High Data Rate Meteor-Burst Communications

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ABSTRACT

The meteor burst communications channel offers a largely untapped means of communications that can alleviate congestion in many existing communications systems. This paper presents the results of an experimental study of the meteor burst channel which illustrates its time-varying bursty nature. In addition, the authors describe an innovative approach to data transmission over meteor burst systems, i.e., the use of the Feedback Adaptive Variable Rate (FAVR) system which allows the maximum amount of information to be transmitted over each meteor burst channel.

For underdense meteor channels the FAVR performance is compared to an optimum system, i.e., a system capable of changing its bit rate instantaneously to channel conditions so as to maintain a constant SNR in each bit, and to a constant optimum rate/burst system. It is shown that for such a system FAVR can result in a throughput increase exceeding a factor of 10.

INTRODUCTION

As the world wide demand for communications increases, there is an urgent need for new means of communications that would avoid the congestion that currently exists in conventional channels. This congestion is a particular problem at the lower frequencies often used in Beyond Line of Sight (BLOS) communications systems. There are also performance limitations associated with many existing BLOS systems that compound the congestion problem. HF systems, for example, are quite sensitive to solar disturbances and other galactic phenomena and are often limited by degradations due to multi-path return and other ground and atmospheric conditions.

Meteor burst channels provide a relatively new and uncongested means of communications that offer a significant opportunity for overcoming many of the limitations of existing BLOS systems. The meteor burst channel operates in the relatively unused lower portion of the Very High Frequency (VHF) band ranging from 30 to 100MHz and at path lengths up to 1500 miles. It therefore avoids the degradations exhibited by HF due to noise on the low end of the HF spectrum and ionospheric phenomena at the high end. This region of the spectrum also provides a sufficiently large bandwidth for efficient data communication. A meteor burst channel is not easily destroyed and has an inherent privacy feature due to its limited footprint [1, 9].

Early uses of meteor burst channels, however, have been restricted to relatively low throughput due to the random nature of the meteor burst phenomena. Indeed typical systems operate at bit rates of 8kb/s and less and use modulation techniques, such as BPSK or QPSK. Rate -1/2 codes are typical and such code rates also limit the information transfer.

The research presented in this paper describes an innovative technique to enhance the performance of meteor burst communications. We call the technique: The Feedback Adaptive Variable Rate (FAVR) system. Using this system approach, a feedback channel is maintained which allows the transmitted bit rate to mimic the time behavior of the received power so as to maintain a constant bit energy, i.e., the bit duration varies in a reciprocal manner to the received power variation so as to maintain a constant bit energy. This results in a constant probability of bit error in each transmitted bit.

EXPERIMENTALLY DETERMINED CHANNEL CHARACTERISTICS

The meteor burst channel is a non-continuous channel. When a channel is present the power received varies with time. Further, the duration of the channel, the peak and rms signal strengths, and the time between channels are random processes. A typical underdense waveform measured by SCS Telecom is shown in Fig. 1. Note that the peak SNR is about 12dB and that the SNR decreases exponentially with time. Figure 2 shows an overdense trail with wind shear. The channel is seen to be present for about 0.4s. Note that the peak SNR is about 15dB and it lasts about 1s.

These are but two of numerous waveforms that are obtained in practice [10]. Hence, to communicate efficiently using such a channel requires a robust modulation technique: FAVR.
METEOR BURST COMMUNICATION SYSTEM ALGORITHMS

Introduction

To demonstrate the operation of FAVR we employ the underdense Meteor Burst channel since this type of channel is usually of short time duration and low received SNR. The underdense trails are modelled as

$$ P_T(t) = P_0 e^{-t/r} $$

(1)

where $P_0$ is the power received at the start of the trail and $r$ is the time constant of the trail. Note that $P_0$ and $r$ are random variables which differ from trail to trail. Their actual statistics are unimportant to the FAVR system.

The Constant Bit Rate System

For a constant bit rate system, the duration of each bit $T_b$, is a constant. The usable time duration, $T_U$, for a meteor burst with peak power, $P_0$, and decay rate $r$, is determined from Eq. (1) as

$$ T_U = r \ln \frac{P_0}{P_K} $$

(2)

where the minimum acceptable received power $P_K$ is selected so that

$$ P_K T_b = E_b $$

(3)

the energy required for a specified error rate. Note that if $P_0 > P_K$, many bits are transmitted with a lower probability of error than that required.

