Low Complexity Turbo Decoders for Noncoherent FH/SS over Partial Band Jammed Channel

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Abstract
In this study, turbo codes were investigated in a slow frequency-hopped binary frequency shift keying spread spectrum (FH/BFSK-SS) system with partial band jamming and full-band thermal noise. A soft decision decoding metric which includes automatic gain control (AGC) is proposed for turbo code decoding with a non-coherent square law receiver of FH/BFSK. The study focused on the performance comparison of various reduced complexity turbo decoding algorithms using the above-mentioned soft decision decoding metric. These low complexity turbo decoding algorithms included Log-MAP, Max-Log-MAP and SOVA. From the simulation results, Log-MAP performed the best, but with the highest complexity. While, although SOVA performed the worst, it had the lowest complexity. Max-Log-MAP performed about 0.1dB worse than Log-MAP. The performance degradation was about 0.4dB between the SOVA and Log-MAP algorithms.

Keyword: FH, SS, turbo code, AGC

1. Introduction
Frequency hopping spread-spectrum (FH-SS) is an efficient multiple-access technique for packet data communications [1]. In FH-SS systems, the system performance is subject to the partial band interference and the forward-error correction coding is required to mitigate the interference [1]. Previous investigations into the application of coding to FH-SS were carried out using Reed–Solomon codes [3] and concatenated Reed–Solomon/block codes or Reed–Solomon/convolutional codes [4].

Turbo codes are an exciting new channel coding scheme that approaches the Shannon limit. The original turbo decoder [5] uses two maximum a posterior probability (MAP) decoders which utilize a prior information. There are other less complex algorithms that can be used in place of the MAP algorithm for each decoder such as Log-MAP, SOVA and Max-Log-MAP [12]. All previous studies on the turbo decoder assumed coherent detection using linear modulation [5],[6],[7]. In [8] and [9], the turbo code performance of coherent and non-coherent FH-SS was investigated for the/a MAP algorithm for a channel with and without memory. In [10], the turbo code was analyzed considering partial band interference. Hence, for the purposes of this study, the turbo decoder where each component decoder used an approximate MAP algorithm with reduced complexity to calculate a posteriori likelihood estimates for each bit was considered.

2. System Model

2.1 Turbo Coded FH/BFSK over Jammed Channels
The system block diagram of turbo coded FH/BFSK system over a jammed channel is shown in Fig. 1. In the transmitter, the encoder is formed by parallel concatenating two constituent codes separated by an interleaver [12]. The constituent codes are recursive systematic convolutional (RSC) codes. The encoder uses as input the information sequence of length K and then outputs three streams: the data bit, the parity bit of the first component encoder with non-interleaved as input and the parity bit of the second component encoder with interleaved as input. The convention that information 0 is mapped to −1 and information 1 is mapped to +1 is used here. Denote and as the mapped symbol of , then the encoded bit stream at time index is denoted as

\[ y_i = \begin{cases} \sqrt{2} & \text{if } x_i = 0 \\ -\sqrt{2} & \text{if } x_i = 1 \end{cases} \]  

(1)

where . The effective code rate is a . The encoded bit stream is then BFSK modulated and frequency-hopped using a random hopping pattern. The channel is assumed to be an on-off jammed channel. The jammer evenly distributes its power over a fraction of the frequency range. Hence, the interference in the channel includes full band thermal noise with double sided spectral density and partial band interference.
Fig. 1. Block diagram of turbo coded FH/BFSK system over jamming channel with double-sided power spectral density which covers a fraction of the available band.

In the receiver, the received signal is dehopped and demodulated by two banks of filter followed by non-coherent square law detectors. Channel information is estimated from the received signal to aid the signal detection. The power of noise plus interference is estimated and used to control the gain of received signal. In this way, the receiver functions like the behavior of automatic gain control (AGC). Channel reliability information, the ratio of signal energy and noise power, is used to aid the turbo decoding, which is described in detail in the next sub-section.

2.2 Original Log-MAP decoding algorithm

Turbo decoding is an iterative algorithm that makes use of the MAP or its simplified version Log-MAP or SOVA algorithm. The derivation of these algorithms is well documented in literature [5], [15] and [12]. In the traditional derivation of the MAP algorithm, linear modulation such as phase shift keying (PSK) or quadrature amplitude modulation (QAM) is used and the noise is additive white Gaussian noise (AWGN) with fixed power. Hence, the MAP algorithm is simplified to the/a Log-MAP algorithm where the log likelihood ratio (LLR) is used as the soft-in soft-out (SISO) variables. The Log-MAP decoding algorithm is a soft-in soft-out (SISO) decoding algorithm for decoding convolutional code. While in turbo decoding, the extrinsic information is extracted in each component code decoder and transferred to the other component code as the a priori information. The process is iterated and eventually converges to some low bit error rate if SINR is higher than some threshold.

