IEEE TRANSACTIONS ON COMMUNICATIONS

AUGUST 1989 VOLUME 37 NUMBER 8 (ISSN 0090-6778)

A PUBLICATION OF THE IEEE COMMUNICATIONS SOCIETY

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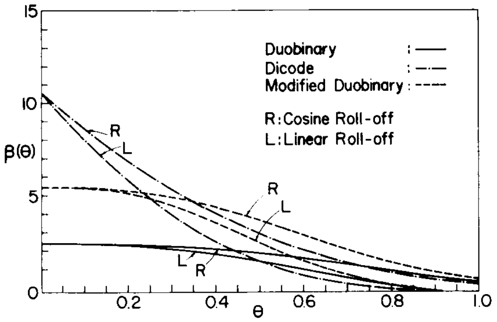

Fig. 1. $\beta(\theta)$ for continuous filters.

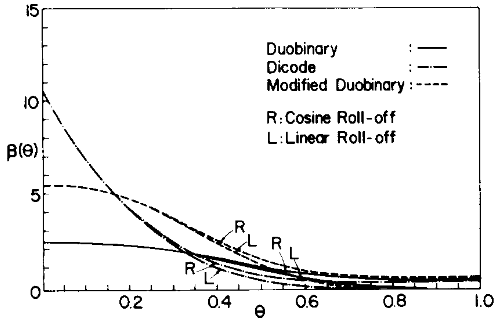

Fig. 2. $\beta(\theta)$ for modified filters.

filters $G(f)$ used in the system are cosine roll-off (C), modified cosine roll-off (MC), linear roll-off (L) and the modified linear roll-off (ML) filters. The spectra of these filters are given in the above paper.[1]

Figs. 1 and 2 show $\beta(\theta)$ (with $T = 1$) for all PRS systems for normal and modified filtering, respectively. The best performance is obtained with the duobinary signaling for $\theta < 0.5$ for the continuous filters and for $\theta < 0.35$ for the modified ones. Dicode gives the largest values for the low values of θ. This result is in contrast to the conclusions in the paper[1] where it is stated that jitter performance of dicode is the best of all and that of the duobinary is the poorest. It seems that the normalization of $\beta(\theta)$ curve to $\beta(0)$ prior to plotting them (Appendix of the paper[1]) has caused this misinterpretation. Actually, it is true the rate of decrease of normalized $\beta(\theta)$ functions is highest for dicode signaling as stated in the paper.[1] However, $\beta(\theta)$ should not be normalized for comparing the three PRS systems, since the samples of $r(t)$ at optimum time instants take the same values for all techniques.

Author's Reply

A. GRAMI AND S. PASUPATHY

We thank Y. Tanik for drawing our attention to the issue of normalization of $\beta(\theta)$. As stated in the Appendix to our paper,[1] we have indeed plotted the normalized measure $\beta(\theta)/\beta(0)$ in our figures. This was done in order to study the effect of excess bandwidth θ on the rate of decrease in sensitivity to timing phase jitter and also to show clearly that the relative sensitivity stops decreasing after a certain value of θ for certain schemes. As mentioned in our paper, such normalized plots show (and we quote) ''the rate of decrease in $\beta(\theta)$ as a function of excess bandwidth is more significant in $1 - D$ than in $1 + D$ and $1 - D^2$.'' This is also consistent with the other results our our paper, namely, the rates of increase in speed tolerance and eye width (slopes of Figs. 5 and 6) are more significant for $1 - D$ than for the other schemes. However, Tanik is also correct in his interpretation of the plot of (unnormalized) $\beta(\theta)$. In terms of the absolute performance measure $\beta(\theta)$ [as well as in terms of speed tolerance and eye width] $1 + D$ is the best of all. Thus, in summary, unnormalized and normalized $\beta(\theta)$ how different aspects of timing jitter sensitivity as a function f excess bandwidth.

