

METHOD FOR MINIMIZING MESSAGE DELIVERY TIME IN METEOR-BURST COMMUNICATION CHANNELS

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ABSTRACT

Context. In special conditions, particularly during emergencies, when satellite and terrestrial communication channels become vulnerable or completely unavailable, communication via meteor burst channels can effectively serve as a backup or even a primary path for information transmission. The operational range of such a radio channel can reach up to 2000 km, and the absence of “dead zones” ensures broad territorial coverage that is comparable to other types of long-range radio communication.

Objective Improvement of the method for one-way message transmission via meteor burst communication channels and its implementation algorithm, enabling minimization of message delivery time at a given reliability level.

Method. Further development was achieved for the method based on minimizing the message structure through merging the address field with the synchronization flag. Additionally, a hybrid synchronization algorithm combining threshold and non-threshold signal processing is applied for the first time. To enhance reliability, the majority algorithm is utilized instead of classical ARQ methods through repeated message transmission.

Results. An improved method for alert transmission over meteor-burst channels has been proposed, ensuring minimized delivery time and high reception reliability. Based on this method, a transmission protocol was developed, the message delivery time was evaluated, and synchronization techniques were identified, confirming the method’s effectiveness. The practical value lies in the development of an implementation algorithm suitable for deployment on DSP and FPGA platforms in alert systems without relying on satellite communication channels.

Conclusions. The proposed method and implementation algorithm enable the minimization of short message delivery time at a specified reliability level and improve communication reliability under challenging conditions.

KEYWORDS: alert system, meteor radio channel, transmission protocol, synchronization, transmission time, delivery time.

ABBREVIATIONS

ITU is an International Telecommunication Union;
ITU-R is an International Telecommunication Union Radiocommunication Sector;
MBC is a Meteor Burst Channel;
MRC is a Meteor Radio Communication;
SNR is a Signal-to-Noise Ratio;
FSK is a Frequency Shift Keying;
MSK is a Minimum Shift Keying;
DSP is a Digital Signal Processors;
FPGA is a Field-Programmable Gate Array;
ARQ is an Automatic Repeat Request;
DMF is a Digital Matched Filter;
BS is a Base Station;
SS is a Subscriber Station;
EPMR is a Energy Potential of Meteor radio line;
RSL is a Received Signal Level;
PBS is a Preamble for Bit Synchronization;

MRL is a Meteor Radio Line.

NOMENCLATURE

N_{INF} is a length of the information (payload) field of the message packet;
 τ_m is a duration of a usable meteor trail;
 V_{INF} is an information transmission rate;
 N_{SS} is a length of the preamble for bit synchronization;
 N_F is a length of the start-of-packet flag;
 N_τ is a length of the time field τ in the message structure;
 N_{KS} is a length of the checksum field;
 N_{F*} is a length of the end-of-message flag;
 N_T is a length of the status (message type) field;
 P_T is a radiated power of the transmitter;
 G_R is a receiving antenna gain at the operating frequency
 G_T is a transmitting antenna gains at the operating frequency
 P_{GN} is a galactic noise power;

ΔF_s is a spectrum width;
 P_{SIGN} is a signal level at the receiving point;
 K is a location-dependent coefficient of the galactic noise model;
 f is an operating frequency.

INTRODUCTION

In emergency and critical situations, where commonly used communication channels – such as satellite and terrestrial links – become vulnerable or unavailable, meteor burst communication (MBC) can serve as a backup or even primary means of information transmission. The radio channel range (up to 2000 km) and the absence of so-called “dead zones” allow for wide-area coverage, placing meteor communication alongside other types of beyond-line-of-sight communication.

The intermittent nature of MBC and the random waiting time for a meteor trail with sufficient electron density to support data transmission limit its applicability for real-time high-volume information exchange. However, it can be used effectively in alerting systems.

A key temporal parameter in message transmission systems is the delivery time of a fixed-length message, as the informational value decreases with increased delay. This parameter directly depends on the transmission protocol being used.

One of the widely employed protocols for unidirectional (paging) communication is POCSAG (Post Office Code Standardization Advisory Group), recommended by the ITU-R as an international standard and registered as RPCN I (Radio Paging Code No. 1). Its main characteristics are described in [1]. Another protocol developed by PHILIPS, APOC (Advanced Paging Operations Code), is generally compatible with POCSAG but additionally allows the substitution of frequently used words and phrases with encoded three-byte messages [2]. However, both protocols, in their original form, are not suitable for use under MBC conditions and require modification [3].

A specialized protocol has been proposed for delivering alert signals with a predefined information payload, which accounts for the specific characteristics of MBC and aims to minimize message delivery time with optimal software and hardware cost-efficiency. This is achieved through the selection of an appropriate message structure, the use of clock and frame synchronization methods, and the implementation of an algorithm to enhance transmission reliability. The protocol also includes the option for cryptographic protection of transmitted data.

According to the proposed approach, transmission is carried out continuously over a specified period, with periodic repetition of the same message. Minimum Shift Keying (MSK) is selected as the modulation technique, offering sufficient data rate while ensuring a high probability of correct reception even at low signal-to-noise ratios (SNR). MSK demodulation and synchronization require relatively low computational resources, enabling implementation using digital signal processors (DSPs) in combination with field-programmable gate arrays (FPGAs).

