resources in the net. This is particularly important (and necessary) for the mobile subscribers.

C. Mobility

The system should support mobile terminals and computers at normal vehicular ground speeds within the area of coverage. Packet radios in mobile applications must satisfy reasonable size, weight, and power consumption constraints.

D. Internetting

The packet radio network structure should be capable of internetting in such a way that a user providing a packet address in another net can expect his network to route the associated packet to a point of connection with the other net or to an intermediate (transit) net for forwarding. Similarly, arriving internet packets should also be routed to the local user.

E. Coexistence

Radio frequency characteristics of the packet radio system should allow coexistence with existing users of a chosen frequency band. This could provide a greater degree of spectrum sharing, particularly among similar systems, and may facilitate the introduction of the technology in new geographic locations.

F. Throughput and Low Delay

The capacity of the packet radio system should allow for variable length packet sizes up to a few thousand information bits, and provide delivery of packets with delays on the order of 0.1 s in nets of 100 mi area coverage size. Parameters on this order are required to provide the real-time interactive services, and to accommodate efficient data transfers. With 100 kbits/s signaling rates, a maximum packet size might be a few thousand bits.

G. Rapid and Convenient Deployment

Deployment of the packet radio net should be rapid and convenient, requiring little more than mounting the equipment at the desired location. No alignment procedure should be required, and in most applications omni-directional antennas would be used, thus eliminating the need for antenna alignment. Once installed, the system should be self-initializing and self-organizing. That is, the network should discover the radio connectivity between nodes and organize routing strategies on the basis of this connectivity and on the source/destination data of traffic presented to the net. Packet radios should be capable of unattended operation.

H. Error Control

Data integrity is crucial for most computer applications. Error control should be provided by the network, so that packets delivered to a user with undetected errors occur less frequently than about one in 10^{10} packets. This is a critical requirement for computer communications, since even one undetected error in a large file may render it useless or cause troublesome and unpredictable problems during subsequent use of such a file. While detection of errors is essential, choices exist in dealing with the detected errors. In some cases, error detection and retransmission may be used, while in other environments, more sophisticated forward error correction technology must be used in order to maintain satisfactory throughput and delay when communicating through land mobile radio channels.

I. Routing Options

The network should support efficient communication between any pair of users and the capability for users to broadcast a packet to a subset or to all users on the net. Land mobile radio traditionally has been used for point-to-point voice communications. Dispatching services, walkie talkies, and, recently, CB radio all have supported a broadcast mode of operation as well. These capabilities could be requested by a "type of service" field provided by the user in the packet header.

J. Addressing Options

The network should provide a capability for addressing a subset of the network participants and for efficiently establishing communication among them. This might be used for real-time conferencing or to support message delivery to a list of addressees with the minimum number of network transmissions. Logical network connectivity is a necessary foundation upon which protocols for these services can be built.

K. Tactical Applications

In tactical military applications, the RF waveform used by packet radios should provide resistance to jamming, spoofing, detection, and direction finding. In many cases, waveforms with these capabilities lead naturally to the capability for position location and relative navigation. With the addition of a communication security function, the packet radio net would then provide an integrated communication, navigation, and identification system for secure tactical use.

III. Signaling in the Ground Radio Environment

Packet radio technology is applicable to ground-based, airborne, seaborne, and space environments. In this paper, we focus on ground-based networks which encounter perhaps the most difficult environment in terms of propagation and RF connectivity. Ground radio links, particularly when mobile terminals are involved, are subject to severe variations in received signal strength due to local variations in terrain, man-made structures and foliage. In addition, reflections give rise to multiple signal paths leading to distortion and fading as the differently delayed signals interfere at a receiver [13]. As a result of these phenomena, RF connectivity is difficult to predict and may abruptly change in unexpected ways as mobile terminals move about. An important attribute of a packet radio system is its self-organizing, automated network management capability which dynamically discovers RF connectivity as a function of time for use in packet routing. The multipath phenomena also provide a strong motivating factor for the use of spread spectrum waveforms in packet radio systems. In the paragraphs which follow, we first bound (roughly) the radio frequency choices which are most appropriate for ground-based radio networks. We then discuss the characteristics of propagation path loss, multipath effects, and man-made noise at these frequencies, and conclude with a discussion of spread spectrum signaling [14] and its applicability to ground-based packet radio systems.

A. Frequency Band

The operational characteristics of the radio frequency band have a major impact on the packet radio design. The lowest and highest frequencies which can be used for a packet radio system are determined primarily by considerations of bandwidth and propagation path loss (and the associated RF power generation requirement) respectively.

