A NARROWBAND/WIDEBAND PACKET RADIO SYSTEM

Robert K. Morrow, Jr.
(513) 255-2024

Air Force Institute of Technology
2950 P St
Wright-Patterson AFB OH 45433-7765

INTRODUCTION

Packet radio systems have become widely used for many forms of digital communication. Although various channel access protocols exist, the underlying trait of all packet systems is a shared communication channel, and stations are allowed access to this channel when they have something to transmit. Spread-spectrum signaling may be used to reduce the effect of the inevitable packet overlaps (collisions) by deliberately increasing the bandwidth of all users of the channel through either direct-sequence or frequency-hopping methods. When a signal is processed in this manner, multiple-access capability is achieved; that is, multiple users can transmit together without necessarily causing mutually destructive multiple-access interference (MAI). Much effort has been devoted to coupling packet radio networks with spread-spectrum signaling in an attempt to gain the advantages of both (Ref. 1). Since generating and receiving the wideband signal adds complexity to the radios at each node in the network, it is necessary to select transmission and channel access protocols so that communication can proceed in an orderly fashion. This paper presents and analyzes a packet radio system that combines certain features of both narrowband and wideband signaling techniques to allow a number of advantages over systems that utilize narrowband or wideband methods exclusively. This system was granted US Patent 5,022,046 on June 4, 1991 (Ref. 2).

SYSTEM OVERVIEW

In this network, packet preambles and headers are transmitted on a narrowband channel, using one of the established protocols such as ALOHA or CSMA, while the body of the packet is sent using spread-spectrum techniques (Fig. 1).

Figure 1. Narrowband/wideband packet.

The spreading sequence is common to all nodes in the network and does not repeat throughout the entire packet. Every node in the network uses the same narrowband channel for packet headers, and identical signature sequences on the wideband channel, so transmission codes are simplified. Packet broadcasting is done by simply listing multiple destination node identifiers in the header; all specified receivers can then acquire the data portion of the packet together. Receiver synchronization is facilitated because the time between the end of the narrowband header and the beginning of the wideband data is fixed and known by all nodes in the network, and is independent of propagation delay. The "blurring" effect of multipath on the narrowband signal and timing errors in the transmitter and receiver are the only sources of uncertainty which prevent the receiver from knowing exactly when the wideband signal begins. The unslotted packet transmission scheme precludes the need for a master synchronization clock among the nodes. Nodes can monitor the narrowband channel for header traffic and any associated acknowledgment packets to determine which nodes are in range, which of these are busy, and how heavily the channel is loaded. Furthermore, a node can use the relative power of a received narrowband header to set its own power to a level that will provide reliable communication with a desired node while minimizing interference to others. A CSMA narrowband channel effectively controls access to the spread-spectrum channel, so wideband flow control is facilitated. However, since the narrowband channel is susceptible to jamming, it should not be exposed to a tactical environment.
ANALYTICAL MODEL

The process of developing throughput performance figures for a traditional narrowband packet radio network centers around finding the probability that two or more packets will overlap (Ref. 3). If receivers in the network have no signal capture capability, then the communication channel is considered useless during these periods of overlap and all affected packets are presumed destroyed. The multiple-access characteristic of spread-spectrum means that packet overlap no longer results in mutual destruction, but instead produces a gradual degradation of bit error performance as the number of simultaneous users increases.

Like their narrowband counterparts, spread-spectrum packets on a network can also appear in either a slotted or unslotted ALOHA configuration. Unslotted ALOHA nodes transmit packets immediately upon arrival, while slotted ALOHA systems require that all packets arriving during a particular time slot be transmitted together during the next time slot. Although slotted ALOHA systems are easier to analyze, it is often more practical to implement the unslotted scheme, since no time synchronization among nodes is required. Since only the header of each packet is carried on the narrowband channel, we will examine narrowband network performance when short packets are transmitted with either unslotted ALOHA or CSMA channel access protocols. For the wideband analysis, we introduce an approximation to obtain unslotted performance results based upon findings in Refs. 4 and 5, but at a greatly reduced computational complexity. Additionally, we account for the effect of bit-to-bit error dependence in our wideband model. We assume that the signal-to-noise ratio between each pair of nodes in the network is high enough that the effect of thermal noise on packet performance is small compared to degradations caused by collisions on the narrowband channel and MAI on the wideband channel. We also assume that a receiver will always be able to synchronize on the wideband signal after successfully acquiring its narrowband header.