To further enhance transmission reliability, a majority-voting principle [4, 5] is proposed, whereby the value of each message element is determined by the majority of matches among repetitions. This method is well aligned with continuous message replication during the transmission period and is simple to implement.

The transmission time of a single message may vary from several seconds to several minutes, depending on the energy budget of the radio link, the message length, data rate, required reliability level, and the time of day and season.

Thus, the development of a method that integrates message structure optimization with a hybrid synchronization algorithm (combining threshold and non-threshold processing) and a majority-voting principle for repeated transmissions is of current relevance. This approach reduces delivery time and increases the probability of successful reception under the specific conditions of meteor radio channels, extending existing ARQ methods and paging protocols.

The object of study is the process of transmitting alert signals over meteor radio channels under conditions where conventional satellite and terrestrial communication lines are compromised or unavailable.

This process is characterized by the need to ensure the reliable delivery of information within short meteor burst windows, considering variable meteor trail parameters and the overall energy potential of the radio link.

The object of study is the process of unidirectional alert message transmission via meteor radio channels under conditions of limited availability of traditional communication paths, using an improved method that combines message structure optimization and hybrid synchronization to increase the probability of successful delivery.

The subject of study is the development of specialized communication protocols, signal structures, and synchronization methods aimed at improving the message transmission method to ensure efficient and timely delivery of alerts via meteor radio channels.

The purpose of the work is to develop an improved method for unidirectional alert message transmission via meteor channels, along with its implementation algorithm and technical solutions that ensure the minimization of message delivery time at a specified level of reliability and the efficient use of available resources.

1 PROBLEM STATEMENT

Let the energy potential of the meteor radio line, $EPMR$ the fixed length of the information message, L_{msg} and the required reliability level for message delivery R_{req} be given. Also known are the average duration of a useful meteor trail τ_{trail} , which defines the maximum allowable transmission time for a single message, and the information transmission rate V_{inf} , determined by the constraints of the Meteor Burst Channel (MBC) and the required signal-to-noise ratio (SNR).

It is necessary to determine the information message structure S_{msg} that provides the minimum transmission duration T_{msg} for a given informational payload. Addi-

tionally, it is required to develop a synchronization method *Syn*, minimizing the synchronization establishment time *Tsyn* under conditions of low SNR. To ensure the specified reliability level *Rreq*, the number of message repetitions *Nrep* must also be determined, with subsequent processing based on the majority-voting principle.

Thus, the research task is to develop a synchronization method *Syn* and to determine the optimal transmission parameters (message packet structure *Smsg*, number of repetitions *Nrep*), that minimize the message delivery time *Tdel*.

Tdel → min subject to the following constraints:

- the duration of information packet transmission should not exceed the average duration of a useful meteor trail: $Tmsg \leq t_{trail}$;

- the probability of successful message reception must be no less than the specified reliability level: $pr_{success} \geq Rreq$;

- the energy potential of the meteor radio line remains constant and cannot be altered during the transmission: $EPMR = const$.

Consequently, the stated problem is to develop an optimized method for transmitting short unidirectional messages via MRC, ensuring minimal alert signal delivery time under specified meteor radio line parameters and communication reliability requirements.

2 REVIEW OF THE LITERATURE

The use of meteor burst communication (MBC) for alert systems and as a backup means of information delivery under emergency operating conditions has been studied for a considerable time; however, most attention has historically been focused on MBC systems with Automatic Repeat reQuest (ARQ) mechanisms [6–11].

A concise description of the key characteristics of such systems, as well as the equipment employed, is provided in the monograph [15].

Variants of one-way transmission protocols for alert signals, whose effectiveness depends on the characteristics of MBC systems, are presented in [1–3, 16–23] and numerous other publications. The analysis of these protocols and the methods for improving message transmission efficiency led to the proposal of a specialized protocol for delivering alert signals with a specified information volume, tailored to the specific features of MBC and aimed at minimizing message delivery time with optimal software and hardware resource usage.

The methods of modulation, demodulation, error-resilient coding, as well as frame and clock synchronization considered in [24–26], which are oriented toward implementation using Digital Signal Processors (DSPs) and Field-Programmable Gate Arrays (FPGAs), formed the basis for developing solutions that enable realization of the proposed protocol while minimizing delivery time and ensuring the required reliability. The results of experimental studies conducted in [27–29] were also taken into account.

3 MATERIALS AND METHODS

The proposed method represents an improved approach to unidirectional alert signal transmission via meteor radio channels, enabling the minimization of message delivery time while maintaining a specified level of reception reliability.

Unlike conventional ARQ (Automatic Repeat reQuest) techniques and standard paging protocols, the method optimizes the message structure by minimizing service fields and merging the address field with the synchronization flag. This reduces the transmission duration within the limited “window” of meteor burst availability.

A distinctive feature of the method is the integration of a hybrid synchronization algorithm that combines threshold and non-threshold signal processing with a majority voting principle to enhance transmission and reception reliability without relying on complex error-correcting codes.

This approach increases the probability of correct reception and ensures method effectiveness even under low signal-to-noise ratio conditions.

The implementation algorithm with a step-by-step description is presented in Table 1.

