MULTIPLE ACCESS TECHNIQUES IN FUTURE ARMY COMMUNICATIONS*

R. Berry, S. Finn, R. Gallager, H. Kassab, and J. Mills†

Massachusetts Institute of Technology
77 Massachusetts Avenue, Rm 35-209
Cambridge, MA 02139

ABSTRACT

It is argued that military networks will have to operate in channels which exhibit a wider range of fundamental characteristics than are present in commercial systems. It is then demonstrated that these channel characteristics can make it difficult for modifications of existing commercial systems to operate acceptably for every possible channel. Both CDMA and frequency hopping systems are considered.

INTRODUCTION

Our goal in this research is to help the army in achieving a universal tactical voice and data radio system. We believe that one of the most important objectives for such a system is to be sufficiently close to commercial technology that the army can leverage on the rapidity of product cycle improvements in the commercial world. Robustness, however, is an equally important, or more important, objective. In particular, this means that, while an army system may well take advantage of stationary or mobile base stations, there is a need for relaying messages from mobile user to mobile user under adverse conditions when base stations are destroyed. Channel conditions in relaying mode are diverse and quite different from channel conditions under user to base station communication. Even for user to base station communication, a military system must operate over a broader range of conditions than a commercial system. This means that an army system should be evaluated in terms of adequate performance over this entire range of channel conditions rather than its performance over any single channel model. It also appears that an army system will have to operate in a frequency band considerably higher than commercial cellular networks. We investigate whether modifications of commercial systems have much hope of operating acceptably under the above conditions.

We consider two multiple access techniques which are in some ways natural choices for use in a tactical network. These are, first, direct sequence, code-division multiple access (DS-CDMA), and, second frequency hopping. One reason for considering these systems is that they both use forms of spread-spectrum modulation that provide anti-jam and LPI benefits. Another reason is that these techniques are used in commercial systems. For example the IS-95 cellular system uses DS-CDMA while GSM has provisions for frequency hopping.

CHANNEL CHARACTERISTICS

In a wireless network, multiple propagation paths exist from the transmitter to the intended receiver. The received signal will then be the sum of several copies of the transmitted signal, each with a different delay and attenuation. As the transmitter moves, these paths vary. These two effects are modeled by treating the channel as a time-varying linear filter whose response at time t to an impulse τ seconds earlier is denoted as $h(t,\tau)$. We assume that $h(t,\tau)$ can be modeled (over time intervals of interest) as a stationary random process in t whose statistics depend on the environment. Since a working system must function in a variety of environments, instead of focusing on a particular statistical model we consider a few characteristics that are commonly used to classify any such channel.

The delay spread of the channel, Δ, is a measure of the time spread between the signal that arrives on

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the shortest path and the signal that arrives on the path with the longest delay. The delay spread depends largely on the surrounding environment, in particular on the number of reflectors and the distances to them. The delay spread can range from a fraction of a μsec for communication over short ranges in an urban environment to 20 μsec for longer ranges in hilly rural environments. The antenna size and distance from the ground can also effect the delay spread. The average attenuation on a signal path typically varies as $\frac{1}{R^\gamma}$, where R is the path distance. For example in free space γ is 2. In [4] it is shown that in an urban environment, when both the transmitter and receiver antennas are below the roof line and there is no line of sight path, then γ is larger than in the case when one antenna is higher than the roof line; in the latter case γ has a value of approximately 4, while in the former case it may be larger than 5. Larger values of γ cause the signals over longer paths to be attenuated more than short paths; thus the longer paths become negligible, yielding a smaller delay spread. Similar results have been reported for short antennas used in forests [1]. Thus delay spreads for user to user relaying are expected to be substantially smaller than delay spreads for user to base station communication.

The frequency dual of the delay spread is the coherence bandwidth, B_C. The coherence bandwidth gives a measure of the required frequency separation between two sinusoids for the fading they experience to be substantially uncorrelated. The coherence bandwidth is proportional to $1/\Delta$. The constant of proportionality depends on the channel's statistics and how 'uncorrelated' the sinusoids are required to be. If W is the bandwidth of a transmitted signal and $W < B_C$ then we can consider the fading to be flat across the frequency band, while if $W > B_C$ the signal suffers frequency selective fading.

