Proposal of Go-Back-i-symbol ARQ Scheme and its Performance Evaluation in Meteor Burst Communications

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***Abstract*—In this paper, we propose a new automatic repeat request (ARQ) scheme, named Go-Back-i-symbol (GBi) ARQ scheme, suitable to Meteor Burst Communications (MBC). The scheme realizes symbol-wise ARQ by using the Viterbi decoding algorithm for convolutional codes. We also propose a practical transmission protocol for applying the GBi-ARQ scheme to packet communications over time varying short burst channels such as meteor burst channels. Fundamental performances of the GBi-ARQ scheme in MBC are evaluated by computer simulations. Effectiveness of the GBi-ARQ scheme is shown by comparing the performance with that of a conventional block-wise ARQ scheme.**

***Index Terms*—Automatic repeat request, Convolutional codes, Meteor burst communication, Viterbi decoding.**

I. Introduction

BILLIONS of tiny meteors (space dust particles) enter the earth's atmosphere daily. They collide with air molecules and form ionized trails (so-called meteor bursts) at the altitude of 80-120km, capable of reflecting or scattering radio waves in the low VHF band. Meteor burst communication (MBC) systems utilize the phenomenon for over horizon communications. MBC is known to have superiority over other long distance communications (e.g., HF and satellite communications) for low rate traffic applications in many aspects such as simplicity of implementation and operation, lower initial and running costs, and reliability. Existing and proposed applications of MBC include meteorological data acquisition, remote monitoring, vehicle tracking and so on [1], [2].

Among a great number of meteors entering the earth's atmosphere, only those entering at proper location and correct orientation support communication between two specific points. Thus, the meteor burst channel between two stations opens randomly with average interval in order of ten seconds. The channels established by meteors typically last less than one second since the ionized trails diffuse rapidly. As the electron density in the trail changes, the received signal power in a packet varies with time, which mostly exhibits exponential attenuation.

Although error control is employed in almost all digital communications for efficient and reliable data transmissions, especially in MBC, it is indispensable because of the brief duration and intermittent nature of the channel. Thus, various error control methods using Forward Error Correction (FEC), Automatic Repeat reQuest (ARQ) and their combination Hybrid-ARQ (HARQ) are actively studied for MBC systems [3]–[6].

Conventional Stop-and-Wait (SW) ARQ schemes, however, may not be efficient in MBC because the channel has the property that the received signal power varies with time and mostly attenuates exponentially. Due to the rapidly attenuating signal power, a packet transmitted via MBC channel tends to have errors only in its tail part [7]. Even though in such a case, conventional SW-ARQ schemes inevitably discard whole of the packet.

One solution to this issue was given by Mukumoto et al. in [8]. They introduce a Go Back N-block (GBN) type ARQ scheme into the MBC system in which a packet is divided into several blocks. By adopting block by block decoding and requesting retransmission only the block having errors and the following blocks, the scheme successfully decreases loss of correctly decoded data. In fact, as mentioned in [1], [2], many MBC systems developed thereafter employ similar type of ARQ schemes. However, it is naturally expected that the throughput performance is further improved if we adopt a symbol-wise ARQ technique.

In this paper, we propose a new ARQ scheme named Go Back i-symbol ARQ (GBi-ARQ) scheme [13]–[16] which can achieve symbol-wise retransmission by using a convolutional encoder and a Viterbi decoder. The scheme uses the algorithm proposed in [9] by Yamamoto and Itho to evaluate the reliability of received data and modifies their algorithm for the GBi-ARQ scheme. We also propose a practical transmission protocol for applying the GBi-ARQ scheme to MBC, named Advanced MBC protocol(AMBC protocol).

It is worth pointing out that the concept of GBi-ARQ, i.e., symbol-wise retransmission, can be considered as a new class of ARQ techniques in packet communications. In that context, the term GBi-ARQ represents the symbol-wise ARQ techniques in general and the scheme proposed in this paper is one of the methods to realize GBi-ARQ technique. In this paper, however, we will conveniently use the name GBi-ARQ to refer the proposed scheme, since our discussions are restricted for it. Also, it is worth noting that the GBi-ARQ scheme can be applicable to many communication systems other than MBC. In particular, it is expected to have good performances for the systems with time varying channels.

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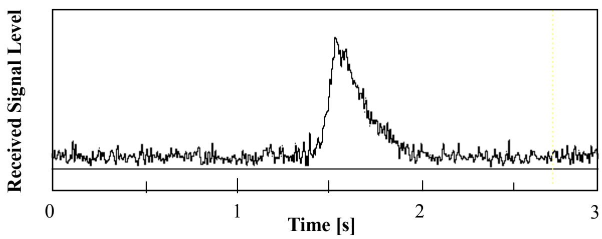

Fig. 1. A typical example of received signal from an underdense burst.