Table 1 – Step-by-step description of the implementation algorithm

Step	Description	Purpose / Expected Effect
1	Select base parameters: frequency, power, antenna gain	Ensure sufficient energy potential for stable link
2	Calculate energy potential (EPMR)	Verify link budget and required SNR
3	Set transmission parameters: data rate, message length, modulation	Match parameters to meteor trail duration
4	Optimize message structure: minimize overhead, combine address and sync flag	Reduce transmission time within time window
5	Apply hybrid synchronization: threshold + threshold-free	Shorten sync time, increase reliability
6	Generate and detect flags using digital matched filter	Accurately detect message boundaries and address
7	Transmit with majority voting	Improve error resistance without complex codes
8	Make final decision and verify checksum	Deliver alert with required reliability

The reduction of message delivery time and the increase in reception probability in the proposed method are achieved through the following:

- the use of a majority voting algorithm applied to multiple message repetitions instead of classical error-correcting codes, which reduces redundancy;

- optimization of the data packet format in accordance with the limited time window of the “useful” ionized trail;

- the application of MSK modulation, which ensures the required transmission speed even under low SNR conditions with moderate computational overhead.

The structural diagram of the proposed method is shown in Figures 1–3.

To justify the proposed method, a detailed description of the implementation of each stage is provided below.

A systematic analysis of the available publications made it possible to identify the key principles for design-

ing an alert system under conditions where conventional communication channels are unavailable and to propose a dedicated protocol for information delivery via meteor radio channels (MRC).

A transmission algorithm without feedback requires prior selection of the main parameters of the base station (BS), such as operating frequency, transmitter power, and antenna gain (G) of the transmitting antenna, as well as the parameters of the receiving system, including the antenna gain (G) of the receiving antenna, the receiver noise figure, and the level of galactic noise. These parameters determine the energy potential of the meteor radio link (EPMR) and must be sufficient to provide reliable service within the designated geographical area at any time of day and throughout the year.

The specified energy potential of the meteor radio link (EPMR) and the required length of the information message determine the data rate, modulation method, and the

structure of the information message, which together define the transmission protocol.

Since the “time window” is limited by the duration of a usable meteor trail, it is essential to minimize the overhead portion of the information message – namely, the length of the preamble for clock synchronization, the flags for frame synchronization, the addressing segment, and message type indicators. The total message duration must not exceed 0.3 seconds.

Figure 1 shows the proposed format of the information message, which includes a preamble for bit synchronization (PBS) composed of N_{SS} alternating “1” and “0” bits, a start-of-packet flag (F) of N_F bits in length, message status information (T), the payload consisting of N_{INF} information bits, a checksum (CS) of N_{KS} bits, and an end-of-message flag (F^*).

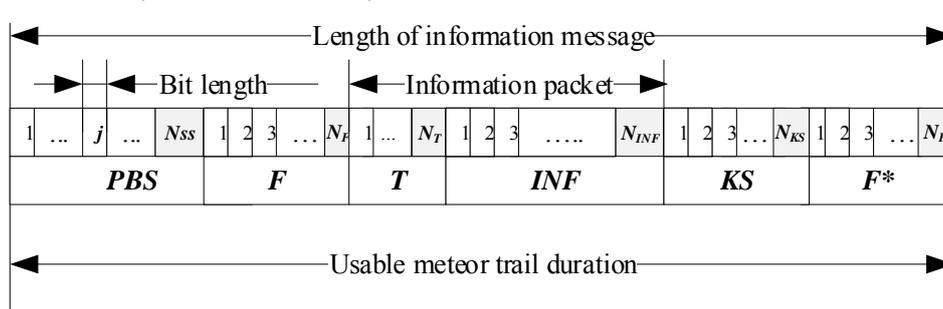


Figure 1 – Format of the information message transmitted via the meteor burst channel (MBC)

The preamble is necessary to ensure clock (bit-level) synchronization. It can also be used as an indicator for detecting the start-of-packet transmission flag.

To perform bit synchronization, it is proposed to divide the clock interval T into N equal **subclock intervals**, each assigned an address A_j , where $j=1,2,\dots,N$. The goal of

the analysis is to determine the subclock interval during which the **accumulated value of the processed signal samples** reaches its maximum over the duration of one clock period. A simplified version of this algorithm (for $N=4$) is illustrated in Figure 2.

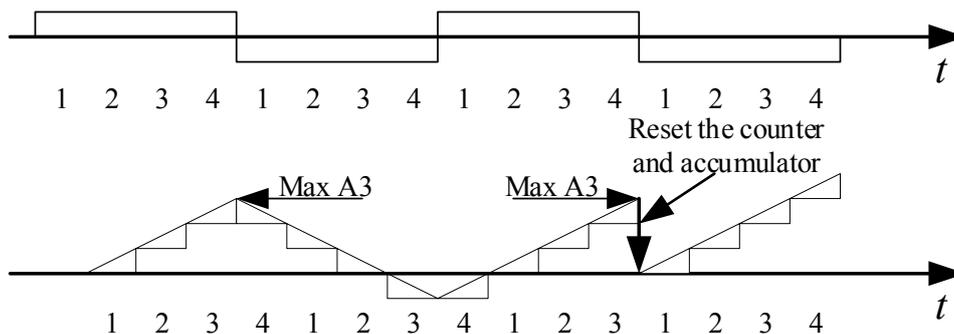


Figure 2 – Simplified clock synchronization algorithm based on the preamble

To make a reset decision, the value $A_{j_{max}}$ must be repeated at least P times within the duration of the preamble. The decision threshold P depends on the preamble length and the energy potential of the radio link. A high value of P increases the likelihood that the threshold will not be exceeded within the given preamble length, resulting in a failure to achieve synchronization. Conversely, a low value of P increases the probability of false synchronization. Therefore, there exists an optimal value of P . Experimental studies have shown that when using a 32-

symbol preamble in a channel with a bit error probability of approximately $P_{bit} \sim 10^{-2}$, an acceptable threshold is $P \approx 8$.

