METEOR BURST COMMUNICATION

Billions of small meteors enter the earth's atmosphere daily. Upon entering the atmosphere, these meteors quickly vaporize, leaving behind a trail of ionized particles. Ionized particles reflect, or actually reradiate, radio signals; so if properly oriented, a meteor trail can be used to establish a long-range communication link between a pair of radios. Meteor trails diffuse quickly, however, resulting in a rapid decay in signal strength. In many systems, usable trail lifetimes are on the order of 1 s. Communication that takes place via meteor trails is known as *meteor-burst communications.*

The utility of meteor-burst communications is evidenced by the snowpack telemetry system (SNOTEL) (1), which has been in operation for over 15 years, as well as by the commercial success of companies such as Meteor Communications Corporation and StarCom, which design meteor-burst communication systems. SNOTEL is a system that collects snowfall and weather data for 12 states in the western United States. In addition to remote telemetry, applications of meteor-burst communications include vehicle tracking and two-way messaging (1). The U.S. military was one of the first proponents of meteor-burst systems because it was determined that such systems would be among the first beyond-line-of-sight media to resume operability after a nuclear war.

The two primary alternatives for wireless communication at ranges beyond 100 km are satellite communications and terrestrial communication in the high-frequency (HF) band of 3 MHz to 30 MHz. For certain commercial applications, however, satellite communication is prohibitively expensive and HF communication is too unreliable. With regard to military applications, satellite and HF systems have additional disadvantages. For example, satellite and HF communication signals can be received over a large area and are therefore easy to intercept. In addition, satellite and HF communication links can be relatively easy to disrupt. These problems can be overcome by meteor-burst systems, which provide relatively low-cost, reliable, survivable, long-range communication.

PROPERTIES OF METEOR-BURST COMMUNICATION SYSTEMS

A typical meteor-burst protocol and network topology is as follows. The meteor-burst terminals are arranged in a network with one master station and many remote stations. The master station transmits a probe signal continuously using 1 kW to 5 kW of power. Once a meteor of appropriate size and trajectory enters the atmosphere, the probe signal is reflected from the meteor trail down to a remote station, which remains idle until the probe signal is detected. Once the probe signal is detected, the remote station transmits a burst of digital data to the master station via the meteor trail. Once the trail has diffused, the master station begins transmitting the probe signal again, and the process repeats. This basic protocol is illustrated in Fig. 1.

Meteor trails are generally categorized as either underdense or overdense based on their electron line density (1). For underdense trails, the received signal power decreases

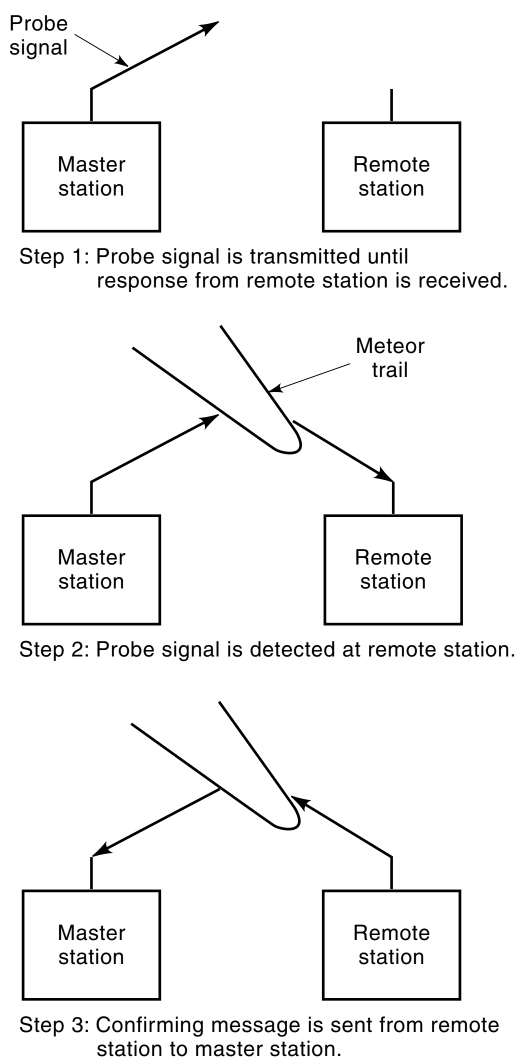

Figure 1. Basic meteor-burst communication protocol.

with time and is generally modeled as an exponential decay. Underdense trails occur much more frequently than overdense trails, and the underdense trail model is used almost exclusively in the analysis of system performance.