However, studies on such systems are left for future work since their performances depend on their channel models. Discussions in this paper are focused on applying the GBi-ARQ scheme to MBC, the most suitable application.

This paper is organized as follows. Section II briefly introduces meteor burst channels and presents the channel model used in this paper. In Section III, the GBi-ARQ scheme is proposed and explained in detail. A new data transmission protocol, AMBC protocol, is also proposed in Section IV to show how to apply the GBi-ARQ scheme to MBC systems in practice. Fundamental performances of the GBi-ARQ scheme are evaluated in Section V by computer simulations. Finally, Section VI shows the effectiveness of the GBi-ARQ scheme by comparing the performance with that of a block-wise ARQ scheme.

II. Channel Model for Meteor Burst Communications

By convention, meteor trails are classified into two categories, underdense bursts and overdense bursts, based on the electron line density of the trails [2]. However, as for the performance evaluation, only underdense bursts are taken into account in most literature because they largely outnumber the overdense bursts and the channel model is mathematically tractable. In this paper, we also use the channel model based on underdense bursts.

Underdense bursts are the trails with electron line density less than 10^{14} electrons/meter. In general, a channel opened by an underdense burst has a short lifetime and signal power passed through the channel is exponentially attenuated. Fig. 1 shows a typical time variation of received signal power from an underdense burst, actually observed by our experimental MBC system.

By adopting the underdense burst channel model, the received signal power reflected from a meteor burst is expressed as an exponentially decreasing function of time. Thus, a packet passed through the channel is assumed to have symbol energy, $E[j]$, given by

$$E[j] = E[1]\cdot \exp\left[-(j-1)T_S/\tau\right] \quad (1)$$

where j is the sequence number of symbols, T_s is symbol interval, and τ is decay time constant that depends on the height of the meteor burst trail, the transmission distance, and so on. In the equation, $E[1]$, representing the energy of the first symbol, is a function of the electron line density that varies from burst to burst.

Now, let us consider the signal of the packet passed through a matched filter at a receiver. Under the assumption of no intersymbol interference, the soft decision value, $r[j]$, of the filter output at the j-th sampling point, is expressed as

$$r[j] = A[j]\cdot s[j] + n[j] \quad (2)$$

where $A[j]$, $s[j]$, and $n[j]$ represent the signal amplitude, the transmitted sequence, and the matched filter output of noise, respectively. Using $E[j]$ in (1), the signal amplitude, $A[j]$, is given by

$$A[j] = K_M\sqrt{E[j]} \quad (3)$$

where K_M is the gain of the matched filter. $s[j]$ is a complex number corresponding to the transmitted data symbol. Assuming that channel noise is Additive White Gaussian Noise (AWGN) with one-sided power spectral density N_0, $n[j]$ is a complex random variable whose real and imaginary components independently follow a gaussian distribution with zero mean and variance

$$\sigma^2 = K_M^2 N_0/2. \quad (4)$$

III. GBi-ARQ Scheme

A. Introduction to GBi-ARQ Scheme

MBC channels open randomly and the received signal power passed through the channel mostly exponentially decays with time. Thus, a packet transmitted via the MBC channel tends to have errors only in its tail part. Even in such a case, conventional SW-ARQ schemes inevitably discard whole of the packet.

As a solution to this issue, Mukumoto et al. proposed in [8] to adopt a GBN type ARQ scheme in MBC. In their scheme, a packet is divided into several blocks and the receiver performs block by block decoding. If the receiver detects errors in a block, then it requests the retransmission of the packet including the block and the following blocks as illustrated in the upper part of Fig. 2.

Although the GBN-ARQ scheme succeeds in reducing the loss of correctly decoded data, it is naturally expected that the throughput performance is further improved if we adopt a symbol-wise ARQ scheme. Thus, we propose the GBi-ARQ scheme.

The concept of the GBi-ARQ scheme is also shown in Fig. 2. In the GBi-ARQ scheme, the receiver decodes received symbols and simultaneously evaluates the reliability of the decoded data. If the reliability is not enough, the receiver stops decoding and requests retransmission for the rest of the packet. When the transmitter receives a request of the retransmission, it will send the rest of the packet in the next opened channel.

In order to realize this ARQ scheme, we have to consider how to decide a point before which the received symbols are correct. In addition, the code used for the scheme needs to have the ability to be decoded no matter when it is truncated.

