Packet Detection for Onboard Switching Broadband IP Satellite Networks

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Abstract

The signal detection performance is studied for an onboard switching broadband IP satellite network. The probability of false alarm, miss and early detection is analyzed and simulated using either CFAR or the classic method. The unique word length is 108 symbols and the SNR is $Eb/No = 1.8$ dB. It is shown that the overall probability of packet loss can be less than 10^{-9}.

1. Introduction

Recently several giant broadband satellite networks have been developed in North America [1]. Targeting the capacity of 10 Gbps per satellite, one satellite network has the cost of 4 billion US dollars and is designed to form a full-mesh digital IP network that will interconnect with a wide variety of end-user equipment and systems. This network has employed the most advanced onboard digital processors, packet switching, and spot beam technology. The transmit antenna has an 1500 element phased array, which can form multiple hopping spot beams, and provide services to terminals of smaller apertures than in the traditional VSAT systems. The onboard routers will enable mesh connectivity, allowing users to directly communicate with each other through the satellite, without any hub.

The specifications of the new generation satellite networks has challenged both communication theory and technology. The specifications were extremely demanding and well beyond the existing technology, which were driven by the demand of business success. Even seasoned top researchers and engineers doubted if the specifications could be realized within the time table, which was a few years. After several years of hard work, many headaches in technology have been solved, and very few have been published. The modem technology was a famous success [2], [3]. The multiple access protocol was studied in [4].

A challenge in the onboard switching broadband IP satellite network is to detect packets. Before a user terminal is allowed to transmit, it has to detect the beacon signal, where the SNR can be extremely low, such as during a hurricane. After it detects the beacon signal, the user terminal can derive system timing information, and start the the registration process [4], through which the user terminal can achieve approximate synchronization with the satellite. After completing the registration process, the user terminal can start sending packets in the traffic channels. The satellite has to detect the packets. There are two types of traffic channels. The first type is called the point to point (PTP) channel. The second type is called the continental US (CONUS) channel.

Unique words are usually employed for packet detection in satellite networks [5]. In the onboard switching broadband satellite IP network, there were over 20 unique words for PTP, beacon and CONUS. Packets are differentiated by unique words. The results in [5] are classic to determine the probability of a miss and the probability of false alarm for the constant false alarm rate (CFAR) method. A sub-burst DFT method was introduced in [7] to detect continuous wave bursts in mobile satellite communications. The probability of early detection was neither in the specifications of the corresponding systems nor considered in [5], [7]. Interference was not consider in [5], [7].

This paper evaluates the packet detection performance for onboard switching broadband IP satellite networks. The probability of early detection is studied, along with the probability of miss and the probability of false alarm. The goal is to make sure that the total probability of packet loss in the detection stage is not higher than 10^{-7}. If this goal is achievable, the appropriate region of detection threshold should be provided.

2. System Model

The unique word length was $L = 108$ symbols. The UW detection for PTP has an aperture of 30 symbols. For the CONUS, the detection aperture is 10 symbols. The beacon UW detection can start at an arbitrary time. In other words, the beacon UW detection has an open aperture. For UW detection, the system model is the same for PTP and CONUS.

The packet detector architecture in [6] has the lowest complexity among all of the packet detectors of optimal performance. Employing the architecture in [6], the I-channel and the Q-channel transmit the same binary sequence as the UW [6]. Let the desired UW be $\mathbf{a} = (a[1](1+j), a[2](1+j), \cdots, a[L](1+j))$, $a[k] \in \{1, -1\}$ for $1 \le k \le L$, and L is the UW length in symbols. Let $\mathbf{r} = (r[1], r[2], \cdots, r[L])$ be the received signal whom the correlator correlates with. The correlator output power can be written as

$$P = |\mathbf{r}\mathbf{a}^{+}|^2 \tag{1}$$

where $\mathbf{a}^{+}$ is the transpose conjugate of $\mathbf{a}$. As will be seen in the next section, the correlator output power or the correlator output power normalized by the estimated signal energy will be used as the statistic for decision. For PTP and CONUS, the received signal has three hypotheses:

$$\begin{aligned} H_0: r[k] &= n_I[k] + jn_Q[k], 1 \le k \le L \\ H_1: r[k] &= \begin{cases} n_I[k] + jn_Q[k], 1 \le k \le M < L \\ a[k-M](1+j) + n_I[k] + jn_Q[k], \\ M < k \le L \end{cases} \\ H_2: r[k] &= a[k](1+j) + n_I[k] + jn_Q[k], 1 \le k \le L \end{aligned}$$

where $n_I[k] + jn_Q[k]$ is the AWGN. When H_0 occurs, the correlator correlates with noise only. When H_1 happens, the correlator correlates with an incomplete UW corrupted by noise. When H_2 is true, the correlator correlates with the entire UW corrupted by noise.