The usable time duration is obtained from Eq. (2):

$$ T_U = r \ln \frac{P_0}{P_K} $$

(4)

The number of bits $N_c$, transmitted in the underdense trail for a constant rate system, is given by

$$ N_c = \frac{T_U - T_b}{T_b} $$

(5)

The Optimum Communication System

We now define the optimum communication system for transmission, using the underdense channel characterized by Eq. (1), in the sense of maximizing the number of bits transmitted with a desired error rate. Such a system changes the duration of each bit transmitted during the trail in such a way as to maintain the energy of each bit, constant, and equal to $E_b$. Then, from Eq. (1) the maximum energy in the meteor trail is

$$ E_T = \int_0^\infty P_0 e^{-t/r} dt = P_0 r $$

(6)

Hence the maximum number of bits having the energy $E_b$ that can be transmitted over the trail is

$$ N_0 = \frac{E_T}{E_b} = \frac{P_0 r}{E_b} $$

(7a)

and the bit durations can readily be shown to be

$$ T_{bi} = r \ln \left[ \frac{1 - \frac{E_b}{N_0}}{\frac{P_0}{P_K}} \right] $$

(7b)

ARQ System

In an ARQ system, a packet of $N$ bits is transmitted during each meteor burst. As an approximation, we assume that the packet is successfully transmitted if the last bit is transmitted at the acceptable level $P_K$ as defined by (3). Hence the required peak power level is:

$$ P_R = P_K e^{N T_b/r} $$

(8a)

The transmitted bits in a trail is:

$$ N_Q = \begin{cases} N, & \text{if } P_K \geq P_R \\ 0, & \text{if } P_K < P_R \end{cases} $$

(8b)

If $N_Q = 0$, the entire packet of $N$ bits is retransmitted.

FAVR

The Feedback Adaptive Variable Rate (FAVR) system is a practical embodiment of the optimum system.

Signal Composition

Figure 3 shows the received signal power. During the time interval $T_1$ the transmitted bits will all be of the same bit rate $f_b$, having a bit duration $T_b$. Referring to Fig. 4 we see that each bit is assumed to consist of a number of incremental chips, $n_{bi}$, of fixed duration, $t_1$, so that

$$ T_{bi} = n_{bi} t_1 $$

(9)

We further assume that the bits are collected into packet segments. Each packet segment has a segment number appended so that if an error occurs in a segment the segment can be repeated.

We take cognizance of the fact that reciprocity exists in the channel. Thus, the signal power seen at the transmitter and receiver are, to all intents and purposes, the same. The above assumption is crucial to FAVR operation (just as Link Quality Analysis (LQA) is crucial to adaptive HF). The channel delay, which affects reciprocity, is only 6ms and is assumed to be negligible. Of far greater importance is the fact that the noise level at transmitter and receiver is different and non gaussian external noise is often the main reason for the difference. In this paper the authors have assumed that noise cancellation, whether by null steering or other means, has been used and that
the only noise present in each receiver is normal gaussian noise.

During the time interval $T_i$, the transmitter and receiver each see the signal power decrease from $P_{i-1}$ to $P_i$. For ease of calculation let

$$F_{i-1} = F_i F_k$$

where $F_i$ is a factor greater the unity. For example, let $F_i = 2$, so that the bit rate changes only when the power level changes by 3 dB. From Eq. (11) we see that in this system the bit rate will halve at each transition. Using this algorithm

$$NF = \frac{\ln P_i - \ln P_0}{\ln F_i}$$

To insure that a specified probability of error is achieved, each transmitted bit must contain an energy greater than or equal to some minimum value, say $E_b$. Then, in the interval $T_i$ (see Fig. 3)

$$E_b = P_i T_i$$

Then, since

$$F(t) = F_0 e^{-t/\tau}$$

where $F_0$ is the maximum received power from the trail, we have, using Eq. (6),

$$F_i = F_0 e^{-T_i/\tau}$$

Hence,

$$T_i = \tau \ln F_i$$

The total number of bits sent in interval $T_i$ is then,

$$N_i = \frac{T_i}{r} - \frac{r F_i}{T_i}$$

Thus, the total number of bits sent, $N_F$, in a time interval $T_k$, is

$$N_F = \sum_{i=1}^{K} \frac{T_i}{r} - \frac{r F_i}{T_i}$$

where $K$ packet segments can be practically sent. Thus, assuming a minimum acceptable received power $P_k$, we have from Eq. (10),

$$P_k = F_1 F_2 \ldots F_k P_k$$

Substituting Eq. (10) into Eq. (16) yields

$$N_F = \sum_{i=1}^{K} \frac{r F_i}{E_b}$$

where $r F_i/E_b = N_F$ the maximum number of bits that can be transmitted (see Eq. 3). The FAVR system selects the $F_i$ in such a manner to allow $N_F$ to approach $N_o$.