One good clue for this issue is given in [9]. In [9], Yamamoto and Itoh successfully proposed an algorithm to evaluate the reliability of received data by using Viterbi

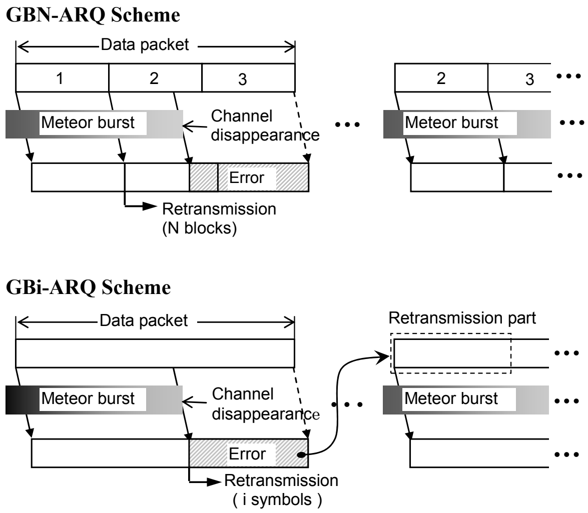

Fig. 2. Concept of GBN-ARQ and GBi-ARQ schemes in MBC.

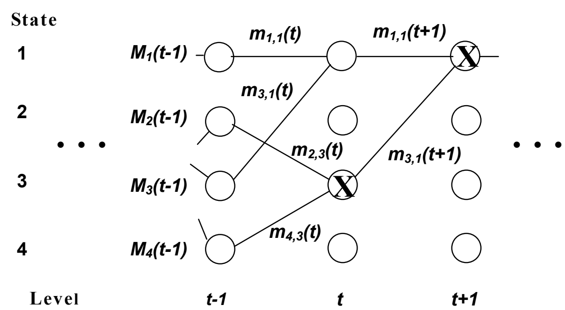

Fig. 3. Example of reliability decision procedure in Y-I algorithm.

decoding for convolutional codes. It is worth noting that there are several methods to evaluate the reliability of decoded data as mentioned in [10], [11]. Among those schemes, Yamamoto and Itoh's algorithm is much simpler and sufficiently reliable, so that it is very suitable to the GBi-ARQ schemes.

B. Method to Evaluate the Reliability of Decoded Data

Similar to the ordinary Viterbi Algorithm (VA), the Yamamoto and Itoh's algorithm (Y-I algorithm) proposed in [9] is explained by a trellis diagram in which nodes represent states of the encoder and paths correspond to the possible codes. At each node on the trellis diagram, a path with the largest metric among the paths merging into the node is selected as a survivor path or survivor. However, it is different from the ordinary VA that the survivor in Y-I algorithm survives with label X if the difference between the metrics of the survivor and the others is smaller than a threshold U, a predetermined positive constant. Label X indicates that the path is unreliable and it is not removed as long as the path survives.

Fig. 3 illustrates the algorithm by an example. In this figure, $M_j(i)$ represents a path metric for a survivor of state j at level i and $m_{j,k}(i)$ represents a brunch metric for a branch from state j at level $i-1$ to state k at level i.

At level t, for example, paths with the metrics $M_2(t-1)+m_{2,3}(t)$ and $M_4(t-1)+m_{4,3}(t)$ merge at state 3. Then, the

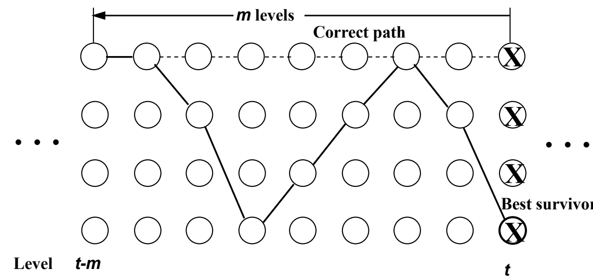

Fig. 4. Example of trellis diagram for Y-I algorithm.

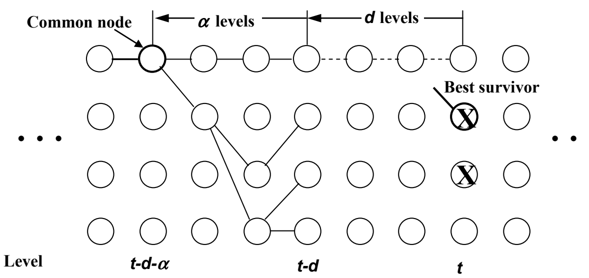

Fig. 5. Example of trellis diagram for the proposed algorithm.

metric of the survivor at level t, $M_3(t)$, is given by

$$M_3(t) = \max[M_2(t-1)+m_{2,3}(t), M_4(t-1)+m_{4,3}(t)] \quad (5)$$

and if

$$|\{M_2(t-1)+m_{2,3}(t)\} - \{M_4(t-1)+m_{4,3}(t)\}| < U, \quad (6)$$

the survived path is labeled X as shown in the figure, in which X's on nodes represent that the survivor into the node is labeled X.

The label X is never removed even if the labeled survivor meets good condition. For example, the survivor into state 1 at level $t+1$ in Fig. 3 has label X even if the following condition holds;

$$M_3(t) + m_{3,1}(t+1) \geq M_1(t) + m_{1,1}(t+1) + U. \quad (7)$$

C. Stopping Criterion of Decoding Process

In Y-I algorithm, the above procedure is continued until all the survivors are labeled X, then the decoder stops the decoding process as shown at level t in Fig. 4.