Packet Reservation Multiple Access for Local Wireless Communications

D. J. GOODMAN, R. A. VALENZUELA, K. T. GAYLIARD, AND
B. RAMAMURTHI

Abstract—**Packet reservation multiple access (PRMA) allows a variety of information sources to share the same wireless access channel. Some of the sources, such as speech terminals, are classified as ''periodic'' and others, such as signaling, are classified as ''random.'' Packets from all sources contend for access to channel time slots. When a periodic information terminal succeeds in gaining access, it reserves subsequent time slots for uncontested transmission. Computer simulations and a listening test reveal that PRMA achieves a promising combination of voice quality and bandwidth efficiency.**

I. BACKGROUND

Wireless access to public telecommunications networks is at present a topic of intense interest to researchers, developers, manufacturers and service providers throughout the world. There are healthy markets for the present generation of cellular mobile telephone services and residential cordless telephones. Plans for second generation products and services are advancing rapidly [1], [2], [3].

Looking further into the future, we see several wireless access issues that remain to be resolved. Three important questions are as follows:

1) how to create wireless private branch exchanges and local area networks that fill a gap between mobile telephony (serving a metropolitan area) and cordless telephones (serving a single residence),

2) how to use the same resources to communicate efficiently voice, computer data, images and other types of information, and

3) how to unify a variety of wireless access modes including cellular radio, cordless telephones, wireless private branch exchanges, wireless local area networks, dispatch services, and radio paging.

Paper approved by the Editor for Voice/Data Networks of the IEEE Communications Society. Manuscript received March 14, 1988; revised September 6, 1988. This paper was presented at the IEEE 38th Vehicular Technology Conference, Philadelphia, PA, June 1988. This work was performed while the authors were at AT&T Bell Laboratories, Holmdel, NJ 07733.

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IEEE Log Number 8929108.

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This paper examines a key component of all of these issues, the multiple-access technique. Current and emerging systems use frequency division [1], [3] and time division [2] to provide many users with simultaneous access to the same wireless medium. Code division is another alternative that has received extensive attention [4], [5]. Here we explore a fourth one, packet contention.

Packet contention techniques such as ALOHA and carrier sense multiple access [6] find widespread use in data communications, including common control channel signaling in cellular mobile radio systems [7]. Among the principal merits of packet contention methods is their ability to serve a large number of terminals, each with a low average data rate and a high peak rate. While they function with little or no central coordination, packet contention techniques often make inefficient use of the shared transmission medium. When too many terminals try to communicate at once, throughput goes down and transmission delay increases substantially. While recent studies [8], [9], [10] indicate that packet contention schemes perform better in local radio environments than elsewhere, unpredictable, possibly long, delays have made packet contention appear unattractive for voice transmission.

Addressing this problem, this paper explores PRMA, packet reservation multiple access, a technique for transmitting, over short range radio channels, a mixture of voice packets and packets from other information sources. The PRMA protocol is organized around time frames with duration matched to the periodic rate of voice packets. In each frame, time slots are dynamically reserved for packets from active voice terminals. As a consequence, the terminals with reservations share the channel in a manner closely resembling time division multiple access (TDMA). The throughput is high and the voice packet delay is constrained to meet a specific design limit. To enforce this constraint, terminals discard packets that encounter excess delay. Dropped packets are the main cause of speech impairment.

PRMA is closely related to the reservation ALOHA protocol, *R*-ALOHA [11], [12]. PRMA is distinguished from *R*-ALOHA by its response to network congestion and by its short round trip transmission time. In *R*-ALOHA, congestion causes long packet delays. In PRMA, information packets from periodic sources, such as speech, are discarded if they remain in the terminal beyond a certain time limit.

In local wireless access systems, the roundtrip propagation time between terminals and base stations is on the order of a few tens of microseconds outdoors, and less than one microsecond indoors. Packet durations typically are 500–1000 μs. The short propagation times allow terminals to learn quickly the results of transmission attempts. In many cases, an acknowledgment message for the current time slot can arrive at the terminals before the beginning of the next time slot, or, at most, one slot later. In our studies, we have assumed immediate acknowledgments are possible. A one slot delay would have little effect on performance.

In the configuration we have studied, PRMA makes efficient use of speech activity detectors to obtain a bandwidth efficiency improvement over time division multiple access. The control complexity of TDMA makes it a difficult matter to use speech detection to improve efficiency. PRMA, on the other hand, is simple to implement and gracefully accommodates many types of information.