Underdense trails are formed by meteors whose mass is between 10^{-5} g and 10^{-3} g. The number of meteors of a given size that enter the atmosphere per day is inversely proportional to mass. For example, the number of earth-bound meteors per day that have a mass of 10^{-5} g is 10^{10}, and the number of earth-bound meteors per day that have a mass of 10^{-3} g is 10^{8} (2), where all numbers are approximate.

The average data rate of a meteor-burst system is a function of the frequency of occurrence of useful meteor trails, which has a daily and a seasonal variation. The maximum to minimum daily variation is approximately 4 : 1, and the maximum to minimum seasonal variation is between 2 : 1 and 4 : 1 (1). A meteor-burst system is usually designed based on pessimistic assumptions about the frequency of useful meteor trails.

The selection of the operating frequency for a meteor-burst system is a compromise between opposing criteria. As the operating frequency increases, the strength of the received signal decreases and the trail decay rate increases, so the operating frequency should be as small as possible according to this argument. Important practical considerations favor higher frequencies, however. For example, the desired signal may be reflected by the ionosphere at frequencies below approximately 30 MHz, and these lower-frequency signals are subject to higher atmospheric noise and are unreliable. Also, antenna size and cost increase as the operating frequency is decreased. As a result of the opposing criteria, the operating frequency of most meteor-burst systems lies between 40 MHz and 60 MHz. Several key characteristics of meteor-burst systems and channels are presented in Table 1.

THE METEOR-BURST CHANNEL

As a meteor enters and descends into the earth's atmosphere, it collides with increasing numbers of atmospheric particles. The collisions convert kinetic energy into a combination of heat, light, and ionization. As collisions continue, the outer layers evaporate and the meteor loses velocity and breaks up. Although portions of the very largest meteors retain solid form all the way to the earth's surface, the vast majority of meteors completely evaporate long before this point. Because the outer layers of the meteor are the first to lose velocity, the result is a "tail" of ionized particles that forms behind the meteor. It is the ionized particles that provide a communication medium, because free electrons in the meteor tail are capable of re-radiating a radio-frequency signal.

The geometry between the meteor tail and the transmit and receive antennas plays a crucial role in the degree to which the transmitted signal is received, if at all. Maximum signal power is received if two things occur: (a) The tail forms a tangent line to an ellipsoid for which the foci coincide with the two antennas, and (b) substantial ionization occurs at and around the point of tangency (3). Ionized particles all along the tail contribute to the signal to some extent, but most important are the particles close to the point of tangency. These particles add constructively to the received signal provided that the distance from transmitter to meteor particle to receiver does not vary more than a half-wavelength from the corresponding distance for the point of tangency.

The length of the region on the tail for which this constructive contribution occurs is proportional to the square root of the wavelength of the signal. Because wavelength is equal to the speed of light divided by the carrier frequency, it follows that the length of the region decreases as the carrier frequency increases. A reduction in the length of the region corresponds to a reduction in the number of ionized particles that contribute to the signal strength.

Table 1. Typical Meteor-Burst System and Channel Parameters

Carrier frequency:	40–60 MHz
Transmitter power:	100–5000 W
Communication range:	Up to 2000 km
Trail height:	80–120 km
Typical application:	Vehicle tracking, environmental monitoring, two-way messaging
Trail lifetime:	0.2–1.0 s
Throughput:	1000 bits/min

For those ionized particles for which the distance from transmitter to particle to receiver is between a half-wavelength and a full wavelength different from the corresponding distance for the point of tangency, *destructive* interference results. Differences in distance of additional multiples of a half-wavelength alternatively add constructively and destructively to the signal.

When the meteor first enters the atmosphere, very little ionization is present, and the received signal level is zero. Fairly quickly, ionization begins, and while the tail is relatively short, most of the ionized particles add constructively. The optimal time for a meteor's usefulness typically occurs when the meteor is at an altitude between 120 km and 80 km (4). As the meteor continues to descend, the tail elongates and a higher percentage of particles add destructively until the numbers tend to cancel out and the received signal level again drops to zero. The period of time for which a usable signal is present is called a *meteor burst.*

The length of a meteor burst ranges from milliseconds to seconds. The time duration is a function of many factors including the ionization density along the trail. If the density is sufficiently low, the trail is termed *underdense.* Theoretical analysis and experimental data show that underdense trails provide a received signal level that very rapidly rises to a peak value and then decays exponentially. Most trails are underdense. If the density is not low enough to result in the exponentially shaped signal level, the trail is termed *overdense.* The received signal level of overdense trails typically rises and decays more slowly, although eventually the trail usually exhibits an exponential decay.

