Detection of Fatal Transient Impairments Using an Embedded Secondary Channel

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Abstract

Unlike voice communication, voiceband data communication can be seriously affected by transient channel impairments. In some cases, synchronization between the transmitter and the receiver may not be recovered from these kinds of impairments without a reinitialization process. Therefore, it is highly desirable for data communication equipment to have an efficient transient channel impairments detector for fast recovery. In this paper, one such detector is proposed for high speed modems using a secondary channel synchronously embedded in the main channel. A known code word being multiplexed with the secondary port data is sent through the embedded secondary channel. The received code word is tested for detection of fatal transient impairments. For reliable detection, the confirmation is sequentially performed based on a modified up/down counter scheme. The performance of the proposed detector is analytically evaluated in closed form.

1 Introduction

Although transient disturbances such as impulse noise, gain hits, drop outs and phase hits are regulated, they account for a substantial portion of performance degradation when signals are transmitted through a network system. These types of transient impairments can cause audible clicks or pops and thus may result in an unobnoxious effect to listeners on the telephone lines. However, it can seriously affect data communication since it can cause loss of system synchronization.

In particular, when a signal is transmitted through a digital carrier system such as T1, it can be corrupted by slips. A slip is an intended insertion or deletion of a single DS1 (T1) data frame in the digital switching operation to avoid loss of network synchronization due to either the lack of frequency synchronization of clocks at various network nodes, or phase wander and jitter on the digital bit stream [1]. Like the above transient noises, slips cause occasional audible clicks and thus do not cause serious degradation in voice communication [2]. However, a single slip can seriously affect data communication. For example, a slip affects Group 3 facsimile transmission, where a maximum of eight horizontal scan lines can be missed [3]. Experimental results on voiceband modems indicate that a single slip causes a long burst of errors over a time period which can be up to several seconds depending on the modem type and data rate [4]. In some cases, the modem never recovers from a slip and requires a forced manual reset. Therefore, it is highly desirable for a modem to have a detector for rapid recovery from a fatal loss of synchronization due to such transient impairments.

High speed modems usually have a secondary channel to support other functions, such as the digital network management. The secondary channel can be implemented using a separate FSK modulation module. However, to maximize the use of the channel bandwidth and to reduce the implementation cost, the secondary channel is frequently embedded into the main channel. Using a time division multiplexing method, for example, the secondary channel data is synchronously multiplexed into the main channel data before being modulated.

The characteristics of a time division multiplexed signal can be used for detection of fatal transient impairments which cause a loss of system synchronization. After being multiplexed with the secondary port data, a predetermined sync code word is repeatedly transmitted through the embedded secondary channel. Only if the receiver is properly operating (i.e., is synchronized with the transmitter), can the sync code word be correctly received (after being demultiplexed from the main channel data). Note that the additional bandwidth of the secondary channel for transmitting this sync code word can be obtained with only a fraction of a dB increase of signal to noise ratio (SNR).

The proposed detector is composed of two processes: the detection and confirmation processes. If the Hamming distance between the received sync code word and the reference exceeds a threshold, it can be declared that loss of synchronization due to a sudden transient impairment has occurred. Since a single decision is not reliable, an additional confirmation process is required. Considering a possible modem operation under high bit error rate (BER) conditions, we adopt a sequential confirmation process based on a up/down counter scheme. Once a loss of synchronization is confirmed, the modem needs to initiate retraining.

Section 2 briefly explains how the sync code word can be efficiently sent through an embedded secondary channel. The proposed sequential detection scheme is
described in Section 3. The performance of the detector is analytically evaluated in Section 4. Section 4 also presents some numerical results.

2 The Embedded Secondary Channel

To make embedding the secondary channel independent of the data rate, we consider a baud rate based embedding. Each bit of the secondary channel data is synchronously inserted into the main channel data stream at every \( L \) bauds of the main channel data, which costs approximately an additional \( 3/L \) dB of SNR on the average. With proper choice of the multiplexing index number \( L \), the embedded secondary channel can have a data bandwidth larger than one baud of the main channel. This marginal bandwidth can be used for sending the sync code word (SCW).