II. SCOPE OF THIS WORK

We are concerned with a wireless packet communication network with a star topology. All terminals use a single channel to transmit information packets to a central base station. This upstream (terminal-to-base) channel is slotted, and after each time slot, the base station transmits a short acknowledgment packet in addition to a downstream information packet. Downstream traffic can be transmitted in a separate channel (using a different frequency band). Or, it can time share a single channel with the upstream traffic. In either case, the base station schedules the downstream traffic avoiding all contention. In this paper, we concentrate on the problem of dispersed terminals competing for access to the upstream channel.

We are interested in possible applications of this network in an indoor or other localized service area. In terms of radio transmission, two salient features of these environments are short round-trip propagation delays, and wide variations in path attenuations (near/far phenomenon). The short delays permit rapid acknowledgments of the results of packet transmissions. The near/far phenomenon admits the possibility of packet capture when two or more terminals transmit packets in the same time slot. In the absence of capture, all contending packets require retransmission. On the other hand, accurate detection of the strongest received packet could lead to substantial performance improvements [8], [9], [10].

To explore the capabilities of such a network for telephony, we have simulated on a computer the transmission of up to 50 simultaneous conversations. To do so, we have created an elaborate statistical model of the patterns of talkspurts and silent intervals in conversational speech. In addition to artificial speech generated under the control of this model, we have also simulated the transmission of real speech. In a listening test, the simulated speech transmissions reveal the subjective effects of impairments caused by network congestion.

Each terminal contains a sensitive voice activity detector, a 32 kbit/s speech encoder, and a packet assembler. Packets consist of 64 bits of header and other non-speech material plus 512 coded speech bits. Our study explores two important variables. One is the packet transmission protocol which can be ALOHA or PRMA, defined in detail in the next section of this paper. The other variable is the strength of the capture phenomenon. We have studied performance with no capture, partial capture, and perfect capture [13].

A fundamental requirement in speech communication is prompt delivery of information. This is in contrast to packet data systems which respond to congestion and transmission impairments by delaying packets in queues. In our study, terminals discard speech packets that are not successfully transmitted within 32 ms. A figure of merit is the amount of voice traffic carried in the upstream channel without exceeding a specified probability of packet dropping.

A transmission delay as long as 32 ms implies that echo control will be required when PRMA is used for access to the public telephone network. This is comparable to the delay budget of Pan-European mobile radio [2] and the delay budget of a statistical multiplexer used in a terrestrial packet speech network [14]. In response to congestion, this multiplexer reduces the lengths of speech packets, rather than discard entire packets. Although packet length reduction leads to higher efficiency than packet dropping, it is a difficult matter to provide variable length packets in a system with dispersed terminals.

III. PACKET RESERVATION MULTIPLE ACCESS

At a speech terminal, the time slots are grouped in frames. Each slot in a frame is recognized as "reserved" or "available" according to the acknowledgment message received from the base at the end of the slot. When a talkspurt begins, the terminal uses the ALOHA protocol to contend for an available slot. When it successfully transmits a speech packet, it reserves that slot in future frames and there are no subsequent collisions with packets from other terminals. At the end of the talkspurt, the terminal releases its reservation by leaving the reserved slot empty.

A. Packet Categories

The packet assembler distinguishes between two types of information packets: periodic information packets and random information packets. The packet category is communicated by means of one bit of the packet header. Speech packets are always labeled as "periodic." Certain data packets, such as those involved in file transfers, can also be "periodic." Other data packets, such as keyboard entries to a computer terminal, signaling messages and system control information, are labeled as "random."

B. Information Frames

Each terminal organizes the transmission time slots in frames with N slots per frame. N is a system parameter common to all terminals. However, it is not necessary for all terminals to agree on which slot is the first in the frame. The terminal contains a *frame reservation register,* with one bit for each slot in the frame. It sets a bit to "0" when informed by the base station that the corresponding time slot is unreserved; otherwise it sets the bit to "1."

C. Contention

To begin to send periodic information, a terminal uses the slotted ALOHA [6] protocol to contend with other terminals for an unreserved time slot. If the terminal does not successfully transmit the first packet of a talkspurt in the first unreserved time slot, it retransmits the packet with probability q in subsequent unreserved slots. It continues to do so until the base station acknowledges successful reception of the packet. The permission probability q is a design variable.