For longer bursts, multipath fading may occur. In terms of the received signal, the result is multiple short dropouts of the signal occurring before the burst ends. Multipath can be caused by upper-atmosphere winds that bend the meteor trail in such a way that multiple communication paths between transmitter and receiver result. Because of their shorter duration, meteor bursts due to underdense trails typically are less affected by multipath than overdense trails.

Between meteor bursts, communication is not possible, unless other beyond-line-of-sight propagation mechanisms occur. Additional propagation mechanisms seen to occur on meteor links include sporadic-E propagation, ionospheric scatter, auroral scatter, diffraction, and troposcatter (3). Some of these effects, when present, can provide much higher data rates than can be obtained when propagation occurs solely by the meteor-burst mechanism.

PERFORMANCE MODELING AND CHARACTERIZATION

One of the factors that affect the performance of a meteor-burst communication system is the time waveform for the received signal power. For underdense trails, the received signal power is given by

$$P(t) = P_0 \exp\left(-\frac{t}{\tau}\right), \qquad t \geq 0$$

where P_0 is the peak received signal power and τ is a time constant related to the decay rate. Both P_0 and τ depend on the trail characteristics and vary from trail to trail. Since most trails are underdense, this model is often used in the design and analysis of meteor-burst communication systems. For overdense trails, the received signal power is more difficult to model. One model that does reasonably well for overdense trails has the form (5)

$$P(t) = P_0 \exp\left(\frac{1}{2}\right) \sqrt{\frac{at+b}{c} \ln\left(\frac{c}{at+b}\right)}, \qquad t \geq 0$$

where a, b, and c are constants that vary from trail to trail. Unfortunately, a significant number of overdense trails are not well-fit to this model. The general shape of $P(t)$ for an overdense trail is an initial rapid rise followed by a slower rise, which is in turn followed by a slow decay and, finally, an exponential decay. Although meteor bursts due to overdense trails usually have a longer duration than those due to underdense trails, they may or may not have larger peak power.

With regard to underdense trails, because P_0 varies from trail to trail, it can be modeled as a random variable (6). Experimental studies indicate that P_0 is reasonably well-modeled as a Gaussian random variable (3). The parameter τ can also be modeled as a random variable, and experimental studies indicate that either a Rayleigh or a log-normal distribution provides a reasonably good fit (7). An apparently untested assumption in the literature is that P_0 and τ are statistically independent.

The number of meteor bursts in a given time window is well-modeled as a Poisson random variable; that is, the probability that i bursts occur in T seconds is $(aT)^i \exp(-aT)/i!$, where a is a parameter that depends on the time of day, the time of year, and the region of the sky to which the antennas point. This model corresponds to a Poisson process (6), and it follows that the time between meteor bursts is exponentially distributed; that is, the probability that the time between bursts is at least T seconds is $\exp(-aT)$.

An additional important characterization of the performance of meteor-burst systems relates to the geographical region for which communication is possible using a particular meteor trail. The *footprint* of a meteor trail can be defined as the region on earth for which, at a particular time and a particular location of the transmitter, the received signal power exceeds some specified threshold. This footprint might more properly be termed the instantaneous footprint, because the size and location of the footprint changes over the course of the burst. As might be expected, the size grows and then shrinks, and the location drifts as a result of the fact that the meteor trail drifts with the winds in the upper atmosphere.

The *trail footprint* can be defined as the total accumulated region in which the instantaneous footprint ever extends over the course of the burst. The size of the trail footprint gives an indication of the degree that the communication is secure. A small footprint implies that the communication link has low probability of detection (LPD).

The size of a footprint is significantly affected by the location of the trail relative to the locations of the transmitter and receiver. Meteor trails close to the transmitter tend to have larger footprints than trails close to the receiver (3). This fact implies that the footprints for two radios transmitting back and forth to each other may be of different sizes.

CODING AND MODULATION FOR METEOR-BURST SYSTEMS

The nature of the meteor-burst channel implies that for all trails, the received signal power is time-varying and the trails are short-lived. Therefore, the capability to adapt transmission parameters, such as the ratio of data to redundancy in an error-control coding system or the rate at which channel symbols are transmitted, is desirable provided that the following two conditions are satisfied: (1) The channel conditions can be estimated quickly and accurately, and (2) the cost of adaptivity is not prohibitive.