Assume that the embedded secondary channel bandwidth is \( W(= B/L) \) bps, where \( B \) is the baud (symbol) rate of the main channel. Assume also that the maximum data rate of the secondary port is \( V(<W) \) bps. Then, the rest of \( (W-V) \) bits can be used for sending the SCW. Each SCW is multiplexed with the secondary port data before being embedded into the main channel data. For ease of implementation, an \( M \)-bit SCW is sent after an 8-bit secondary port data word is transmitted, where \( M \) is an integer less than or equal to \( 9 \). Note that only an additional 0.3 dB of SNR is required for the main channel to have this embedded secondary channel without performance degradation.

3 The Detector Scheme

Since each bit of embedded secondary channel data is transmitted every \( L \)-baud time interval, a single secondary data frame spans a time interval of \( (M+8)L \) bauds. Under the normal modem operating condition, the transmitted SCW can be correctly received only when no transient impairment occurs. The only exception can be when there occurs a bit loss event whose duration is exactly equal to a multiple of the time span of a secondary channel data frame. However, this has very low probability of occurrence. Although detection can be performed by bit by bit basis, for ease of implementation, we consider a detection process based on a single SCW. A simplified block diagram of the proposed detector is shown in Fig. 1.

Whenever an \( M \)-bit SCW is received, it is compared with the transmitted (reference) SCW by measuring the Hamming distance \( \eta \), which can be easily calculated using a look-up table. If \( \eta \) is larger than a threshold \( h \), it is assumed that a transient performance occurred during this data frame interval. Here, the threshold level \( A \) should be chosen so as to accommodate the channel BER under the worst permissible operating condition. Since this single test cannot satisfy the required detection performance, an additional confirmation process is required. A sequential test based on the \( c \)-successive counter or modified up/down counter scheme is widely used for confirmation of PCM frame synchronization [5,6]. The \( c \)-successive counter scheme declares confirmation if bad frames (i.e., \( \eta > h \)) are received \( c \) times in a row. The up/down counter declares confirmation if its content exceeds a threshold, where the content of the counter increases by \( \ell \) if \( \eta > h \), and decreases by \( n \) if not. For efficient confirmation even under possible high BER conditions, and for simplicity of implementation, we use a simple up/down counter scheme, where \( \ell \) and \( n \) are set to the same value of 1. In the case of the normal operation condition, \( \eta \) is usually less than \( h \), i.e., the content of the counter \( C \) is less than zero. Since the confirmation test should detect a true loss of synchronization as fast as possible, the content of the counter is bounded so that \( C \) has non-negative value. The updating algorithm can be summarized as follows. Set \( C(0) = 0 \). Then, at time \( t = kT \), where \( k = 1, 2, \ldots \),

\[
C(k) = C(k-1) + \xi(k);
\]

\[
C(k) = 0, \quad \text{if } C(k) < 0,
\]

where \( \xi(k) \) is the quantized output of the tester,

\[
\xi(k) = \begin{cases} 
1, & \text{if } \eta(k) > h, \\
-1, & \text{otherwise}. 
\end{cases}
\]

If \( C(k) \) becomes larger than a threshold \( K \), a loss of synchronization is verified and the modem needs to retrain. The threshold level \( K \) should be determined so that the confirmation process guarantees the desired detection criteria such as the true and false detection time. The design of these parameters, \( M \), \( h \) and \( K \), will be discussed in the next section.
4 Performance Analysis

The up/down counter scheme is easy to describe, but it is difficult to analyze because of the boundary conditions at the normal (sync) state $S$ and the final (sync lost) state $F$. Although statistical analysis of this counter scheme can be fairly well formulated in a matrix form by using a probability generating function (PGF)\[5\], to the best of the author's knowledge, no formal solution has been obtained in closed form. For analytical evaluation of the detection performance, the detection problem can be modeled as a simple hypothesis test against another simple alternative. Let $H_0$ be the null hypothesis corresponding to the normal condition and $H_1$ be the alternative corresponding to the sync lost condition due to a fatal transient impairment.