The required systems bandwidth effectively determines the lowest desirable radio frequency in two ways. Practical, cost-effective radio equipment is difficult to achieve if the ratio of RF bandwidth to RF center frequency is much larger than about 0.3. This lower bounds the range of acceptable RF center frequencies. In practice, a center frequency well in excess of this lower bound is also desirable if the received signals would otherwise have too wide a multipath spread (e.g., due to sky wave phenomena at HF). For a packet radio system to deliver 2000 bit packets through a network with delays on the order of a tenth of a second, the data rate of the system must be in the range of a few hundred kilobits per second, which implies RF bandwidths of a few hundred kilohertz. From an implementation point of view, then, the RF center frequency should be at least a few megahertz, or in the lower high-frequency (HF) band extending from 3 MHz to 30 MHz. Propagation in the HF band can provide long distance communication due to sky wave reflections from the earth's ionosphere, but the propagation suffers from noticeable multipath spreading of the signal which, as will be described later in the section, limits the data-rate of signals which can be used. Multipath spreading in the very-high-frequency (VHF) band from 30 MHz to 300 MHz, where line-of-sight propagation dominates, is typically reduced to a few microseconds as compared to the millisecond spreads encountered at HF, and data rates on the order of a hundred kilobits can be supported. Multipath fading and distortion are still a problem at VHF, particularly for terminals which are mobile or do not operate with radio line-of-sight. However, diversity techniques or the spread spectrum signaling techniques discussed later can overcome these difficulties.

The upper limits on usable radio frequencies for packet radio are primarily established by propagation path loss. As the operating frequency rises to about 10 GHz, absorptive losses due to the atmosphere and rain rapidly increase, and the resulting radio range is reduced accordingly. In general, packet radio systems must use closely spaced relays in order to provide adequate area coverage at these frequencies. The cost of providing a dense relay population may be acceptable if the distribution of users is also dense and if packet radios co-located with the users can provide the relay function. For most applications, however, 10 GHz is a practical upper limit for a useful radio frequency in a ground-based packet radio system. We conclude, then, that practical packet radio systems should use radio frequencies in the upper VHF band, in the ultra-high-frequency (UHF) band from 300 MHz to 3 GHz, and in the lower portion of the super high frequency (SHF) band from 3 GHz to 30 GHz.

An additional factor which must be considered for operational systems is the authorization to radiate packet radio transmissions. The VHF and UHF bands are already heavily allocated. The use of spread spectrum signals potentially could allow coexistence of a packet radio system with existing users of some frequency band. However, this is a relatively new concept from the regulatory point of view, and significant technical issues would have to be resolved to establish the feasibility of coexistence.

The discussion of propagation, multipath, and background noise which follows focuses on the UHF band, although, qualitatively, the phenomena discussed apply to the VHF and SHF bands as well. Later sections of the paper describe an experimental packet radio which operates at 1710–1850 MHz in the upper UHF band.

B. Propagation Characteristics

Packet radio network operations would be greatly simplified if all radios were sited such that a radio line-of-sight path existed to nearby radios. Link design procedures for such paths are well understood, and RF connectivity within the network would then be fixed and reliable. Such stringent restrictions on siting are not reasonable from the user point of view, however. Many users of a packet radio network will have to operate from facilities previously established without consideration of radio propagation. Use of packet radio in a mobile environment would be almost useless if siting were required for reliable operation.

The minimum theoretical path loss is achieved on a radio link in free space (i.e., a vacuum), where received signal strength decreases as the inverse square of link range. For a ground radio link, the path loss of free space may be approached on a link having a radio line-of-sight path, although even under this desirable condition diffraction and multipath phenomena can greatly reduce received signal strength.

When a radio line-of-sight path does not exist on a given link, one can still speak of sited or non-sited terminals, due to

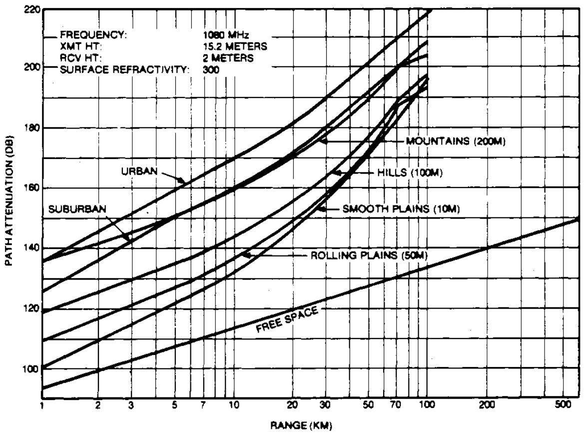

Fig. 1. Path loss versus range. 15-m transmitter height.