An alternative approach is the threshold-free synchronization method described in [15, 30–32].

The method presented in [30] involves detecting the repeated occurrence mmm times in a row of the address of the subclock interval where the maximum convolution value of the composite signal is observed (the “mmm-in-a-row” criterion), or the occurrence of the same maximum

address at least kkk times over nnn consecutive observation intervals (clock periods) (the “ k -out-of- n ” criterion). These algorithms can be implemented as synthesizable, parameterizable, and structured VHDL models designed for use on FPGAs from various manufacturers [31].

A patent for a similar system was obtained in [32]; however, for meteor burst channels (MBC), the proposed synchronization method can be improved through the combination of threshold-based and threshold-free techniques. The core idea is that the current threshold level is set to ensure information reception with a given reliability, and a decision is made when both of the following conditions are satisfied: (1) the address of the subclock interval with the maximum convolution value is repeated mmm times consecutively (the “ m -in-a-row” criterion) or meets the “ k -out-of- n ” condition, and (2) the observed value exceeds the predefined threshold.

This combined approach allows reducing the values of mmm or nnn , thereby decreasing the synchronization time while maintaining a fixed false alarm probability. For example, it is recommended to set $m=2$ (for the “ m -in-a-row” criterion) with the additional condition that the threshold is exceeded during the second observation of the accumulated value. Alternatively, one may use $k=2$, $n=3$ (the “ k -out-of- n ” criterion) and require that the threshold be exceeded at least once over the three observation intervals. This strategy effectively shortens synchronization time while preserving the desired probability of false alarm.

The flag FFF is required to identify the beginning of the information packet, which includes message status information consisting of N_T bits and the payload of N_{INF} information bits. In the proposed protocol, the flag F serves an additional important function – message addressing.

The flag FFF is selected from an ensemble of complex signals with favorable autocorrelation and cross-correlation properties. Currently, sequences with the required characteristics include Walsh sequences, linear and nonlinear recurrent sequences, derived orthogonal sequences, Gold and Kasami sequences – all of which have been extensively studied by various researchers. Of particular interest are sequences formed by pseudorandom permutations of the elements of codewords derived from maximum-length register codes (e.g., m -sequences) [33, 34].

Permutation transformations are a particular case of affine transformations. They allow for a significant increase in the size of any signal ensemble without altering the distances between signals in the signal space and can be used to enhance the subscriber capacity of MBC systems (i.e., the number of simultaneously served receiving stations). An algorithm for generating such signals, designed for implementation on FPGAs, is presented in [15].

The end of the message is indicated by the flag F^* , which is defined as the bitwise inversion (replacement of “1” with “0”) of the flag FF. This approach reduces soft-

ware and hardware complexity as well as computational resource requirements for generating and processing the required flags.

Digital matched filtering (DMF) can be used to detect the flags FF and F^* . Since the flag is also used as a network address in the proposed protocol, provisions must be made for its reconfiguration and for corresponding reprogramming of the DMF. A structural diagram of a programmable DMF implemented on an FPGA is shown in Figure 3 for a flag length of 32 bits.

The information symbols from the output of the decision device (DD) are fed into the input of Shift Register 1. Its state is loaded in parallel into Shift Register 2 at each clock cycle. Shift Register 3 operates with a cyclic shift. Its initial state is set during the initialization of the selected address. After 32 shifts, the initial state repeats.

If all zeros (or all ones) are written to Register 1 at the output of the accumulator, which is a 6-bit adder with a sign, the value accumulated at 32 subcycles is equal to zero (the number of “1’s” in the flag is equal to the number of “0’s”). When writing to the Register 1 sequence corresponding to the value of the flag, at the output of the accumulator at the 32nd subcycle a value equal to 32 is obtained (in the absence of symbolic errors in the communication channel).

If two symbol errors occur within the flag (corresponding to a bit error probability $P_{bit} \sim 10^{-1}$, the accumulated value over 32 subclock intervals becomes 26. Clearly, at such high error rates, reliable message reception is practically impossible – even when using advanced error-correcting codes. Therefore, the decision threshold for flag detection is chosen to be ≥ 26 .

When the sequence corresponding to the inverted flag is written into Register 1, the output of the accumulator yields a value of minus 32, assuming no symbol errors occur in the communication channel. Based on this, the decision threshold for detecting the inverted flag is set to ≤ -28 (Fig. 3).

The message status field T allows identification of the message format and helps reduce transmission time. For example, by indicating a “voice message” flag within the T frame and specifying the required message number (1 byte) in the information field INF , any pre-recorded message corresponding to that number can be played back on the receiving side.

The indication of the “numeric-only” message format signifies that the information consists exclusively of decimal digits along with spaces, hyphens, and opening and closing parentheses. In this format, each character is represented by 4 bits, which reduces the required transmission time [1, 35].

The alphanumeric or general data format can be used to transmit messages that require a broader range of characters than those supported by the “numeric-only” format. In this case, each character is represented by 7 bits.