Since each bit of an SCW is transmitted exactly $L$-baud time intervals apart after being scrambled, the test statistic $\rho_j$ of Eq. (2) can be treated as an independent binomial random variable. Let $q_j$ be the BER of the received data under the hypothesis $H_j$, and $p_j = 1 - q_j$, for $j = 0, 1$. For given threshold $h$ and SCW bit size $M$, the probability $\lambda_j$ that a bad frame is detected, i.e., $\xi = 1$, by each test is given by

$$\lambda_j = \text{Prob}\{\xi = 1|H_j\} = \sum_{i=k+1}^{M} \binom{M}{i} p_j^{M-i} q_j^i,$$

under the hypothesis $H_j$, $j = 0, 1$.

For a given threshold $K$, the confirmation process based on the modified up/down counter by (1) can be represented by an equivalent finite state machine as depicted in Fig. 2, where $\lambda$ denotes $\lambda_0$ and $\lambda_1$ under $H_0$ and $H_1$, respectively, and $\mu = 1 - \lambda$. When the channel has no fatal transient impairments, the state machine usually resides in the normal state $S$. When the machine reaches the final state $F$, loss of synchronization is declared. The states $\{W_i\}, i = 1, \cdots, K$, are intermediate transition states. The average true (under $H_1$) or false (under $H_0$) detection time $T_D$ is equivalent to the mean time of first transition from state $S$ to $F$, which can be estimated using a PGF.

The timing transition of each state for a given value of $K$ is represented by its neighbor states as

$$S(z) = 1 + \mu z^{-1}[S(z) + W_1(z)]$$
$$W_1(z) = \lambda z^{-1}S(z) + p_1 z^{-1}W_2(z)$$
$$W_2(z) = \lambda z^{-1}W_1(z) + p_1 z^{-1}W_3(z)$$
$$\vdots$$
$$W_{K-1}(z) = \lambda z^{-1}W_{K-2}(z) + \mu z^{-1}W_K(z)$$
$$W_K(z) = \lambda z^{-1}W_{K-1}(z)$$
$$F(z) = \lambda z^{-1}W_K(z),$$

where $z^{-1}$ denotes the time delay corresponding to the test interval $T$. For an intermediate state $W_i$, $i = 1, 2, \cdots, K$, define $G_i(z)$ by

$$G_i(z) = \frac{W_{K-i+1}(z)}{W_{K-i}(z)}. \quad (4)$$

Then, the state flow between the states can be represented by an equivalent transfer function shown in Fig. 3. From Eq. (4), $G_i(z)$ is expressed by

$$G_i(z) = \frac{\lambda z^{-1}}{1 - \mu z^{-1}G_{i-1}(z)}$$

for $i = 2, 3, \cdots, K$. \quad (5)

where $G_1(z) = \lambda z^{-1}$. Let $G^N_i(z)$ and $G^P_i(z)$ be the numerator and denominator of the intermediate state transfer function $G_i(z)$, respectively. Then, it can be shown that the denominator $G^P_i(z)$ can be expressed in terms of a sum of power series as

$$G^P_i(z) = \sum_{j=0}^{\infty} \alpha_{ij}(-\mu \lambda)^j z^{-2j}, \quad (7)$$

and the numerator $G^N_i(z)$ is simply given by

$$G^N_i(z) = \lambda z^{-1}G^P_{i-1}(z). \quad (8)$$
Here, the coefficients \( \{a_{i,j}\} \) can be recursively calculated using

\[
\alpha_{i,j} = \begin{cases} 
\alpha_{i-2,j-1} + \alpha_{i-1,j}, & j = 1, 2, \ldots, \kappa; \\
0, & \text{otherwise},
\end{cases}
\]  

where \( \alpha_{i,0} = 1 \), for all \( i \), and \( \kappa \) is the largest integer \( \leq \frac{K}{2} \). Note that, in Fig. 3, the normal state \( S(z) \) is replaced with an equivalent state \( W_0(z) \) given by

\[
W_0(z) = \frac{1}{1 - \mu z^{-1} - \mu z^{-1}G_K(z)}. 
\]  

Thus, for a given \( K \), the PGF \( F(z) \) of timing transition from state \( S \) to \( F \) is

\[
F(z) = \frac{(\lambda z^{-1})^{K+1}}{(1 - \mu z^{-1})G_K^{-1}(z) - \mu z^{-1}G_K^{-1}(z)}. 
\]  