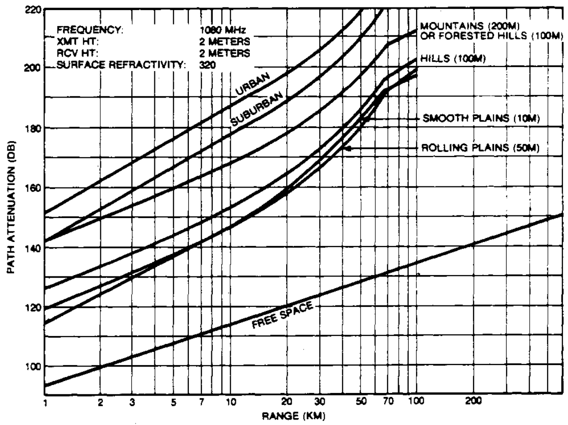

Fig. 2. Path loss versus range. 2-m transmitter height.

the strong influence of shadowing by local terrain and objects and of the elevation of the antenna above the ground. A sited terminal is one which has been located to avoid surrounding obstacles and whose antenna has been elevated to the maximum extent possible, while a terminal operating from a moving vehicle would generally be nonsited.

Average path attenuation exceeds that of a free space radio link by a significant amount in the ground radio environment, depending on the type of terrain and the elevation of the radio antenna. The curves in Fig. 1 and 2 show path loss as a function of link range for a frequency near 1 GHz, and illustrate these dependencies for two different transmitter heights. These curves are typical of propagation of UHF, and the variation of mean path loss as a function of frequency is typically much less than the variations due to terrain at a particular frequency. For example, the mean path loss from 700 MHz to 2000 MHz varies about 8 dB, while path loss at a 20-km range is seen from the figure to exceed that of free space by 25 to 80 dB depending on terrain and antenna heights. Furthermore, the path loss in urban and suburban areas, where many area coverage packet radio net applications might occur, is more severe than that of most natural terrain. The curves shown reflect average values of path loss which apply to a link of a given length which is randomly selected without regard to user siting. Well sited radios will typically encounter less path loss than shown in the curves, while poorly sited radios will encounter larger path losses [35], [36]. These factors lead to large variations in achievable radio range among users and make RF connectivity difficult to predict in a large, mobile user community. The objective of packet radio net design is to overcome this difficulty without placing undue restrictions on allowable user locations. In general, this requires automated network management procedures capable of sensing the existing RF connectivity in real-time and instantly exploiting this connectivity for network control and packet routing.

In addition to the wide variations in path loss, the ground-mobile, nonsited radio channel is subject to the effects of multipath propagation. When several differently delayed versions of the radio signal arrive at a receiver, constructive and destructive interference results. For stationary users, the effect of this phenomenon is that additional attenuation of the signal may be observed when the receiver is located at a point on the ground where the signal interference is destructive. Nulls on the order of tens of decibels may be observed. When communicating users are in motion, or when a multipath component arises from a moving reflector, received signal strength fading is observed as a function of time. The rate of fading is proportional to the velocity of user motion. Movement by a mobile user of only a few meters can cause received signal strength to drop below the threshold of the receiver, thus effectively disabling the link. Radio connectivity to a mobile terminal may change dramatically even for small displacements, and for continuous motion, signal strength may fluctuate above and below the receiver threshold several times during the reception of a packet, causing several short bursts of errors in the data or even loss of synchronization altogether.

We assume the modulation technique used by the packet radio results in a transmitted signal which is structured as a sequence of identifiable segments called symbols, where each symbol is one of a finite set of waveforms. In a simple binary modulation technique, one of two symbols is selected for each transmitted bit, depending on the value of the bit. In a spread spectrum system, the set of symbols may change with time, but a binary system would still choose each transmitted symbol from the set of two, which is in use at that particular time. Typically, a receiver processes the arriving waveform symbols one at a time, making a decision on each one as to which of the finite set has been received. The existence of multipath signal components affects the reliability with which symbol decisions can be made by causing symbol distortion and intersymbol interference. Intersymbol interference occurs when a symbol is overlapped by the delayed components of adjacent symbols. Such interference can lead to lower limits on symbol error probability which cannot be improved by increasing the signal to additive noise ratio on the radio link. When simple modulation techniques, such as phase-shift keying (PSK), are used, the symbol rate must be low enough that only a small portion of the symbol is overlapped by multipath signals of adjacent components. More sophisticated receivers (e.g., using adaptive equalization) can improve performance by suppressing the multipath components, but in order to do so they must rapidly obtain good estimates of the channel impulse response, which can be very difficult if not impossible to achieve. Spread spectrum signals are capable of reducing intersymbol interference effects, as described in Section III-D.

One way to break through the intersymbol interference barrier and achieve megabit rates with binary signaling is to use an

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