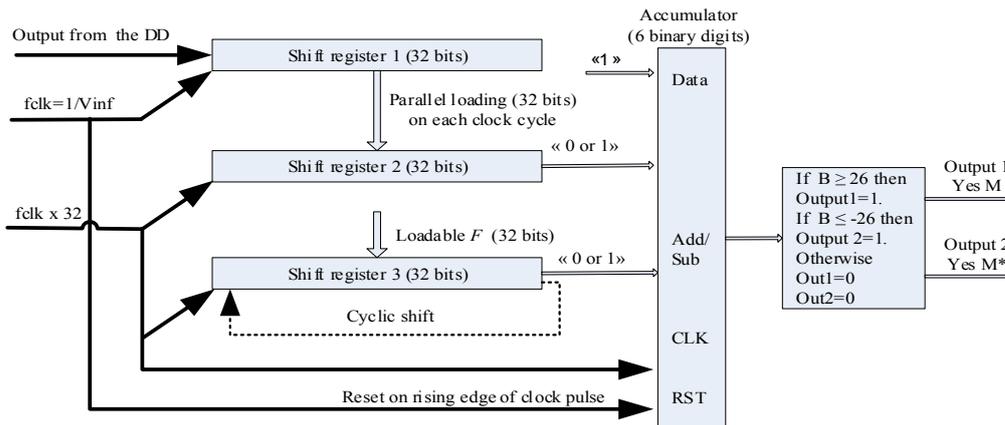


Figure 3 – Block diagram of a digital matched filter providing software tuning

It may also be useful to specify a message template in the T field, with the number and content of the unfilled fields to be transmitted in the information part of the message. The template sizes must be consistent with the capacity of the information field.

The T field may also indicate a “Encrypted Message” flag, with the INF field containing a reference to the encryption key. The “encryption key” refers to the starting address of flash memory pages that store a random sequence of “1”s and “0”s, which is loaded by the Administrator during the initialization of radio network data. If each key is used only once and in a single message, the cryptographic algorithm is considered to be unconditionally secure. This type of algorithm is implemented in one-time pad ciphers, such as the Vernam cipher.

The length of the message payload N_{INF} is limited by the total message length, the data transmission rate, and the size of the “time window”. The value of N_{INF} is determined by the duration of a usable meteor trail τ_m and the data rate V_{INF} . It is given by the expression:

$$N_{INF} = \tau_m \cdot V_{INF} - (N_{SS} + N_F + N_\tau + N_{KS} + N_{F8}). \quad (1)$$

The checksum is calculated only for the informational part of the packet, which includes the T and INF fields. A method of byte-wise summation modulo 2 may be used.

The information message ends with the transmission of the F^* flag. After that, transmission continues uninterrupted for a specified duration with periodic repetition of the same message.

To improve error protection, the use of the majority voting principle has been proposed [4, 5], whereby the value of each message element is determined based on the majority of matches among multiple repetitions. This approach is well-suited to message replication over the entire transmission period and is simple to implement.

The delivery time of a single message with 95% reliability may range from several tens of seconds to several minutes. It depends on the energy potential of the radio

link, the message length, the transmission rate, the geographic coverage area, as well as the time of year and time of day.

4 EXPERIMENTS

To verify the proposed method of improved unidirectional alert signal transmission via meteor radio channels and to evaluate the conditions affecting message delivery time and reception probability, experimental studies were conducted.

The objective of the experiment is to assess the effectiveness of using the hybrid synchronization algorithm, the majority voting principle, and the optimized message structure under real meteor communication conditions.

The experimental studies presented in [27–29] were aimed at investigating the diurnal and seasonal variations in the number of observed meteor trails, as well as the average hourly data transmission rate over the Meteor Burst Channel (MBC).

In [27], the results of predicted and calculated daily variations in the average hourly number of observed meteor trails are presented for the X–Y radio path (X: 55°30' N, 37°36' E; Y: 55°47'27" N, 49°06'52" E), corresponding to a distance of 717 km. Measurements were conducted from May 16 to May 24, 1992. A 5-element Yagi antenna mounted 9 meters above the ground was used at each communication site. The transmitter operated at a frequency of 57.4 MHz with an output power of 700 W.

The minimum average hourly number of meteor trail reflections – detected at a received signal level above –114 dBm – was recorded at 15:00 UTC (18:00 local time) and was approximately 9 meteors per hour. The maximum value, approximately 60 meteors per hour, was observed at 03:00 UTC (06:00 local time). These results exhibit the classical diurnal variation in meteor activity.

In all such forecasts, discrepancies between predicted and measured values may be attributed to differences between the modeled and actual values of the radiant density of sporadic meteors, meteor velocity distributions,

antenna radiation patterns, atmospheric constants, physical parameters of the trail, and mechanisms of trail scattering losses.

In [28], the results of measurements of the average hourly throughput of the Meteor Burst Channel (MBC) are presented for a radio path with a total length of approximately 1200 km (750 miles) between facilities located in Charleston, South Carolina (32°55'18"N, 79°58'4"W) and Verona, New York (43°9'0"N, 75°37'9"W). The geographic bearing from Verona to Charleston is approximately 200 degrees east of true north, meaning the communication path is oriented roughly north to south.