On the other hand, we modify the algorithm to improve the performance in GBi-ARQ scheme as follows: the above procedure is continued until the best survivor, i.e., the survivor with the largest metric at the current level, is labeled X, then the receiver stops decoding process as shown at level t in Fig. 5.

In a properly designed GBi-ARQ system, the correct path will be the best survivor in most decoding process. If the correct path is not the best survivor, it is probably not survived or already labeled X. Thus, if the best survivor is labeled X, it means that the correct path is unreliable with high probability. For this reason, we adopt the modified stopping criterion in our proposed GBi-ARQ scheme.

Moreover, in the case of applying the GBi-ARQ scheme to MBC, more sensitive stopping criterion is preferable since the received signal power passed through an MBC channel rapidly attenuates as mentioned before. Obviously, the modified stopping criterion stops the decoding earlier than Y-I algorithm. Hence, we can expect that the throughput performance of the GBi-ARQ scheme in MBC is improved by this modification .

D. Method to Decide the Termination Node

Ordinarily, encoders for convolutional codes are forced to terminate in all-zero state by adding $K-1$ dummy zeros to the end of the information sequence, where K denotes the constraint length of the code. The Viterbi decoder thereby selects the survivor into all-zero state at the final level of the trellis as the ultimate survivor and outputs the corresponding data sequence as the decoded data.

In general, the decoder needs to terminate the VA at a single node so called termination node to decide the ultimate survivor corresponding to the decoded data sequence. In the ordinary VA, the termination node is always fixed to a predetermined state, conventionally all-zero state, at the final level of the trellis.

In the GBi-ARQ scheme, we also assume that the encoder appends $K-1$ dummy zeros to the end of the information sequence. Therefore, if the receiver accepts all the symbols as reliable, the termination node is all-zero state at the final level of the trellis. However, in the case of detecting unreliable reception, the receiver stops the VA at that point. Since the VA is truncated in the middle of the trellis diagram, the decoder needs to decide a new termination node certainly connected with the correct path to determine the received data sequence in this transmission. Note that in the GBi-ARQ scheme, the termination node is not fixed at a specific level and its state is not necessarily all-zero state. In this section, we will discuss how to decide the termination node.

After having decided the termination node, the receiver decodes the data symbols corresponding to the survivor path into the termination node as the received data sequence in this transmission and then requests the transmitter to send the remaining data symbols in the next packet transmission.

As for the way to determine the termination node, Yamamoto and Itoh adopted the following method:

> *The termination node is the node traced back m levels along the best survivor at the trellis level truncated, where m is a predetermined integer.*

This method is also illustrated in Fig. 4 by using an example. In the figure, the upper broken line on the trellis diagram indicates the correct path and the solid line expresses the best survivor at the level truncated, which has errors. As mentioned before, Y-I algorithm stops the decoding when all the survivors are labeled X, shown at level t in the figure. After that, the decoder traces back m levels along the best survivor at level t to find the termination node.

Originally, Yamamoto and Itoh intended to apply their method for continuous communications over time invariant AWGN channels and employed the parameter m for the purpose of memory truncation. However, Niinomi et al. mentioned in [12] that throughput performance of the ARQ system can be improved by deciding repeat positions independently of memory truncation. They also mentioned that the value of m should be optimized for system and channel parameters because if m increases, the decoder discards many uncertain symbols, so that decoding error will decrease, but it may also discard many number of reliable symbols, which causes performance degradation.

In this paper, memory truncation is not considered since packets used in MBC are generally short and the value of m is optimized for properly deciding the termination node. However, we also refer to the method as Y-I algorithm in this paper. Then, in the followings, we treat the Y-I algorithm as one of the methods to realize GBi-ARQ scheme. The GBi-ARQ scheme with Y-I algorithm is used to compare the performance with a newly proposed GBi-ARQ scheme described below.

As mentioned before, in our GBi-ARQ scheme, the decoder stops VA when the best survivor is labeled X. Then, the decoder determines a termination node using the following method:

> *The termination node is the common node that all the survivors at the level of d steps before the truncated level stem from, where d is a predetermined integer.*

Fig. 5 illustrates this method by using an example. In the figure, the decoder stops VA at level t since the best survivor is labeled X. After stopping VA, the decoder firstly goes back d levels and then traces back all survivors from all nodes to their common node. If the value of d is properly determined, we can expect that the correct path is survived at level $t-d$, so that the common node is connected to the correct path with high probability. The number of traced back levels is indicated by α in the figure. The key point of the algorithm is that α is not fixed but adaptively changes according to the reliability of the received symbols.

E. Metric Calculation in MBC Channels

In this subsection, we discuss metric calculation used in VA for decoding a convolutionally coded packet passed through an MBC channel.