When a user is moving, the signal received along each path i has a corresponding Doppler shift given by $\frac{f_c v_i}{c}$ where f_c is the carrier frequency, v_i is the speed at which the path length is changing, and c is the speed of light. The Doppler spread, B_D is the difference between the maximum and minimum Doppler shift over all paths. For a user moving at speed v then B_D is usually approximated by $\frac{f_c v}{c}$. The Doppler spread is related to the coherence time, T_C, of the channel. The coherence time is a measure of how long the channel's impulse response remains relatively constant. It is proportional to $1/B_D$ where the constant of proportionality again depends on the statistical model and interpretation of "relatively constant". For example in commercial systems operating at 900MHz, a user moving at 60mph would see a Doppler spread of approximately 90Hz and a coherence time of 2.2msec. But when the same user is walking, the Doppler spreads would be much smaller and the coherence times much larger. Due to spectral crowding at lower frequencies it is expected that future army communications will take place at higher carrier frequencies [6]. Since Doppler spread increases linearly with carrier frequency, Doppler spreads become larger and coherence times smaller.

From the above considerations we conclude that in a military network the channels encountered may have a larger variability in delay spreads and coherence times (and thus also in coherence bandwidths and Doppler spreads) than are encountered in commercial cellular systems. Also the range of coherence times will start at a smaller value. In the following we consider the effect these parameters have on both direct sequence and frequency-hopping systems.

IMPACT ON DS-CDMA

In a DS-CDMA system many users share a bandwidth of W, where W is much larger than the Nyquist bandwidth required by each user. In this section we will focus on a suboptimal direct sequence CDMA system such as IS-95 where other users are treated as noise while receiving a given user. In other words, we are not considering the use of multi-user detection [7] or multiple-access decoding strategies [3]. Though these approaches offer a means to improve performance, they are not yet used in commercial systems. Even without such approaches, direct sequence CDMA offers several advantages over unspread systems. One is that a receiver in such a system can resolve delayed paths that are separated by more than $1/W$ in time. The signals on such paths can then be added together rather than interfering with each other, and one then gets the advantage of diversity over these paths. In essence, with a Rake receiver, one gets frequency diversity between each coherent bandwidth within the DS-CDMA band of W. To get a major gain from this diversity, we must have $W \gg B_C$ or, equivalently, $1/W \ll \Delta$. On the other hand, because of cost considerations, the IS-95 system separates only 3 paths with the Rake receiver. Thus, for any given choice of W, if Δ is very small, then there is no diversity advantage to the DS-CDMA system, and if Δ is very large, the potential frequency diversity might be lost if the number of resolvable paths is large. Even if all the paths could be received, the signal to noise ratio on each path may be very small, since the signal energy is spread out between many paths, and this can also hurt the performance of a rake receiver. [1] In a practical system the spreading bandwidth W must be fixed and one cannot change this parameter according to the channel conditions. The above arguments then can be summarized by saying that in a system which will have to operate in a wide range of delay spreads, it becomes difficult to choose a spreading bandwidth that provides good performance across this entire range.

Since we are assuming that other users are treated as noise, power control becomes important to insure good system performance. Such power control schemes require the receiver to estimate the received power of a user and, based on this estimate, tell the user to adjust its transmit power to an appropriate level. In channels with a short coherence time, as pointed out in [6], it is difficult for the receiver to estimate the current power level, and the power control loop will function poorly. This leads the author in [6] to conclude that as the coherence time of a channel gets shorter, the performance of DS-CDMA suffers.

Fortunately, there is another effect in DS-CDMA that leads to improved performance as T_C becomes smaller. In IS-95, data is interleaved and encoded with a convolutional code. When the coherence time of the channel gets small, the samples coming out of the interleaver will be less correlated than when the coherence time is large. This provides time diversity and improves the performance in deep fading. In [5], the performance of a direct sequence CDMA system with a finite interleaver and power control is simulated in a flat fading channel. The number of users that can be supported is examined as a function of the coherence time of the channel. Here it is found that for short coherence times, even though the power control loop performs poorly, the improved coding performance more than compensates for this. In fact, more users can be supported as the coherence time gets small. The power control in such systems becomes important, not in compensating for very fast fading but instead to aid performance when the fading is slow enough that there is little time diversity. [2]

It should be noted that in the previous section we were addressing the use of power control to combat fast fading effects. Even with a short coherence time it is still necessary to have some form of power control to compensate for other effects such as shadowing or differing distances of users from a receiver. These effects occur on a slower time scale that does not depend on the carrier frequency. Thus a power control loop that compensates for these effects can average the received power over a number of coherence times and obtain good estimates of these quantities regardless of the coherence time. Another way in which short coherence times could effect performance is if coherent receivers are used. In this case the receiver must estimate the amplitude and phase of the received signal, which becomes difficult if the fading is too fast. To avoid this one can use incoherent receivers as on the reverse link in IS-95.