Error-control coding, also referred to as forward error correction coding, must be used in many communication systems to provide acceptable levels of performance. It is not clear at the outset, however, that error-control coding will improve the performance of a meteor-burst system. This is because the use of error-control coding requires the inclusion of redundant symbols in the encoded packet, and this in turn requires a larger transmission time than an uncoded packet if the symbol transmission rate is fixed. The received signal strength may be large during early portions of a trail, but the power decays rapidly so there is a penalty for longer transmission times. The following question therefore arises: Do the benefits of error-control coding outweigh the penalty that results from a longer transmission time? As shown in several research articles, the answer is "yes." Several approaches to the use of error-control coding in meteor-burst systems along with selected results are discussed below.

There are at least three approaches to the use of error-control coding for meteor-burst communication systems. In the first approach we consider, referred to as standard coding, a fixed-rate code is used. In the second approach, which we refer to as singly adaptive-rate coding, a fixed-rate code is used for each trail but the rate of the code is allowed to vary from trail to trail. In the third approach, which we refer to as doubly adaptive-rate coding, the ratio of data to redundancy is allowed to vary throughout a trail lifetime as well as from trail to trail. In the singly and doubly adaptive-rate approaches, the channel characteristics must be measured in order to adapt the code rate correctly, but these approaches have the potential to offer much higher throughput than the standard coding approach.

In Refs. 8 and 9 the authors study the performance of systems that use standard coding with block codes and confirm that systems that use error-control coding outperform systems that do not use coding. In Ref. 10 a study of doubly adaptive-rate coding is presented for systems that use Reed–Solomon codes, and in Ref. 11 a doubly adaptive-rate system that uses adaptive trellis-coded modulation is presented and analyzed. The latter two articles demonstrate that a doubly adaptive-rate coding can have a much larger throughput than uncoded systems and standard coding systems. In Ref. 12 an implementation of an adaptive-TCM system is presented, and a standard coding system has been fielded (13) that uses a rate $\frac{1}{2}$ convolutional code with Viterbi decoding.

Some form of automatic-repeat-request (ARQ) may be required in some applications, and ARQ may be used with any of the three error-control-coding approaches described above. Additional ways of using ARQ with error-control coding are presented in Refs. 14 and 15. In Ref. 14 a system is investigated in which only part of the redundancy of the error-control code is transmitted initially along with the data. If errors are detected, the transmitter is alerted and additional redundancy is transmitted thereby increasing the error-correcting capability of the code that was sent previously. In Ref. 15 two practical methods for implementing doubly adaptive-rate coding are investigated which use feedback from ARQ to determine when to change the code rate. Other work in ARQ (without error-control coding) for meteor-burst communications includes Ref. 16, in which three different ARQ protocols are compared. The protocols are designed to study the relative advantages of a simple stop-and-wait ARQ scheme as well as the ability to detect the presence of a meteor channel. Symbol interleaving can also be used effectively with error-control coding (17). The idea is that interleaving can provide additional burst error correction capability. This is especially important near the end of the packet where the rapidly decreasing received signal power results in a large number of errors.

Adaptive-rate coding is one approach to adapting the transmission parameters to the channel conditions. Another approach is to adapt the rate at which channel symbols are transmitted, and this approach is known as variable-rate signaling. The goal is to vary the signaling rate in direct proportion to the received signal power so that the received symbol energy is maintained within a desired range. In Ref. 18 an analysis of a system that uses variable-rate signaling is presented. Furthermore, at least two systems (19,20) that use variable-rate signaling have been implemented. In the approach used for these systems, a feedback channel is maintained for each meteor trail that allows the receiver to communicate information about the new signaling rate to the transmitter. (Note that the systems are designed to change the signaling rate during lifetimes of each usable trail.) Demodulator outputs are used to estimate the current signal-to-noise ratio, and the signal-to-noise ratio estimate is used in turn to determine the new signaling rate.

Finally, note that it is generally believed that channel disturbances, such as multipath propagation, are not severe enough to make tracking of the carrier phase impossible. The existence of several commercial systems (1) that use a carrier-phase tracking system (e.g., a phase-locked loop) for the purposes of coherent demodulation supports this point. Therefore, the evidence suggests that coherent demodulation should be used if the additional cost of a phase tracking device is not prohibitive and if the phase can be acquired in a small period of time.

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