Let us denote the code length as L, the transmitted sequence as $\boldsymbol{s} = (s[1], s[2], \cdots, s[L])$, the amplitude sequence as $\boldsymbol{A} = (A[1], A[2], \cdots, A[L])$, and the received sequence as $\boldsymbol{r} = (r[1], r[2], \cdots, r[L])$. Also, we denote the estimated sequences of $\boldsymbol{s}$ and $\boldsymbol{A}$ as $\hat{\boldsymbol{s}}$ and $\hat{\boldsymbol{A}}$, respectively. Then, the log likelihood function of $\hat{\boldsymbol{s}}$ and $\hat{\boldsymbol{A}}$, $\lambda(\hat{\boldsymbol{s}}, \hat{\boldsymbol{A}})$, is given by

$$\lambda(\hat{\boldsymbol{s}}, \hat{\boldsymbol{A}}) = \ln Pr(\boldsymbol{r} \mid \hat{\boldsymbol{s}}, \hat{\boldsymbol{A}}) = \sum_{j=1}^{L} \ln Pr(r[j] \mid \hat{s}[j], \hat{A}[j]), \tag{8}$$

where

$$\ln Pr(r[j] \mid \hat{s}[j], \hat{A}[j]) = -\ln(\sqrt{\pi N_0}) - \frac{|r[j] - \hat{A}[j]\hat{s}[j]|^2}{N_0}. \tag{9}$$

Since $\lambda(\hat{\boldsymbol{s}}, \hat{\boldsymbol{A}})$ is calculated by adding the log likelihood functions of each symbol, we can take advantage of VA.

Hereafter, we assume the BPSK modulation. By putting $|\hat{s}[j]| = 1$ and removing the terms irrelevant to the estimation of s from (9) in the same way as the metric calculation in the ordinary AWGN channel [17],

$$m_s(r[j] \mid \hat{s}[j]) = r[j]\hat{A}[j]\hat{s}[j] \tag{10}$$

is derived as a sufficient measure for the estimation of s. We thus use (10) instead of (9) as a metric of $\hat{s}$.

Clearly, $\hat{\boldsymbol{s}}$ which maximizes $\lambda(\hat{\boldsymbol{s}}, \hat{\boldsymbol{A}})$ depends on $\hat{\boldsymbol{A}}$, i.e., the estimation of $\boldsymbol{A}$ is required for the maximum likelihood estimation of $\boldsymbol{s}$. In actual, however, exact estimation of $\boldsymbol{A}$ is extremely difficult, so that we simplify the calculation by ignoring the variation of $\boldsymbol{A}$ during a period of deciding the survivor path. By this simplification, (10) is replaced by

$$m_s(r[j] \mid \hat{s}[j]) = r[j]\hat{s}[j]. \tag{11}$$

This is a reasonable simplification when convolutional codes with short constraint length are used. Actually, it is shown in [13] that the influence of the simplification on the throughput performance is very small even for a convolutional code with constraint length of 7.

IV. Transmission Protocol for MBC with GBi-ARQ Scheme

The issue to be considered next is how to implement the GBi-ARQ scheme in MBC networks in practice because channels between their stations open randomly and close unpredictably. As a good answer to this issue, we propose a new transmission protocol named Advanced MBC (AMBC) protocol [14], [15] in this section. To cope with unpredictable channel close, the protocol employs special handshake process, in which, prior to a data packet transmission, the transmitter asks the receiver the number of decoded data as reliable symbols in the previous communication and confirms that they are indeed correctly decoded by using error check sequence sent from the receiver.

By thinking about actual applications using MBC, for example meteorological data acquisition systems, let us assume the following situations:

- The system is configured as a center concentrated MBC network constituted by one master station and many remote stations and they communicate with half duplex mode.
- The remote stations constantly acquire and store data such as temperature and humidity from sensor equipments and attempt to send the data to the master station via MBC channels.
- Since the remote stations usually have simple hardware and a small solar battery, the master station has to control the network. For example, the master station, in general, transmits probe packets to the remote stations for sounding the channel condition and a remote station transmits its packet only when the probe packet is received for saving the energy.

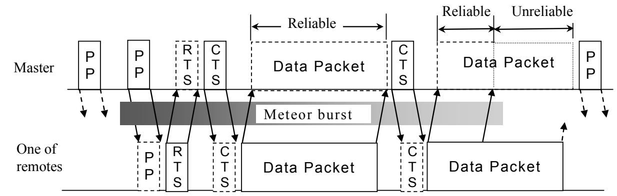

Fig. 6. Example of the behavior of AMBC protocol.

Furthermore, it should be noted that the protocol needs to provide additional error detection method for reliable data transmission since GBi-ARQ scheme does not have exact error detection capability.