IMPACT ON FREQUENCY HOPPING

Next, consider the effects of the above channel characteristics on a slow frequency hopping system such as GSM. In such a system suppose each user transmits in a bandwidth of W_H per hop and that the dwell time per hop is T_H. These quantities must be fixed in a practical system. In order to reduce the out-of-band interference in such systems, some type of partial response continuous phase modulation is typically used, such as the use of Gaussian MSK in GSM. These modulation techniques purposefully introduce ISI to insure that the frequency response is tightly contained in the allotted bandwidth, W_H. Some form of equalizer is then required at the receiver to remove the ISI. Since the channel is varying, there is also a need to send some training data in each hop for this equalizer. For example in GSM, 26 bits are sent for training in each hop, resulting in about an 18 percent overhead. If T_H is larger than the coherence time, T_C, this means the channel will change during a hop. In this case the equalizer will have to track the channel or be retrained (resulting in more overhead). One of the main advantages of a frequency hopping system is that by hopping to new frequency bands, one increases the system's diversity. If the dwell time, T_H, is larger than the coherence time, T_C, then hopping is not really increasing the diversity much over the time diversity one would get without hopping. Thus, when T_C is very small, we both lose the diversity gain inherent in frequency hopping and also lose in performance due to poor equalization. If T_H is reduced so as to maintain good equalization for small T_C, then the efficiency loss due to the training data is increased, and, of course, it is increased over

[1] In fact, it is shown in [2] that in the limit of infinite bandwidth, the capacity of a DS-CDMA system goes to zero.

[2] For example in an IS-95 system operating at 900MHz, when a user is traveling at 60 mph, the coherence time can be less than 2.2 msec, but the roundtrip delay between measuring the users power and the user receiving the feedback is longer than 2.5 msec. Thus the power control is doing little to compensate for the fading, and the system is instead relying on the increased time diversity.

the entire range of channel parameters. Some trade-off between poor equalization (when T_C is small) and poor efficiency (all the time) must be reached in deciding on a value for T_H. At higher frequencies with the resulting smaller value of T_C, this trade-off becomes more difficult than at lower frequencies.

One way to avoid the overhead penalty as T_H gets small would be to transmit at a higher rate while transmitting. This would require scaling W_H up as T_H is scaled down, resulting in the same number of bits in a hop, and the same number of training bits per hop. This means that each user is idle over a larger fraction of the slots, but the time diversity through interleaving and coding would remain independent of this scaling. Unfortunately, as W_H becomes larger than B_C the amount of frequency selective fading will increase. This will cause more ISI at the receiver and thus requires a more complicated equalizer and more training data, or, if the same equalizer is used, it results in poorer performance.

We also note that if the coherence bandwidth is very large, then the fading in different bands will be more correlated and performance will again suffer. As in DS-CDMA systems, a solution to this is to use a large overall bandwidth, W. In frequency hopping systems there do not appear to be any negative effects to increasing the overall bandwidth, and frequency hopping systems often have larger bandwidths than DS-CDMA systems in practice.

CONCLUSIONS

The preceding sections outlined many of the trade-offs that must be considered in designing either a frequency hopping or a DS-CDMA system that will operate over a large class of channels. We briefly summarize some of these issues. For variations in the coherence time, and especially for dealing with the small coherence times to be expected from increased carrier frequencies, DS-CDMA appears to us to have advantages over frequency hopping. In particular, DS-CDMA has a trade-off between power control and coding, power control working better when T_C is large, and coding working better when T_C is small. In a frequency hopping system, short coherence times are difficult because of equalization and overhead issues. On the other hand frequency hopping systems have an easier time coping with variations in coherence bandwidths, since it is easier for such systems to use very large overall bandwidths. Many previous studies have focused on comparing various systems on a given channel, but we argue it is more important to focus on which system can be designed to have the most robust performance over the entire class of channels. If this class of channels becomes very large, it becomes difficult to design either a DS-CDMA system or a frequency hopping system that will operate effectively over every channel in the class. In essence, this suggests that it will be difficult to leverage on commercial systems in developing a universal tactical radio network.

We have focused solely on the effect that the channel can have on DS-CDMA and frequency hopping systems. There are several other issues that must also be considered in comparing these techniques. We briefly mention two of these in closing. First a tactical network will most likely have sessions with a variety of data rates and burstiness, and secondly, the network may not have a traditional cellular structure. When considering a network that must accomodate a variety of data rates and be organized in a variety of ad-hoc structures, the robustness of the underlying protocols becomes even more important.

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