D. Reservations

At the end of each upstream transmission, the base station broadcasts the outcome in an acknowledgment packet. When the base station acknowledges accurate reception of a periodic information packet, the terminal that sent the packet reserves that time slot for future transmissions. All terminals then refrain from using that slot in future frames. The terminal with the reservation thus has uncontested use of the time slot.

When a terminal stops sending periodic information in the reserved slot, this event is broadcast by the base station in the acknowledgment packet. All terminals are then free to contend for that slot in future frames.

E. Packet Loss

While it is contending for unreserved time slots, the terminal holds packets in a first-in first-out-buffer. If the packets are speech, the buffer size is limited according to the delay constraint imposed upon the network. In our study, the buffer holds 32 ms of speech. When a new speech packet arrives at a full buffer, the buffer discards the oldest packet. The number of lost packets and their temporal distribution strongly affect the quality of the received speech. With PRMA, all packet losses occur at the beginnings of talkspurts. It has been observed that this "front end clipping" is less harmful to subjective speech quality than other types of packet loss [15]. Our listening test supports this observation.

F. Random Information Packets

A terminal transmits random information packets in unreserved time slots. In the event of a collision, packets are retransmitted with probability r. This probability could differ from q, the permission probability for periodic information packets. By setting $q > r$, the system would give priority to periodic over random information. When a random packet is successfully transmitted, the terminal does not obtain a time slot reservation. If it has other packets to send, it must contend for subsequent unreserved time slots.

The buffer size for random information packets can be quite long. If it is, the effect of network congestion on random information is long packet delay, rather than packet loss as with periodic information packets.

G. ALOHA

One of our aims is to compare PRMA to conventional, nonreservation slotted ALOHA. In conventional ALOHA, contention takes place as in PRMA. However, all slots are unreserved, and all periodic information packets must contend with transmissions from other terminals. It is known that ALOHA benefits from packet capture. An interesting question is whether a strong capture mechanism also enhances the performance of PRMA.

IV. COMPUTER SIMULATION

We have performed computer simulations to investigate PRMA performance and to compare PRMA with slotted ALOHA. The simulated network carries conversational speech coded at 32 kbits/s. The channel rate is 720 kbits/s which is a conservative (low) estimate of what an indoor channel can support [16].

A. Transmission Format

After obtaining a reservation, a periodic information terminal transmits one packet per frame. Therefore, the frame repetition rate must equal $1/T_p$, the rate at which the terminal generates packets. In our simulations $T_p = 16$ ms and there are 62.5 frames/s. With 32 kbit/s speech coding, there are 512 speech bits per packet. In addition, 64 bits are allocated for header information and other purposes. Therefore, each slot contains 576 bits. This packet size is typical of those considered in general packet voice studies [17], [18]. It is employed in an experimental (wired) packet voice network [14].

With the frame duration 16 ms, the 720 kbit/s channel transmits 11 520 bits per frame. Therefore, there are 11 520/576 = 20 slots per frame. With a delay limit of 32 ms, a packet is dropped after waiting two frames (40 time slots) for a reservation.

B. Packet Collisions

When two or more packets contend for the same time slot, the ability of the base to detect the strongest packet depends on the channel characteristics, the transmission technique (modulation and coding), and on the locations of the active terminals. Our simulation study employs a simple capture model, in which the base station is at the center of a service area and the terminals are uniformly spaced between the cell center and the perimeter of the service area.

We identify three levels of capture: no capture, partial capture, and perfect capture. With *no capture*, the base station is unable to detect any packet when there are two or more simultaneous transmissions. All colliding packets must be retransmitted.

With *partial capture,* the ability of the base station to detect the strongest packet depends on the relative positions of the two active terminals that are nearest the base. In the context of the simplified capture model presented in [10], the capture parameter in this study is $\beta = 1.4$. This means that if the second terminal is at least 40 percent further from the base than the nearest active terminal, the base station successfully receives the packet from the nearest terminal.

With *perfect capture,* the base can always detect the packet from the nearest active terminal regardless of the number and locations of contending terminals.

C. Permission Probability

In order to contend for an unreserved time slot, a terminal must have permission to transmit. The appropriate permission probability q depends on the capture ability of the transmission

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