Fig. 6 illustrates an example of the behavior of a system operating under the AMBC protocol. The description of the protocol is as follows:

1. The master station periodically transmits Probe Packets (PP) with constant interval.
2. When the MBC channel between the master station and a remote station opens, the remote station receives the PP and returns a Request To Send (RTS) packet including the remote station number (for identification) and serial number of the packet.
3. When the master station receives the RTS packet, it stops transmitting PP and sends a Clear To Send (CTS) packet including information of the number of data bits, k, decoded as reliable data in previous communication with the remote station. The CTS packet also includes Cyclic Redundancy Check (CRC) generated from the decoded part of the data with the length of k.
4. When the remote station receives the CTS packet, it compares two CRCs: One is included in the CTS packet and the other is calculated in the remote station using the first k bits of the data in the previous data packet. If the two CRCs do not coincide, the remote station retransmits the previous data packet. On the other hand, if the CRCs coincide, the remote station encodes the current data from the $(k+1)$th bit and transmits a data packet including them. Note that if other data remain in the transmission buffer, they can be added to the packet.
5. The master station receives the data packet and the decoder evaluates the reliability of data by using the algorithm explained in the previous section. If the decoder decides all data are reliable, the master station sends another CTS packet and prompts the remote station to send the next data packet. The master station iterates this process until no data packet arrives or the decoder detects unreliable data in the received data packet. In case of detecting unreliable data in a packet, the master station considers that the channel is already closed, so that it stores only the reliable data and restarts PP transmission (i.e., returns to the first procedure).

In addition, the protocol assumes that the master station returns to PP transmission whenever it detects any packet failure to ensure robustness of the system.

V. Performance Evaluation

A. Assumptions for Performance Evaluation

In order to evaluate elemental performance of the GBi-ARQ scheme under the AMBC protocol, in this section, we focus our attention to the data packet transmission from a remote station to the master station. All the performances are obtained by computer simulations. Assumptions for the simulations, unless otherwise stated, are the followings: the channel opened between the master station and the remote station varies with time as expressed by (1) with relatively short decay time constant, $\tau = 0.15[\mathrm{s}]$. We adopt half rate convolutional codes whose constraint lengths, K, are 3 and 7 and their generator matrices are $(5, 7)$ and $(117, 155)$ respectively [17]. The modulation is BPSK with modulation rate 2400[baud]. The receiver performs ideal coherent demodulation and the error detection by CRC is perfectly achieved. Performance evaluations of the GBi-ARQ systems with other assumptions such as QPSK modulation, differential demodulation, and using punctured convolutional codes are found in [13].

To uniquely determine the relation between the metric and the reliability threshold U, they are assumed to be normalized by the standard deviation of the noise. For the evaluation of fundamental performances, length of the data packet is assumed to be longer enough than the duration of MBC channels. By this assumption, the data packet is transmitted only once per an opened channel. Thus, the performance is evaluated in terms of "average transmitted bits per burst" which denotes the average number of correctly received bits per one communication. The numerical results obtained in the followings are averaged over 10^5 times of simulations.

B. Performance Comparison of the Proposed Algorithm and Y-I Algorithm

In this section, we firstly investigate influence of the parameters on the performance of GBi-ARQ schemes by using numerical examples. Figs. 7 and 8 show the average transmitted bits per burst for the GBi-ARQ schemes using Y-I and the proposed algorithms, respectively. The convolutional code assumed is $(5, 7)$. The initial $SNR(= E[1]/N_0)$ is assumed to be $0dB$, where $E[1]$ is the received signal energy of the first data symbol in a data packet. Note that we ignore handshake process and header part of the data packet since they are common for the schemes considered in this paper. Moreover, because of exponential decay assumption, characteristics of the channel do not change by time shifting.

The performance in Y-I algorithm depends on the parameters U and m, defined in Sec. III-D, as shown in Fig. 7. In the proposed algorithm, it depends on U and d, defined in Sec. III-D, as shown in Fig. 8. The parameter U, the reliability threshold, is used to decide the truncation point for both algorithms. Larger U decreases the number of data to be decoded while it increases the accuracy of the decoded data. On the other hand, m in Y-I algorithm and d in the proposed algorithm are used for searching the termination node. Increment of the parameters also contributes reliable data reception but it reduces the quantity of decoded data. Hence, they have optimum values. However, it is seen from

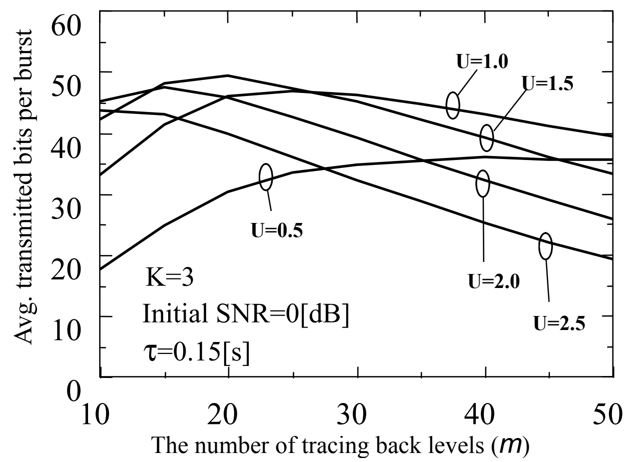

Fig. 7. Influence of the parameters on the performance of GBi-ARQ scheme with Y-I algorithm.