A testbed was developed to measure the effectiveness of an advanced beamforming antenna array, variable-rate data modems, and data compression technologies for improved meteor burst communication (MBC). It includes a main transmission path with a maximum product of $P_T \times G_T \times G_R$ of approximately 80 dBW, and a reference path with a corresponding product of about 60 dBW, which is typical for nominal MBC system designs. The transmission systems in Verona and Charleston were identical. The operating frequencies ranged from 40 to 50 MHz.

In August 1993, the measured throughput at the operating frequency of 41.00 MHz in Verona, averaged over all test hours, was approximately 4.0 kbps. This corresponds to an average hourly data throughput of 2.0 kbps per byte of useful data.

Similar measurements conducted in Charleston at a frequency of 46.65 MHz yielded an average hourly throughput of approximately 2.2 kbps per byte of data, which contradicts the well-known trend (i.e., throughput typically decreases with increasing frequency). However, this deviation is explained by the higher link power budget and more precise antenna beam steering.

The most comprehensive data necessary for predicting the parameters of the proposed alert transmission protocol are presented in report [29]. It contains the results of a technical and economic feasibility study of meteor burst communication between the Nord station (81.60°N, 16.66°W) and Thule station (76.55°N, 67.85°W), separated by a distance of 1160 km.

Measurements were conducted at a frequency of 45.113 MHz using binary frequency-shift keying with minimum shift (MSK), a transmitter power of 1 kW, and six-element Yagi antennas with a gain of 11 dBi. The results showed that the meteor arrival rate is determined by the specified received signal level (RSL), which ensures the required signal-to-noise ratio (SNR). It was found that the distribution of signal durations is largely independent of the selected SNR level across the entire studied range (10–30 dB).

As expected, the arrival rate of underdense meteor trails exceeds that of overdense trails at low SNR values. Conversely, at high SNR levels, the arrival rate of overdense trails exceeds that of underdense trails. No overdense trails were detected with peak amplitudes below -124 dBm.

The achieved communication throughput for the meteor radio link (MRL) using a specified data transmission rate between the Thule and Nord stations in August 1987 is presented in the report as a function of the transmission rate. A required throughput of 100 bps was recorded at a signal transmission rate of 5000 bps.

Measurements of the message delivery wait time for a 2000-bit message are also provided, depending on the transmission rate, assuming a delivery reliability of 0.9. The shortest wait time approximately 35 seconds was observed for transmission rates ranging from 4 to 8 kbps. The wait time increased at both lower and higher transmission rates.

It was shown that, with a transmitter power of 100 W, the optimal transmission rate lies in the range of 2 to 5 kbps, with the minimum delivery wait time being approximately 120 seconds.

An increase in the required message delivery probability leads to a significant rise in the message delivery wait time.

The conducted system-level analysis of the experimental data presented in [28–30] has shown that, in order to obtain more accurate information on the key parameters affecting message delivery (Figure 1), field trials must be carried out in the target service area. These trials should determine the transmission duration that ensures the required message delivery probability under the specified parameters of the transmitting and receiving equipment.

The following baseline parameters are proposed for conducting the field trials:

1. Transmitter power at the base station (BS): $PBS=1P_{\{BS\}} = 1 \text{ kW}$.
2. A six-element Yagi antenna with a gain of $GT=11G_T = 11 \text{ dBi}$ shall be used at the BS.
3. A three-element Yagi antenna with a gain of $GR=6G_R = 6 \text{ dBi}$ shall be used at the subscriber station (SS).
4. Trials shall be conducted at a data transmission rate of 2.4 kbps.
5. Minimum Shift Keying (MSK) shall be used as the modulation method.

Under the specified parameters, the energy potential of the meteor radio link (EPMR) is 47 dB.

For statistical processing of measurement results, the information part of the packet should include the date and time of transmission, with the remaining space filled with a predefined pseudorandom binary sequence ("1"s and "0"s). The date and time will enable the collection of statistical data on seasonal and diurnal variations in message delivery time, while the pseudorandom sequence will allow for estimating the bit error probability (under given conditions) and evaluating the effectiveness of the proposed error protection method (majority voting).

Based on the statistical analysis of the test results, the parameters of the transmitting and receiving equipment may be adjusted accordingly.

5 RESULTS

Message delivery time depends on the message length, the average duration of a usable meteor trail, and the energy potential of the meteor radio link (EPMR), which-at a given data transmission rate-determines the signal-to-noise ratio (SNR) at the receiving end.

Noise power within a specified bandwidth at frequencies above 20 MHz is primarily determined by galactic noise. Galactic noise is a function of frequency and, within the range of 20 to 100 MHz, can be estimated using the formula provided in [18].

$$P_{GN}(dBW) = -K - 27.7 \cdot \lg(f_{MHz}) + 10 \cdot \lg(\Delta F_{s,Hz}), \quad (2)$$

where the coefficient K depends on the location of the receiving station and ranges from 127.2 to 136.8, and $\Delta F_{s,Hz}$, in hertz, is the signal bandwidth determined by the transmission rate and modulation method.

For a bit error probability in the range of 10^{-2} to 10^{-3} , the required signal-to-noise ratio is approximately $SNR \approx 10$, and the required signal power level at the receiving point is given by $P_{SIGN} = P_{GN} + 10$, where P_{GN} is the galactic noise power.