To avoid confusion, it is necessary to give the following definitions.

Definition 1 *The event F of false alarm is to say H_2 is true, when H_0 is true.*

The *false alarm* is to declare the presence of the desired signal, when there is no signal [8], [9]. For PTP and

Conus UW detection, false alarm causes the demodulator to process noise samples only, which will not cost anything but power consumption. To save power, it will be good to minimize the probability of false alarm whenever possible.

Definition 2 *The event E of early detection is to say H_2 is true, when H_1 is true.*

The *early detection* is to declare the presence of the desired signal, when the desired signal has partially arrived in the correlator. When the desired overall packet loss rate is extremely low, the probability of early detection has to be considered.

Definition 3 *The event M of a miss is to say H_0 is true, when H_2 is true.*

A miss is not to declare the presence of the signal, when the desired signal is present [9].

When either an early detection or a miss occurs, the packet will be lost. Because the events E and M are exclusive, $\Pr\{E \cup M\} = \Pr\{E\} + \Pr\{M\}$.

Definition 4 *For PTP and CONUS UW detection, the overall probability of packet loss is the summation of the probability of early detection and the probability of a miss.*

For PTP and CONUS UW detection, the goal is to minimize the overall probability of packet loss and the probability of false alarm at the same time. Previous studies did not consider the probability of early detection [5], [7].

Using the two-correlator structure for signal detection and parameter estimation [6], the received signal at the matched filter output is

$$r[k] = (a[k] + n_I[k]) + j(a[k] + n_Q[k]) \qquad (2)$$

where $\{a[k](1+j)\}$, $a[k] \in \{1, -1\}$ for $L \geq k \geq 1$, is the unique word and $(n_I[k] + jn_Q[k])$ is the AWGN noise with two-side power spectra density N_0. Without loss of generality, it is assumed $a[k] = 0$ for $k < 1$ or $k > L$. The power of the correlator output is

$$P[k] = \sum_{i=1}^{L} |r[k-i+1]a[L-i+1](1-j)|^2. \qquad (3)$$

The power of the correlator output can be used as the likelihood function for signal detection, when the received signal has fixed power or AGC is employed in the receiver. Hereafter, the detection method using (3) as the likelihood function is called the *classic* method.

If the power of the correlator output is normalized by the energy of the received signal, then the likelihood function is

$$\Lambda[k] = \frac{|\sum_{i=1}^{L} r[k-i+1]a[L-i+1](1-j)|^2}{\sum_{i=1}^{L} |r[k-i+1]|^2}. \qquad (4)$$

The detection method using (4) as the likelihood function is called the *constant false alarm rate* (CFAR) method, where the false alarm probability is independent of the signal-to-noise power ratio (SNR).

3. Probability of False Alarm

False alarm can be regarded as the signal detector declares the presence of the signal when the correlator in the signal detector correlates with noise only. This section finds the probability of false alarm for either the classic detection method or the CFAR detection method.

Before the arrival of the signal, the correlator correlates with the AWGN noise only. The likelihood function (3) can be written as

$$\begin{aligned} P[k] &= |\sum_{i=1}^{L} a[L-i+1]n_I[k-i+1]|^2 \\ &+ |\sum_{i=1}^{L} a[L-i+1]n_Q[k-i+1]|^2 \end{aligned}$$

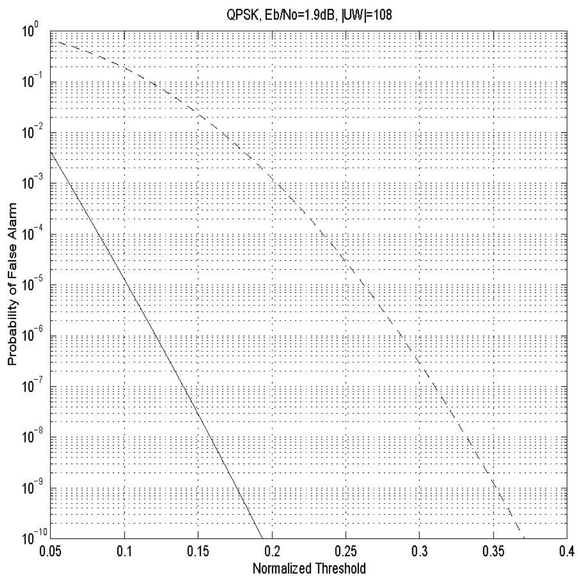

Fig. 1. Probability of false alarm for the classic method (dashed line) and the CFAR method (solid line).