Packet Throughput, Narrowband Channel

By equating the overlap of two or more packets to their mutual destruction, traditional narrowband analysis has avoided complex bit error event calculations while still providing a reasonably good approximation to network performance. It is necessary only to find the probability that a tagged packet will be transmitted alone over the channel. As shown in Ref. 3, if packets in the network arrive according to a Poisson process with arrival parameter $\lambda$ packets per second, and if each packet last for $\tau_n$ seconds, then the packet arrival rate can be normalized to $G_n = \lambda \tau_n$. In an unslotted ALOHA network, some of these packets will be destroyed through collisions, producing the well-known normalized throughput result

$$S_{n1} = G_n e^{-2G_n} \quad (1)$$

Since our narrowband network contains only packet headers, the packet length $\tau_n$ is short compared to networks that transmit the entire packet on the narrowband channel, so our network’s offered rate $G_n$ will be smaller for a given $\lambda$.

For CSMA analysis, we select the unslotted non-persistent protocol (Ref. 6), where the transmitting node first examines the channel and transmits the packet if the channel is sensed idle. Otherwise, the node will wait a random time before once again checking the channel and proceeding as before. Due to non-zero signal propagation and processing delays $\tau_p$, it is possible for a busy channel to be sensed idle and for an idle channel to be sensed busy. In either case, network performance is diminished. Now let $a = \tau_p / \tau_n$, the ratio of propagation and processing delay to narrowband packet length. Then the throughput of this network is given by

$$S_{n2} = \frac{G_n e^{-aG_n}}{G_n(2a + 1) + e^{-aG_n}} \quad (2)$$

Fig. 2 shows a plot of $G_n$ and $S_n$ for non-persistent CSMA with various values of $a$, and for pure ALOHA.

![Figure 2. Narrowband packet throughput.](image-url)

When $a$ is small, non-persistent CSMA approaches perfect channel utilization ($S_{n2} = 1$) for large $G_n$. When $a = 1$, however, maximum normalized throughput is only 0.144 at an offered rate of 0.46, compared to the ALOHA figures of 0.184 at 0.50, respectively. Since our packet headers are short, it is possible that $a$ may be significant, so the added complexity of implementing CSMA instead of pure ALOHA must be weighed against a performance gain which may be modest (or even negative).
One implication of CSMA is that, unlike ALOHA, packets "offered" to the CSMA narrowband channel when it is sensed busy are not transmitted immediately. Offered packets fall into three categories: successfully transmitted, unsuccessfully transmitted, and not transmitted but rescheduled instead. Equation (2) gives the rate of successfully transmitted packets, but packets in the first two categories will be transmitted on both the narrowband and wideband channels. If this occurs with rate $G_0$, then $S_{n2} < G_0 < G_n$ for realizable networks. By combining some results in Ref. 6 we have

$$G_0 = \frac{G_n(aG_n + 1)}{G_n(2a + 1) + e^{-aG_n}}$$  (3)

Packet arrivals on the wideband channel from the non-persistent CSMA process are clearly not Poisson distributed, but retaining the Poisson assumption provides analytical simplicity and matches simulation results closely when calculating CSMA performance figures (Ref. 6).

3.2. Bit Error Probability, Wideband Channel

The spread-spectrum system model used for the wideband channel is similar to that in [19]. The "desired" signal is transmitted by user 0, and there are $K$ interfering users. The $k$-th user's transmitted signal has the form

$$x_k(t - \tau_k) = \sqrt{2P}b_k(t - \tau_k)a_k(t - \tau_k) \cos(\omega_c t + \phi_k)$$  (4)

where $b_k(t)$ and $a_k(t)$ are the data and spectral-spreading signals, respectively, $P$ is the received signal power, and the carrier frequency is $\omega_c$. The differences in propagation and message start times are incorporated into the $\tau_k$, and $\phi_k$ represents the phase parameter in the carrier. Since these parameters are taken with respect to the desired signal, we set $\tau_0 = \phi_0 = 0$.