Taking equation (1) into account, the length of the information packet is determined by the following expression:

$$N_{INF} + N_T = \tau_m \cdot V_{inf} - (N_{SS} + N_F + N_{KS} + N_{F^8}). \quad (3)$$

Table 1 presents the calculated values of the information packet length and the required signal level at the receiving point for a transmission frequency of 40 MHz, a meteor trail duration $\tau_m = 0.3$ s, the selected data rate V_{INF} , and the use of MSK modulation. The following values were assumed: $N_{SS} = N_F = N_{F^8} = 32$ bits, and $N_{KS} = 8$ bits.

Table 1 – Length of the information packet and the required signal level at the receiving point

V_{inf} , bit/s	Length of information packet, bits	Required signal level at the receiving point, dBW
1200	256	-130.78 ... -140.38
2400	616	-127.77 ... -137.77
3600	976	-126.01 ... -135.61

Based on radio wave propagation losses over a path length of 720 km, calculated according to the methodology presented in [35], the expected losses are in the range of 167 to 177 dB. With the selected EPMR value of 47 dB, the expected received signal level is estimated to be within the range of -120 to -130 dB.

These calculations demonstrate that, under the specified equipment parameters at both the base station (BS) and the subscriber station (SS), the transmission of alert signals in the proposed format is feasible.

Based on the experimental results presented in [30], it can be assumed that the message delivery time at a transmission rate of 2400 bps, with a delivery reliability of 0.9, will not exceed one minute. More accurate estimates of

the average message delivery time for a given geographic area, season, and time of day can only be obtained through experimental measurements and subsequent statistical analysis.

6 DISCUSSION

An analysis of available information sources revealed no existing recommendations regarding one-way (“paging”) message transmission protocols over MBC, message format specifications, or the procedures for establishing, maintaining, and terminating a communication session.

Well-known radio communication protocols (e.g., POCSAG) exhibit significant informational redundancy; they include address fields, employ error-correcting codes, and require tens of milliseconds for initial synchronization. As a result, message lengths may exceed the available “communication window” in MBC transmission, leading to increased message delivery time. Furthermore, such protocols do not support message replication as part of the standard.

In the proposed specialized protocol for alert signal delivery, redundancy is significantly reduced. This was achieved by minimizing the preamble length, combining the address field with the start-of-packet flag, and replacing traditional error-correcting coding with majority voting.

To increase the efficiency of the information field, the “Status” field is used to indicate the message format. For example, by specifying a “voice message” flag in field T, and providing the identifier of the required (pre-recorded) message in the information field, the total message length can be limited to 120 bits. At a transmission rate of 2400 bps, the transmission time for such a message is 50 ms, which significantly reduces the message delivery time.

To enhance reception robustness, a majority voting method has been proposed, which integrates effectively with the message replication mechanism provided by the protocol. Unlike traditional error-correcting coding, this method does not introduce redundancy into the message and requires minimal computational resources for implementation.

Although the paging mode lacks information confidentiality due to continuous message transmission over an extended period, intentional jamming becomes problematic when a jamming station is located more than 200 km from the base station (BS). This is due to the differences in the timing of meteor trail appearances along non-parallel radio paths.

Further research may focus on improving the energy stealth of transmission through the use of complex signals – such as direct-sequence spread spectrum (DSSS) signals – which can be transmitted below the noise floor.

The presented estimate of message delivery time using the proposed MBC transmission protocol should be considered preliminary. More reliable data can only be obtained through full-scale field trials conducted in the designated service area, followed by statistical analysis of the collected results.

The results of the experiment confirm the practical applicability of the method for deployment in real-world alert systems under emergency conditions without the use of satellite communication channels.

CONCLUSIONS

The transmission of alert signals under special conditions – where satellite and terrestrial communication lines are vulnerable or unavailable – necessitates the use of meteor radio channels and the development of a new one-way (paging) message transmission protocol, along with technical solutions to support its implementation.

Unlike existing protocols, the proposed specialized transmission protocol accounts for the unique characteristics of the meteor radio channel and enables minimization of message delivery time while maintaining the required quality and reliability. According to the proposed protocol, transmission is carried out continuously over a specified period with periodic repetition of the same message.

Message delivery time is minimized by reducing the length of the transmitted message. This is achieved through the use of an optimized message structure, newly developed methods of clock and frame synchronization, and a reliability enhancement algorithm that does not increase message length.

The protocol also provides for the possibility of cryptographic protection of transmitted data.

The proposed technical solutions are designed for low computational complexity, enabling implementation using digital signal processors (DSPs) and field-programmable gate arrays (FPGAs).

Preliminary calculations and comparison with known experimental data indicate that alert signal transmission according to the proposed protocol can be implemented using MSK modulation at transmission rates ranging from 1200 bps to 3600 bps (assuming a 1 kW transmitter and a six-element Yagi antenna at the base station, and a three-element Yagi antenna at the subscriber station). Under these conditions, the length of the information portion of the message is 256 bits at 1200 bps and 976 bits at 3600 bps.

A preferred transmission rate is 2400 bps, at which the information portion of the message comprises 616 bits (77 bytes), and the estimated delivery time with a reliability of 0.9 does not exceed one minute.

To obtain more accurate estimates of the average message delivery time and delivery time with a specified reliability for a given geographical area, as well as for specific times of year and day, further experimental investigations and statistical analysis of the results are required.

To ensure the energy stealth of alert signal transmission and protection against injection of false messages, future research should consider the use of direct-sequence spread spectrum (DSSS) signals with a spectral bandwidth exceeding 10 MHz for representing the information bits.