Although turbo decoding algorithm is well documented in literature [12], it is re-stated here with minor modification for the consistence and completeness of this paper. The turbo decoding algorithm is depicted in Fig. 2. The notation convention in [12] is used here with a little modification making the channel reliability time variant with time index \( k \). Let \( s' \) denote the current state of the RSC code at time index \( k \), and \( s \) denote the next state of RSC code at time index \( k \). Let \( \hat{\mathbf{s}} \) be the mapped symbol vector corresponding to the input \( s' \), and \( \mathbf{r} \) be the received signal vector for the first component code. And we also denote the a posteriori probability (APP) LLR of \( s' \), the a priori LLR from the other decoder, and the extrinsic information of \( s \). Note that and are the channel reliability factors for received signals \( s' \) and \( s \). Note that in fig. 2, \( \hat{\mathbf{s}} \), and \( \mathbf{r} \) are superscripted with parenthesized numbers to identify the LLR of the \( i \)th component decoder. In an AWGN channel with antipodal signaling such as BPSK modulation, the Log-MAP algorithm for the first component code is summarized in the following steps and can easily be extended to the second component decoder.

(S1) Initialize the forward and backward metrics and.

(S2) Compute the branch metrics .

(S3) Compute the forward metrics .

where \( \mathcal{S} \) is the set of all states at time .
(S4) Compute the backward metrics,

\[ \text{backward} \]

where \( \mathcal{A} \) is the set of all states at time \( t \).

(S5) Compute the APP L-value,

\[ \text{APP} \]

where \( \mathcal{B} \) and \( \mathcal{C} \) are the sets of all state pairs and that correspond to the input bits and at time \( k \) respectively.

(S6) Compute the extrinsic information,

\[ \text{extrinsic} \]

Note that channel reliability factors \( \alpha \) and \( \beta \) are time varying, because they depend on the signal to interference and noise ratio (SINR) of that instant. While in [12], \( \alpha \) and \( \beta \) are a constant because constant signal to noise ratio is assumed. When SINR is high (channel is more reliable), the second term of (4) will give higher weight in calculating . While SNR is low, \( \alpha \) and \( \beta \) have small values and the a priori LLR has higher weight in calculating . If \( \alpha \) and \( \beta \) are not estimated correctly, the decoding algorithm will not perform as expected [16], [18].

3. Turbo Decoder for FH/BFSK over Jammed Channel

3.1 Model of the Received Signals

Since turbo codes also use binary convolutional codes as the component codes, the binary soft decision metric should also be used to exploit the capability of turbo codes. In the FH/BPSK baseband system model, without loss of generality, assume that coded information bit 0 (0) is transmitted. In the proposed receiver in Fig. 1, the received signals and after the AGC squared law detectors at time index are denoted as

\[ \text{received} \]

where \( \phi \) is the phase ambiguity between the receiver and transmitter and , , , , are the in-phase and quadrature phase additive interference components, \( \sigma^2 \) is the noise variance at time index and is the energy per coded bit. Here the noise includes background white noise and intentional jamming. Since \( \alpha \) and \( \beta \) are non-central and central chi-square random variables with two degrees of freedom, their probability density functions (PDF) are [14]

\[ \text{probability density function} \]

where \( I_0 \) is the modified Bessel function of order zero and the non-central parameter is defined as

\[ \text{non-central parameter} \]

The means and variances of and are calculated as follows:

\[ \text{means and variances} \]

3.2 Approximate MAP Decoding

The soft binary decoding metric for the convolutional coded frequency-hopped BFSK system used in MAP decoding is defined as [11]

\[ \text{decoding metric} \]

where the superscript of is skipped in order to simplify the notation. This decoding metric is also used for turbo decoding. Since the decoding metric is not a Gaussian random variable, the probability form of the MAP algorithm must be used in the decoding algorithm for optimal performance. The probability distribution function (pdf) of is a very complex function with exponential and Bessel function. In order to overcome this issue, the approximate Gaussian approach is used, i.e. the decoding metric is approximated as a Gaussian random variable with mean and variance defined as

\[ \text{approximate Gaussian} \]