From Eqs. (7) to (9), \( F^D(z) \), the denominator of \( F(z) \), is given by

\[
F^D(z) = (1 - \mu z^{-1})^{\kappa_1} \sum_{j=0}^{\kappa_2} \alpha_{K,j}(-\mu \lambda)^j z^{-7j} - \mu \lambda z^{-2} \sum_{j=0}^{\kappa_2} \alpha_{K+1,j}(-\mu \lambda)^j z^{-7j}, 
\]  

where \( \kappa_1 \) and \( \kappa_2 \) are the largest integers \( \leq K/2 \) and \( \leq (K-1)/2 \), respectively. The average detection time \( T_D \) is obtained by taking the derivative of \( F(z) \) with respect to \( z \) and then evaluating it at \( z = 1 \), i.e.,

\[
T_D = -\frac{\partial F(z)}{\partial z} \bigg|_{z=1} \cdot T. 
\]  

The detector performance associated with design parameters is evaluated in terms of the false and true detection time. Because of the random nature of the data, the BER \( q_1 \) under hypothesis \( H_1 \) can be assumed to be 0.5. Assume also BER \( q_0 = 10^{-3} \) is the worst permissible operating condition. Fig. 4 plots the detection times versus the threshold level \( K \) for various bit sizes \( M \) of the sync code word with the threshold \( h \equiv 0 \). For a given \( K \), it takes at least \( (K+1)T \) seconds for the detector to confirm a slip. To examine how many tests are required in addition to \( (K+1) \) tests under \( H_1 \), Fig. 4(a) plots the additional average detection time \( \delta T \) normalized by the minimum time \( (K+1)T \), i.e., the average true detection time under \( H_1 \) will be

\[
T_D = (1 + \delta T)(K + 1)T. 
\]  

Fig. 4. Average detection time of the detector
it can be seen that the amount of the additional test time $6T$ is almost constant for a given SCW size $M$, i.e., the average detection time is likely to be linearly proportional to the threshold level $K$. This implies that, for a given $K$, the smaller the SCW size $M$, the larger the true detection time $T_D$. However, since the test interval $T$ also increases as the SCW size $M$ increases, the use of a small $M$ can result in a shorter true detection time $T_D$ than that of a large $M$. Fig. 4(b) shows the average false detection time under $H_0$, which is plotted in the common logarithmic scale. It can be seen that the average false detection time is logarithmically proportional to the threshold $I_t$ for a given $M$. In addition, a smaller size of the SCW results in larger false detection time. However, the variance of the detection time using an SCW with small bit size significantly increases as the threshold $K$ increases. It may be desirable not to use an SCW of too small a bit size.

As another performance indicator of the detector, the miss detection probability associated with various bit sizes $M$ is plotted in Fig. 5, when the threshold levels $h$ and $K$ are set to values of 0 and 5, respectively. The result is obtained by considering all kinds of possible events at each detection time $k$. It can be seen that the use of smaller bit sizes require more tests to achieve the same detection performance. Moreover, a smaller bit size results in larger variance in detection time. Note that the staircase-like shapes in detection probability curves are due to the up and down counting nature. Note also that a larger bit size is required for a larger threshold $K$ to obtain the same detection performance. Without using an excessively large bit size of the code word, however, the proposed detector can have a reasonable performance. For example, when $B = 2400$, $L = 10$, $M = 7$ and $K = 5$, (i.e., $T = 62.5(\text{msec})$), a fatal transient impairment can be detected at $(K+1)$-th test (the minimum trial) with a detection probability larger than 95%. With these values, it takes about $380.4(\text{msec})$ on the average for the detector to confirm a true loss of synchronization. But the average false detection time is larger than several years even when $q_0 = 10^{-3}$. In practice, it may be desirable to set the threshold $K$ to be large enough that the average detection time be longer than the possible recovery time by the modem itself without a retrain.

5 Conclusion

In this paper, using the marginal bandwidth of the embedded secondary channel, an efficient scheme has been proposed for detecting fatal transient impairments which cause loss of synchronization. It can be easily realized without placing a big burden on the main channel operation. The performance of the detector based on a modified up/down counter scheme has been analytically evaluated in terms of the average detection time. The analytical results can be applied to other synchronization problems such as the PCM frame synchronization in a digital carrier system.

References