Alert signal transmission under special conditions, where satellite and terrestrial communication channels are vulnerable or unavailable, requires the use of meteor radio

channels and the implementation of an improved method for unidirectional message delivery that accounts for the specific characteristics of short-duration ionized trails.

The proposed method is implemented as an algorithm that includes step-by-step selection of radio channel parameters, message structure optimization, the application of a hybrid synchronization algorithm, and the use of a majority-voting principle to enhance reception reliability. This algorithm is presented in a structured form and ensures coherent execution of all transmission stages.

Based on this method and algorithm, a specialized unidirectional message transmission protocol has been developed. It minimizes alert delivery time while ensuring the required reception probability. The protocol provides for continuous signal transmission with repeated message broadcasting over a predefined time interval.

Delivery time is reduced through the use of an optimized packet structure, improved bit-level and frame-level synchronization methods, and a reliability enhancement algorithm that does not increase message length. The protocol also supports the option of cryptographic protection of transmitted data.

The practical value of the results lies in the applicability of the developed method and protocol in real-world emergency alert systems to guarantee the delivery of short messages without relying on satellite communication channels. The system architecture is suitable for implementation on DSP and FPGA platforms.

Preliminary calculations and known experimental data indicate that alert signal transmission using the proposed protocol can be implemented with MSK modulation at data rates ranging from 1200 to 3600 bit/s (assuming a 1 kW transmitter and Yagi antennas of appropriate configuration). The optimal transmission rate is 2400 bit/s, under which the estimated message delivery time with 0.9 reliability does not exceed one minute.

To obtain more accurate estimates of message delivery time for specific geographic regions, seasons, and times of day, further experimental studies and statistical analysis of the results are required. Future research will also focus on enhancing the energy-masking capability of the transmission and protecting against message spoofing through the use of DSSS signals with a spectrum width of over 10 MHz.

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DECLARATION

Conflict of interest: The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, institutional, authorship-related, or otherwise, that could have influenced the results or interpretations presented in this paper.

Authors' contributions: Olena Holovan: conceptualization of the research, development of the method for minimizing message delivery time in meteor-burst communication channels, formulation of the transmission protocol, and preparation of the manuscript; Volodymyr Lysechko: methodological supervision, analysis of communication system parameters, and validation of the proposed approach; Volodymyr Tarshin: analysis of practical applicability, system-level evaluation, and contribution to experimental interpretation; Oleh Misiura: investigation of synchronization methods, participation in algorithm development, and contribution to results analysis; Maksym Surhai.: analysis of modulation and synchronization techniques, contribution to protocol optimization, and technical review; Serhii Indyk: analysis of implementation aspects on DSP and FPGA platforms, contribution to system architecture description, and manuscript editing. All authors have read and approved the final version of the manuscript.

Data availability: All data used to support the findings of this study are included within the article.

Software availability: No software was developed specifically for this study.

Use of artificial intelligence tools: The authors confirm that artificial intelligence tools were used exclusively as auxiliary instruments for translation, language editing, and stylistic improvement of the manuscript, as well as to support the search, selection, and analytical processing of relevant scientific literature. Artificial intelligence technologies were not used in the development of the proposed method, in performing calculations or experiments, or in the generation of scientific results and conclusions presented in this paper.

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МЕТОД МІНІМІЗАЦІЇ ЧАСУ ДОСТАВКИ ПОВІДОМЛЕНЬ В МЕТЕОРНИХ КАНАЛАХ ЗВ'ЯЗКУ

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АНОТАЦІЯ

Актуальність. В особливих умовах (зокрема під час надзвичайних ситуацій), коли супутникові та наземні канали зв'язку стають вразливими або повністю недоступними, зв'язок через метеорні траси може ефективно виконувати роль резервного чи навіть основного каналу передавання інформації. Робоча дальність такого радіоканалу сягає до 2000 км, а відсутність «мертвих зон» забезпечує широкую територіальну покритість, порівнянну з іншими видами дальнього радіозв'язку.

Мета дослідження. Удосконалення методу передавання односпрямованих повідомлень через метеорні канали та алгоритму його реалізації, що дозволяють мінімізувати час доставки повідомлень при заданому рівні достовірності.

Метод дослідження. Отримав подальший розвиток метод, що ґрунтується на мінімізації структури повідомлення шляхом об'єднання адресного поля та синхронізаційного прапора, а також вперше використовується гібридний алгоритм синхронізації, який поєднує порогову і безпорогову обробку сигналів. Для підвищення достовірності замість класичних ARQ-методів застосовується алгоритм «більшості» при багаторазовому повторенні повідомлення.

Результати дослідження. Запропоновано удосконалений метод передавання оповіщень через метеорні канали, що забезпечує мінімізацію часу доставки та високу достовірність приймання. На його основі розроблено протокол передавання, оцінено час доставки повідомлень і визначено способи синхронізації, що підтверджують ефективність методу. Практична цінність полягає у створенні алгоритму реалізації, придатного для впровадження на DSP та FPGA у системах оповіщення без залучення супутникових каналів.

Висновки. Використання запропонованого методу та алгоритму реалізації у складі систем оповіщення дозволяє мінімізувати час доставки коротких повідомлень при заданій достовірності та підвищити надійність зв'язку у складних умовах.

КЛЮЧОВІ СЛОВА: система оповіщення, метеорний радіоканал, протокол передавання, синхронізація, час передавання, час доставки.

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