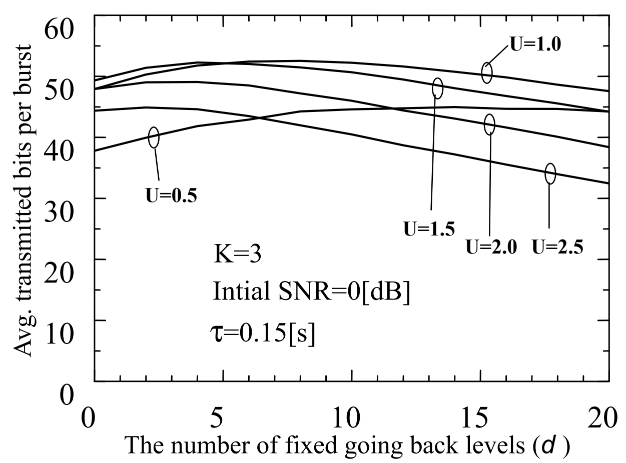

Fig. 8. Influence of the parameters on the performance of GBi-ARQ scheme with the proposed algorithm.

the figures that changes of the curves for both algorithms are gradual, so that shifting the parameters from the optimum values does not largely degrade the performance.

Comparing the two figures, we observe that the proposed algorithm has larger maximum average transmitted bits per burst for all U's. As mentioned in Sec. III-D, in GBi-ARQ schemes, inaccurate estimation of the retransmission point leads to degrade throughput performance by discarding the reliable symbols unnecessarily or decoding unreliable symbols. However, the number of trace back levels decided by Y-I algorithm is not always appropriate since it is fixed. On the other hand, the proposed algorithm adaptively determines the number of trace back levels according to the reliability of the received symbols. Thus, the proposed algorithm yields better performance.

Next, let us compare the maximum performances of the two algorithms. The curves in Fig. 9 indicate the maximum achievable average transmitted bits per burst as a function of initial SNR where the parameters are optimized with respect to each initial SNR. We see from the figure that the proposed algorithm exhibits better performance than Y-

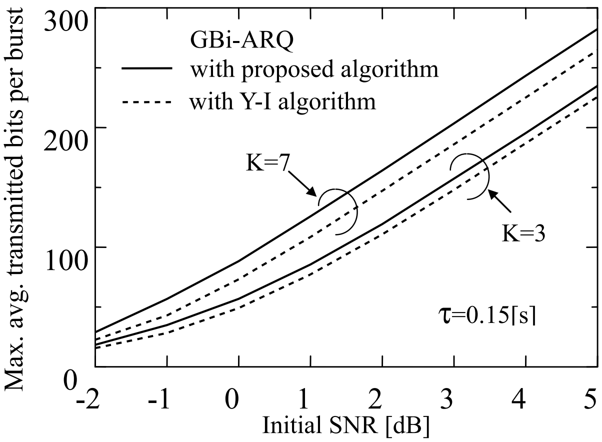

Fig. 9. Performance comparison between GBi-ARQ schemes with the proposed and Y-I algorithms.

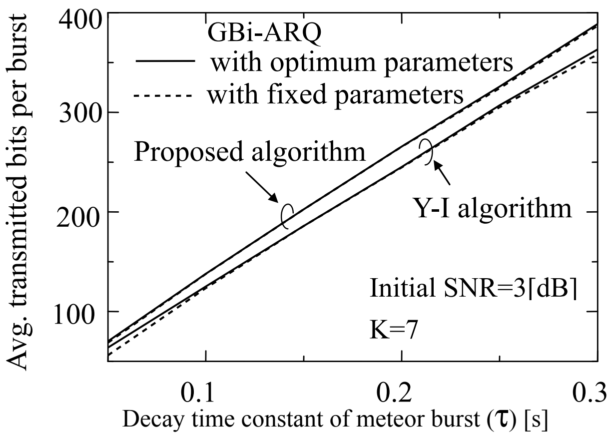

Fig. 10. Performance comparison between the GBi-ARQ schemes with optimum and fixed parameters as a function of decay time constant.

I algorithm for all initial SNR. This is because the number of trace back levels in the proposed algorithm is properly adjusted depending on the received data whereas it is fixed in Y-I algorithm as mentioned before. Moreover, the figure shows that the difference of the performance becomes large for the convolutional code with longer constraint length. This is because the larger the constraint length of the convolutional code, the larger the variance of the proper number of trace back levels, so that the difference increases.