Since the signature sequence of each user is modeled as random from bit to bit, the delays $\tau_k$ in Eq. 4 can be completely characterized by the relative chip delays $s_k$ of the interfering signals (Ref. 8). After normalizing the receiver decision statistic so that the desired signal magnitude is $N$, the variance $\Psi$ of the multiple-access interference for any number of interfering users $K$ is a function of the $s_k$ and $\phi_k$ relative to the desired signal (Refs. 9 and 10), and is given by

$$\Psi(s_1, \ldots, s_K, \phi_1, \ldots, \phi_K) = \sum_{k=1}^{K} N (2s_k^2 - 2s_k + 1) \cos^2 \phi_k$$  (5)

When the chip delays are uniform on $(0,1)$ and the carrier phases are uniform on $(0, 2\pi)$, then the density function $f_\Psi(z)$ of this variance is the $(K-1)$-fold convolution of the density $f_Z(z)$ of the variance of a single interfering user, given by

$$f_Z(z) = \frac{1}{\pi \sqrt{2NZ}} \log \frac{\sqrt{2(N-z) + \sqrt{N}}}{\sqrt{2(N-z) - \sqrt{N}}}$$  (6)

for $0 < z \leq N$ and $z \neq N/2$. Now the probability of wideband data bit error $P_e^{(w)}$ can be accurately calculated using

$$P_e^{(w)} = E \left[ Q \left( \frac{N}{\sqrt{\Psi}} \right) \right]$$

$$= \int_0^{\infty} Q \left( \frac{N}{\sqrt{y}} \right) f_\Psi(y) dy$$  (7)

where

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} \exp \left( -\frac{u^2}{2} \right) du$$  (8)

Eq. 7 is the improved Gaussian approximation introduced in Ref. 9, and is shown to be extremely accurate when measured against bounds on $P_e^{(w)}$ given in Ref. 8 for random signature sequences.

Packet Success Probability, Wideband Channel

If a packet of length $L$ bits is transmitted over a memoryless binary symmetric communication channel with average probability of data bit error $P_e$ throughout the packet, and if the packet includes block error control capability that can correct $t$ or fewer errors, then the conditional probability of packet success $Q_e[P_e = g(P_e; L, t)]$ is a function of $P_e$ for each $L$ and $t$; that is,

$$Q_e[P_e; L, t] = \sum_{i=0}^{L} \binom{L}{i} P_e^i (1 - P_e)^{L-i}$$  (9)

This corresponds to a situation where the number of interfering users, and hence the average bit error probability, remains constant throughout a desired (tagged) packet, which is characteristic of a slotted network. However, both slotted and unslotted CDMA signal analysis is made more complicated by the fact that each interfering user has a relatively constant chip offset from bit-to-bit during its period of overlap with the tagged packet, and carrier phase may be constant, or change slowly, from bit-to-bit as well. These factors produce positively-correlated error events between adjacent bits within the tagged packet
If we assume fixed chip delays and phases for all interfering signals throughout a tagged packet, we can condition on the delay and phase values, use Eq. 9 to find the probability of packet success for each of these values, and average the results, yielding an overall packet success probability of

$$Q_E = E[Q_E|p_e]$$

$$= \int_0^\infty g\left( Q\left( \frac{N}{\sqrt{y}} \right); L, t \right) f_w(y)dy$$

(10)

Eq. 10 incorporates the effect of bit-to-bit error dependence within a tagged packet, and assumes that the number of interfering users $K$ remains constant throughout the duration of the tagged packet. Also, since the function $f_w(y)$ depends on $K$, $Q_E$ may also be expressed as a function of $K$. However, Eq. 10 does not account for the random changes in $K$ that are likely to occur in an unslotted network, nor does it consider the distribution of packets in the wideband channel whose headers were successfully received on the narrowband channel. We examine these issues next.