The channel transition probability is approximated as

\[ \text{channel transition probability} \]

Following the same derivation procedure as in [12], the Log-MAP algorithm described in section 2 can be used to decode the received signal with the decision metric defined in (13). Utilizing (16), and after some manipulation, the channel reliability factor is shown as

\[ \text{channel reliability factor} \]
where we again skip the superscript of in order to simplify the notation. Therefore, the only modification of the Log-MAP algorithm described in Step 2 of section 2 is using the derived here when computing the branch metrics . It has been demonstrated by several researchers that the estimation error of channel reliability factor degrades the performance of the turbo decoder [16]. But, it has been shown in [18] that for turbo-coded FH/BFSK in a partial band jammed channel, automatic gain control of the received signal can reduce the impact of the channel reliability factor. Hence in the rest of paper, the channel reliability factor will be neglected for all turbo decoder algorithms.

3.3 Reduced Complexity Turbo Decoders

The turbo decoding metric derived in the last sub-section can easily be applied to well known reduced complexity turbo decoders. The Log-MAP algorithm described in Section 2 still needs a lot of complex functions such as exponential and logarithm, although it is less complex than the probability form MAP decoder. A method usually adopted to reduce the computation load is using the Max-Log-MAP algorithm where the logarithm-exponential calculations in steps 3-5 of section 2 are replaced with max function through the following approximations:

Another well-known reduced complexity turbo decoding algorithm is the soft output Viterbi algorithm (SOVA) [17] where one decoder passes reliability (confidence) information about its decoded outputs, so-called soft outputs, to a second decoder. This allows the second decoder to use soft decision decoding as opposed to simply processing the hard decisions made by the first decoder. SOVA operates similarly to the Viterbi algorithm while it additionally needs the storing and updating of reliability factors. Compared with the Log-MAP or Max-Log-MAP algorithm, SOVA is the least complex, but it is not an MAP decoder. Therefore, a SOVA decoder usually performs worse than a MAP type decoder.

4. Simulation Results

For all simulations, the component encoders were rate ½-rate recursive systematic convolutional encoders with two memories and octal generators (7, 5). The overall code rate of the turbo code was ½ by puncturing the parity bit of each component code. The SNR with respect to full-band thermal noise was 10 dB. Worst case jamming was assumed in the simulation. In the simulation, receiver with AGC function but no CSI function was assumed because the receiver with an AGC function is not sensitive to an SINR mismatch [18]. Therefore, no accurate estimation of channel reliability factor was needed.

Fig.3. Performance of FH/BFSK with Log-MAP algorithm under worst case jamming

Fig.4. Performance of FH/BFSK with Max-Log-MAP algorithm under worst case jamming

To compare the performance of these reduced complexity turbo decoders, Figures 3-5 depict the bit error rate (BER) performance for Log-MAP, Max-Log-MAP and SOVA, respectively. In all three figures, the performance saturated at about the 5th iteration, and no large coding gain was achieved with more iterations. From the simulation results, Log-MAP had the best performance, but with the highest complexity. While SOVA had the worst performance, it had the lowest complexity. Max-Log-MAP performed only a little worse than Log-MAP about 0.1dB. The performance degradation was about 0.4dB between SOVA and Log-MAP algorithms.
Fig.5.Performance of FH/BFSK with SOVA algorithm under worst case jamming

5. Conclusions
If a soft decision decoding metric is proposed for FH/BFSK spread spectrum systems with non-coherent square law receivers. An approximate Gaussian approach was used to simplify the decoder complexity such that the Log-MAP algorithm could be used without resorting to the probability form algorithm. The automatic gain control (AGC) was also included in the receiver such that no complex estimation algorithm was needed to estimate the channel reliability. Therefore, the complexity of the turbo decoder was reduced compared with the conventional turbo decoder. The extension to other reduced complexity algorithms such as SOVA and Max-Log-MAP was also investigated. The proposed algorithms were verified with computer simulation and found to be quite effective in combating interference and the performance degradation with Max-Log-MAP and SOVA was about 0.1 to 0.4 dB. The work in this paper exemplifies the error correction power of turbo codes in FH/BFSK spread spectrum systems with low complexity algorithms. Future research might extend current work to turbo coded FH/MFSK systems providing more channel capacity for high speed multimedia communications.

References
Biographies

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