Fig. 10 shows throughput performances of the GBi-ARQ schemes as a function of the decay time constant for a meteor burst, τ. The assumed convolutional code has constraint length $K = 7$ and the initial SNR is assumed to be $3dB$. The solid lines indicate the maximum average transmitted bits per burst in which the parameters are optimized for each decay constant. Again, we can observe from the figure that the proposed algorithm exhibits better performance than Y-I algorithm for all decay constant and the larger the decay constant, the larger the difference.

The dashed lines in the figure indicate average transmitted bits per burst for the systems with fixed parameters: $U = 2$ and $d = 7$ for the proposed algorithm and $U = 3.5$ and $m = 55$ for Y-I algorithm, respectively. In an actual MBC, channel parameters such as initial SNR and decay constant change from bust to burst and they are unpredictable, so that it is difficult to adjust the system parameters to the optimum values. However, as seen in the figure, the systems with fixed parameters yield almost the same performance as those with the optimum parameters. Especially for the proposed algorithm, the dashed and solid lines almost perfectly overlap and appear as one curve. The similar results hold for the throughput performances versus initial SNR [14]. This is because varying the channel parameters makes only modest changes to the optimum parameters and shifting the parameters from the optimum values causes only a little performance degradation as shown in Figs. 7 and 8.

Hereafter, we consider only the GBi-ARQ scheme with the proposed algorithm, so that it is simply referred to as GBi-ARQ scheme.

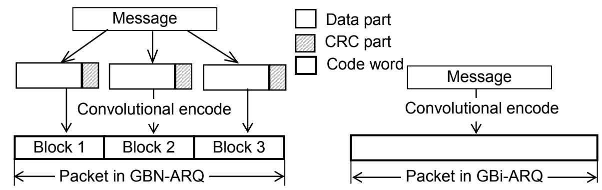

Fig. 11. Packet structure in GBN-ARQ and GBi-ARQ schemes.

C. Performance Comparison of GBi-ARQ Scheme with GBN-ARQ Scheme

In this section, we use the scheme proposed in [8] as an example of block-wise GBN type ARQ schemes to compare the performance with that of the GBi-ARQ scheme. The difference in the packet constructions of the GBi-ARQ and the GBN-ARQ schemes is described in Fig. 11. Although the scheme proposed in [8] has not considered any error correcting code, we assume that each block in the GBN-ARQ scheme is convolutionally encoded to compare the performance of the two schemes. As shown in the figure, a message in the GBN-ARQ scheme is divided into several blocks. Then, after adding CRC bits, each block is convolutionally encoded, and thereafter, the packet composed of the coded blocks is transmitted at once. The length of CRC is assumed to be 16 bits.

Fig. 12 shows the performances of the GBi-ARQ and the GBN-ARQ schemes. The parameters, U and d, in the GBi-ARQ scheme and block length in the GBN-ARQ scheme are optimized for each initial SNR. From the figure, the GBi-ARQ scheme exhibits better performance than the GBN-ARQ scheme. Since the GBi-ARQ scheme achieves symbol-wise retransmission, it can use MBC channel more effectively. Moreover, the difference in the performance increases in higher initial SNR. This is because better channel condition increases the optimum block length in the GBN-ARQ scheme, which causes to increase the number of data to be discarded in case of error detection.

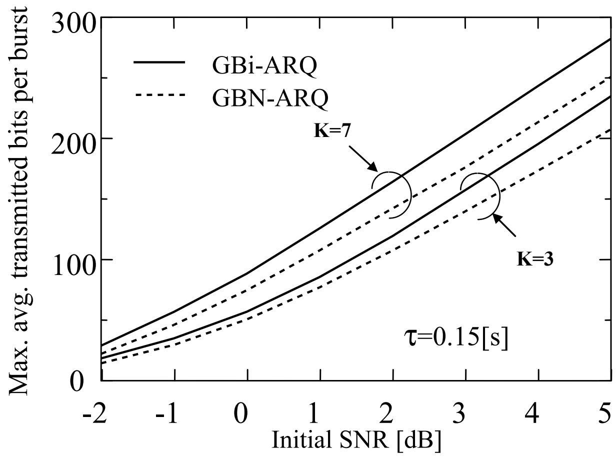

Fig. 12. Performance comparison between GBi-ARQ and GBN-ARQ schemes.

D. Conclusion

In this paper, we have proposed a new ARQ scheme, named GBi-ARQ scheme suitable for MBC. In order to realize this scheme, we utilize an algorithm introduced in [9] and modify the algorithm for applying it to packet transmissions in MBC. We have also proposed a practical transmission protocol, named AMBC protocol, for making the best use of the GBi-ARQ scheme in MBC. Fundamental performances of MBC systems with the GBi-ARQ scheme are investigated in various situations by using computer simulations. The maximum achievable average transmitted bits per burst for the GBi-ARQ scheme and the GBN-ARQ scheme are also numerically evaluated in MBC. Then, it is shown that the GBi-ARQ scheme has better throughput performance than the GBN-ARQ scheme.

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