**Packet Throughput, Wideband Channel**

If the narrowband channel uses the pure ALOHA protocol, then packets entering the wideband channel can be modeled as the narrowband arrival process delayed by $\tau_1$; thus wideband packet arrivals also form a Poisson process with arrival parameter $\lambda$. By letting $r = \tau_w / \tau_n$, the ratio of wideband to narrowband packet transmission times, the normalized wideband packet arrival rate $G_w$ is equal to $rG_n$. For this offered rate, slotted CDMA network throughput $S_w$ is (Ref. 11)

$$S_w = G_w \overline{G}_w^{(w)}$$

$$= G_n e^{-G_n} \sum_{k=0}^\infty \frac{G_n^k}{k!} Q_E^{(w)}(k)$$

(11)

In unslotted CDMA networks, the number of interfering users $K$ may change randomly several times during the transmission of a tagged packet, greatly increasing the complexity of network throughput models compared to those used for slotted analysis. Convexity of the $Q$ function in Eq. 8 supports the conjecture that a particular unslotted CDMA system will experience a lower throughput compared to that of a slotted system for a given offered rate $G_n$. In other words, during unslotted transmission, increases in the number of interfering users above the average for portions of a tagged packet will hurt it more than decreases during other portions will help. In networks using CDMA only, the unslotted ALOHA peak throughput decrease from the slotted peak was shown to be about 15% when using either a $\Lambda$-channel model (Ref. 4) or an improved Gaussian approximation Markov model (Ref. 5). Unfortunately, both methods are somewhat intense computationally.

The probability of packet success for the narrowband/wideband network is equal to the probability that the header is transmitted successfully times the probability that the wideband part of the packet is successful given that the header was successful. We assume that narrowband collision detection is not possible due to the inability of nodes to simultaneously transmit and receive on the narrowband channel. As a consequence, the wideband portion of a packet will be sent immediately after its header is transmitted, regardless of whether or not a collision of narrowband headers occurred. Our goal is to develop a procedure for finding the conditional wideband packet success probabilities that uses the improved Gaussian approximation while retaining the low computational complexity of slotted analysis. We do this by creating some approximations to interfering packet activity.

Suppose a tagged packet in our narrowband/wideband network does not experience a header collision with another narrowband signal. If the wideband part of this packet begins transmitting at time $t_1$, then wideband interfering packets which partially overlap the tagged packet can arrive only within the intervals $I_a = (t_1 - \tau_w, t_1 - \tau_n)$ and $I_b = (t_1 + \tau_n, t_1 + \tau_w)$. Now consider the $i$-th arrival in $I_a$ and the $i$-th arrival in $I_b$, which occur at times $t_{ai}$ and $t_{bi}$, respectively. If $t_{ai} + \tau_w < t_{bi}$, then these two interfering packets are disjoint. In this case, a pessimistic approach assumes that these two packets act as a single interfering user for the duration of the tagged packet. Conversely, if $t_{ai} + \tau_w > t_{bi}$, then there is a period of mutual overlap between these two interfering packets, and we consider these as two interfering users for the duration of the tagged packet. Since this discussion assumes an equal number of arrivals in $I_a$ and $I_b$, we only offer a heuristic approach toward determining the distribution of each of the above conditions. If $\tau_n = 0$, then (on average) about half of the arrivals in $I_a$ will partially overlap their counterparts in $I_b$, but if $\tau_n \geq \tau_w / 2$, then the $I_a$ and $I_b$ counterparts are always disjoint. By using these two possibilities as endpoints, we can define a wideband arrival rate $G_w1$ for pessimistic throughput as

$$G_w1 = rG_n + \left( \frac{1}{2} - r \right) rG_n$$

$$= (1.5r - 1)G_n$$

(12)

for $r \geq 2$. An optimistic approach for calculating wideband packet throughput is to consider the arrivals in $I_a$ as interfering packets that fully overlap the tagged packet (as in a slotted ALOHA network), while ignoring arrivals in $I_b$, giving

$$G_w2 = (r - 1)G_n$$

(13)
Therefore, by letting
\[ G_w = (br - 1)G_n \] (14)
we can adjust \( Q^{(w)}_E(k) \) in Eq. 11 to provide accurate slotted
or optimistic unslotted figures \((b = 1)\), pessimistic unslotted
figures \((b = 1.5)\), or by using \( b = 1.2 \) to produce the
approximately 15% throughput penalty obtained in
Refs. 4 and 5, but without the associated high computational
complexity. We will use \( b = 1.2 \) for the numerical
results in this paper.