Several algorithms concerning the method to be used to select the set of factors $F_i$ immediately present themselves:

**Algorithm 1.** Let $F_1$ be a constant. For example, let $F_1 = 2$, so that the bit rate changes only when the power level changes by 3 dB. From Eq. (11) we see that in this system the bit rate will halve at each transition. Using this algorithm

$$NF = \frac{\ln P_i - \ln P_0}{\ln F_i}$$

In obtaining Eq. (19) we have made use of Eq. (17) and Eq. (7) to show that $P_0/P_k = 2^K$. Thus, the maximum efficiency of this system is always less than $\ln 2 = 70\%$ of optimum system.

**Algorithm 2.** Let $F_i$ vary so that $F_1 = 2$, $F_2 = 3/2$, $F_3 = 4/3$, $F_4 = 5/4$, etc. This algorithm is more difficult to implement but results in an increased number of bits being sent in a given interval. A particular subset of this algorithm is to select the $F_i$ to alternate between $3/2$ and $4/3$. This is the FAVR algorithm.

The efficiency of the FAVR algorithm is obtained from Eq. (18) and yields

$$\frac{N_{FAVR}}{N_o} = \frac{\ln 3/2}{3/2} + \frac{\ln 4/3}{4/3} + \frac{\ln 3/2}{3/2 \cdot 4/3} + \ldots$$

There are $K$ terms in the sum. If we assume, for simplicity, that $K$ is even, we have

$$\frac{N_{FAVR}}{N_o} = 2 \left( \frac{3}{2} \cdot 1 \cdot \frac{1}{2} \right)$$

Since, from Eq. (17)

$$P_k = 2^{K/2}$$

It is readily shown that if $K$ is large the throughput of the FAVR system is $83\%$ of optimum.

Referring to Fig. 4 we see that each packet segment contains $N_k$ bits, where $N_k$ is a constant of the FAVR system. The signal bits in each packet segment are transmitted at the same bit duration $T_b$. In general, $N_k$ is between 40 and 200 bits and a message packet contains 10 to 20 packet segments. A strong burst may contain packet segments belonging to a number of packets, and packet segments from a few successive weak bursts may make up a single packet. Packaging
the transmitted bits into packet segments facilitates the incorporation of a FAVR link into a packet switching network. It is also essential to the FAVR MODEM design. However, if the predicted signal at the end of a packet segment fails to satisfy the requirement that

\[ P_R > P_b/T_b \]

the entire packet must be transmitted at a lower rate. Since the number of remaining bits may be anywhere between 1 and \( N_p-1 \), the average loss of transmitted bits per change of bit rate is

\[ N_{LS} = \frac{N_p - 1}{2} \left( \frac{1}{P_{I+1}} \right) \]  

(23)

Comparison of FAVR and the Constant Bit Rate System

The constant bit rate system transmits \( N_b \) bits during the underdense meteor trail, where from Eqs. (5) and (7):

\[ N_c = N_b \left( \frac{\ln P_o/P_x}{(P_0/P_x)} \right) \]  

(24)

while the number of bits transmitted by the FAVR system is

\[ N_{FAVR} = 0.83N_k \left( 1 - \frac{1}{P_o/P_x} \right) - N_k \]  

\[ N_{LS} \]  

(25)

where \( N_b \) is the number of bit rates used in the transmission. Referring to Fig. 5 we see that if \( P_o/P_x = 20 \) dB (a typical value), and if 1,000 bits can be transmitted over a trail using the traditional fixed bit rate approach, the expected transmission with FAVR is,

\[ N_{FAVR} = 18,000 - 12 \times 30 \times 0.3 = 17,883 \]

Transmission Over Arbitrary Meteor Channels

While an underdense trail is most probable, it usually disappears in several hundred milliseconds. Overdense trails are far fewer in number but each lasts for several seconds. Further, as seen from Figs. 1 and 2, neither of these trails follow the textbook equations.

The FAVR system is a piecewise approximation to each actual trail while the Constant Rate (CR) system is an on-off (binary) approximation. As a result FAVR results in a substantial improvement over the CR system for any set of trails.

CONCLUSIONS

This paper showed experimental evidence of the random on-off nature of the meteor burst channel, and then presented as algorithm and modem design which allows communication at 83% of the maximum bit rate permitted by the channel.

Results are presented comparing the FAVR modem to the optimal fixed bit rate modem and to an ARQ modem. An example using typical numbers was given showing that FAVR can yield an effective data rate 17 times greater than that obtained for the optimal fixed rate system.

REFERENCES

FIGURE 2

FIGURE 3: RECEIVED SIGNAL POWER CURVE SHOWING THE TIME INTERVAL $T_i$ DURING WHICH EACH BIT HAS THE SAME DURATION $T_{bi}$.

FIGURE 4: PACKET COMPOSITION

FIGURE 5: COMPARISON OF THE CONSTANT-RATE AND FAVR SYSTEM.