**Error Control in the Wideband Network**

Packets transmitted using multiple-access CDMA will
benefit from an error control code that can correct the bit
errors due to MAI (Ref. 10), but fewer than \( L \) bits will
now be available for the message. For this analysis, we
select a block BCH code that can correct \( t \) or fewer errors
in an \( L \)-bit packet. If we let \( L = 2^t - 1 \) for a particular
\( t \in \{2, 3, 4, \ldots \} \), then the number of message bits in the
packet will be at least \( L - ti \). By using equality as a lower bound on the number of message bits, we can define the
code rate \( R \) as the ratio of message bits to packet length; thus
\[ R = \frac{L - ti}{L} \] (15)
For example, if \( L = 1023 \) and \( t = 51 \), then \( R = 0.5 \) for
this BCH code implementation. Networks which employ
packet error control will have an effective packet throughput equal to the actual throughput times the code
rate. We will use effective throughput for all subsequent
narrowband/wideband system throughput calculations.

**Narrowband/Wideband Network Throughput**

Now that the analytical foundation is in place, we can find
effective network throughput figures for a given offered rate by combining narrowband and wideband throughput
equations. For our network using pure ALOHA for
packet header transmission, Eqs. 1 and 11 can be com-
bined (using \( G = G_n \)) to give throughput \( S_1 \) as
\[ S_1 = RrG e^{-(br+1)G} \sum_{k=0}^{\infty} \frac{(br-1)G^k}{k!} Q^{(w)}_E(k) \] (16)
where \( Q^{(w)}_E(k) \) is the wideband packet success probability
given by Eq. 11 as a function of \( k \). Although the infinite
summation cannot be evaluated exactly, the fact that
\( Q^{(w)}_E(k) \) decreases monotonically toward 0 as \( k \) increases,
along with rapidly decreasing probabilities that \( k \gg rG \),
allow us to truncate the summation arbitrarily close to the
final throughput value. For the numerical results pres-
tealed in the next section, we truncate the summation at
the point where \( Q^{(w)}_E(k) < 10^{-3} \), or when the packet suc-
cess rate drops below one in one thousand.

When the non-persistent CSMA narrowband protocol is
used, only some of the packet arrivals on the narrowband
channel will be transmitted immediately, so we have
\[ S_2 = RrG \left( e^{-aG} \cdot e^{-(br-1)G} \right) \frac{G(2a+1)}{e^{-aG}} \sum_{k=0}^{\infty} \frac{(br-1)G^k}{k!} Q^{(w)}_E(k) \] (17)
where \( G_0 \) is defined in Eq. 3.

The number of interfering users changes slowly relative to
the packet bit rate for reasonable values of \( G \), so our cal-
culations retain the effect of bit-to-bit error dependence by
using Eq. 10 to generate packet error probabilities. If de-
sired, the procedure in Ref. 5 can be used to calculate
accurate average packet success probabilities (without ac-
counting for bit-to-bit error dependence) for use in
Eqs. 16 and 17 at the expense of higher computational
complexity.

**Collocated Narrowband and Wideband Carriers**

The above analysis assumes that the narrowband and
wideband signals have no bandwidth overlap, and thus
provide no mutual interference. However, an obvious
implementation of this system would use identical carrier
frequencies for both signals. The effect of narrowband in-
terference on spread-spectrum system performance has
been extensively studied (Refs. 12, 13, and others) in the
context of jamming immunity, and we can conclude that
narrowband packet header transmissions on a collocated
carrier will have a slight detrimental effect on wideband
system performance. Conversely, little published infor-
mation exists on the effect that several CDMA signals
have on the error rate of a narrowband data transmission.
However, Ref. 9 presents an approach for random se-
quence CDMA analysis that can be extended to produce
accurate bit error rates for the narrowband data.

For an \( N \)-chip signature sequence \( \{a_1, a_2, \ldots, a_N\} \), where
the \( a_i \in \{-1, 1\} \), we define \( C \) to be the discrete aperiodic
autocorrelation function of this sequence offset by one
chip; that is,
\[ C = \sum_{i=1}^{N-1} a_i a_{i+1} \] (18)
Of particular interest here is the signature sequence con-
sisting of all ones; this sequence has \( C = N - 1 \), and the
transmitted signal is a narrowband data signal. By
combining some results in Ref. 9 and defining \( \tilde{N} \) to be
the number of wideband chips produced by each

interfering signal during a narrowband data bit, the MAI variance \( \Psi \) experienced by the narrowband signal is now

\[
\Psi(s_1, \ldots, s_K, \phi_1, \ldots, \phi_K) = \sum_{k=1}^{K} (2s_k^2 - 2s_k + \bar{N}) \cos^2 \phi_k
\]  

(19)

Likewise, in terms of \( C = N - 1 \), Eq. 6 becomes

\[
\tilde{f}_z(z) = \frac{1}{\pi \sqrt{2z}} \log \left| \frac{\sqrt{2(N - z) + 1}}{\sqrt{2(N - z) - 1}} \right|
\]  

(20)

where \( 0 < z \leq \bar{N} \) and \( z \neq \bar{N} - 1/2 \).

The density function \( \tilde{f}_z(z) \) for the total MAI variance experienced by the narrowband signal is the \((K-1)\)-fold convolution of the density \( f_z(z) \), and Eq. 7 provides the bit error probability for various numbers of interfering users. Fig. 3 compares narrowband \( p^{(s)}_e \) and wideband \( p^{(w)}_e \) vs \( K \) for various values of \( N = 12 \).

The numerical results in this section, we examine some of the implementation possibilities for this packet radio network and develop some throughput results. Network topology issues are avoided by assuming an infinite user model where each user's signal has equal power at each node. Unless noted otherwise, we use a wideband packet length \( L = 1023 \) bits and an error control code rate \( R = 1/2 \). Also, we avoid unnecessary complication by assuming that wideband signals produce negligible interference on the narrowband channel and vice versa. The plots show offered rates and throughputs both normalized to the wideband packet length to provide an indication of relative data rates.

Fig. 4 shows overall effective network throughput when the narrowband headers are transmitted using unslotted ALOHA. Channel capacity (peak throughput) is enhanced by making \( r \) as large as possible, increasing the proportion of traffic on the wideband channel and hence reducing the probability of narrowband collisions. For example, when \( r = 1000 \) in Fig. 4, the probability of header collision is only 0.04 at the offered rate at which channel capacity occurs.

Throughput performance for non-persistent CSMA headers is slightly below that of ALOHA when signal propagation and processing delays are equal to the narrowband packet length (Fig. 5), and shows a similar sensitivity to variations in \( r \).
Figure 5. Network throughput, CSMA narrowband ($a = 1$).

For an existing network, adjusting $r$ can be done either by changing narrowband packet transmission times with a corresponding change in $a$ (Fig. 7), or by adjusting $L$ (Fig. 8).

Figure 7. Adjusting narrowband packet length.

Once $r$ is large enough that narrowband collisions are rare and most packet losses are due to wideband MAI, channel capacity is affected only slightly by further increases in $r$. On the other hand, for a given $r$ and $a$, capacity is significantly affected by changes in the maximum number of correctable data errors $t$, as shown in Fig. 9.

Figure 9. Throughput for different error control code rates.

Since the CSMA narrowband channel controls access to the wideband channel, it is relatively easy to implement a
flow control scheme in a finite-user network. Unlike a packet system using only CDMA, nodes can estimate network activity by simply monitoring narrowband headers. Now they can adjust their own packet transmission and retransmission rates to insure that throughput requirements are met with minimum transmission delay, but without causing channel saturation and instability due to an offered rate beyond that which produces maximum throughput.

CONCLUSION

By transmitting packet headers on a narrowband channel, followed by packet data on a wideband channel, we gain several advantages over using either narrowband or wideband techniques exclusively. All network nodes can easily obtain channel traffic loading and destination information by examining only the narrowband headers. Wideband synchronization is facilitated by using the end of the header transmission as a time index for wideband signal acquisition. Long signature sequences minimize the probability that two or more wideband packets will be transmitted with their sequences aligned, while avoiding the requirement that each receiver search for several different sequences as in a transmitter-oriented protocol. A common signature sequence facilitates packet broadcasting. Finally, flow control can be implemented by monitoring the CSMA narrowband channel and insuring that the network offered rate remains below the saturation point.

REFERENCES