which has a central Chi-square distribution. Its probability distribution function is

$$F_P(p) = \Pr\{P <= p\} = 1 - \exp(-\frac{p}{LN_0}). \quad (5)$$

Let η be the detection threshold. Then, the probability of false alarm for the *classic* method is

$$P_F(\eta) = \Pr\{P \geq \eta\} = \exp(-\frac{\eta}{LN_0}). \quad (6)$$

The probability of false alarm using CFAR is [5]

$$P_F(\eta) = \Pr\{\Lambda \geq \eta\} = (1 - \frac{\eta}{L})^{L-1}. \quad (7)$$

Fig. 1 plots the probability of false alarm for the *classic* method versus $a = \sqrt{\frac{\eta}{L^2}}$, $1 \geq a > 0$. The probability of false alarm for CFAR is shown versus $\frac{\eta}{L}$. It can be seen that the normalized detection threshold has to be higher than 0.18 for CFAR, or higher than 0.35 for the *classic* method, respectively, to have the probability of false alarm lower than 10^{-9}.

4. Probability of a Miss

The probability of a miss is the probability of not detecting a packet at its end, conditioned on the packet is present [9]. At the end of a packet, the likelihood function (3) can be written as

$$P[k = L] = (L + \sum_{i=1}^{L} a[L-i+1]n_I[L-i+1])^2 + (L + \sum_{i=1}^{L} a[L-i+1]n_Q[L-i+1])^2$$

which has a non-central Chi-square distribution. Its probability distribution function is [10]

$$\Pr\{P <= \eta\} = 1 - Q(2\sqrt{\frac{L}{N_0}}, \sqrt{\frac{2\eta}{LN_0}}) \quad (8)$$

which is also the probability of a miss for the *classic* method, where

$$Q(u, v) = \int_v^\infty x \exp(-\frac{x^2 + u^2}{2}) I_0(ux) dx \quad (9)$$

is the Marcum Q-function and $I_0(ux) = \sum_{j=0}^{\infty} \frac{(0.5x)^{2j}}{(j!)^2}$ is the modified Bessel function of the first kind.

Using the CFAR detection method, the probability of a miss is $Pr\{\Lambda[k = L] <= \eta\}$, which is equal to [5]

$$\exp(-2(L-\eta)\frac{E_b}{N_0})\{1 - (1 - \frac{\eta}{L})^{L-1} + \frac{\eta}{L} \sum_{m=1}^{N-2} \frac{1}{m!}[2\eta(1 - \frac{\eta}{L})\frac{E_b}{N_0}]^m \sum_{l=0}^{L-m-2} \frac{(l+m)!}{l!m!}(1 - \frac{\eta}{L})^l\}.$$

Figure 2 shows the probability of a miss for the classic method or the CFAR method. The simulation results are also included. It can be seen that the theory and the simulation results agree for both the classic detection method and the CFAR method. The probability of a miss for the classic method is less than 10^{-9}, when the normalized threshold is less than 0.67. The probability of a miss using CFAR is less than 10^{-9} when the normalized threshold is less than 0.6.

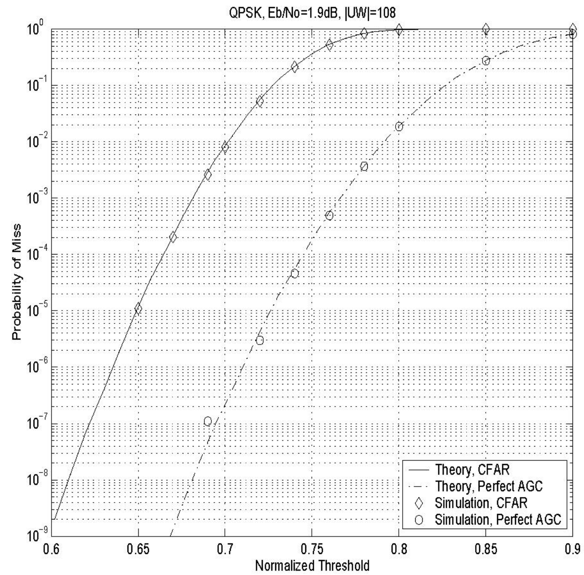

Fig. 2. Probability of a miss for the classic method and the CFAR method.

5. Probability of Early Detection

Early detection is to declare the presence of a signal when the signal has partially arrived. When early detection occurs, timing is wrong for both demodulation and decoding, and the packet is discarded. In addition to noise, the highest sidelobe in the auto-correlation of the signal can cause early detection. Interferers can also contribute to early detection. This section studies the probability of early detection caused by the sidelobe in the auto-correlation of the desired signal.

A. Classic Method

The auto-correlation of the binary unique word $\{a[i]\}$, $a[i] \in \{+1, -1\}$, $L \geq i \geq 1$, is defined as

$$y[\tau] = \sum_{i=1}^{L-\tau} a[i]a[i+\tau], \; L > \tau \geq 0. \tag{10}$$

Let the I-channel and the Q-channel have the same binary sequence as the unique word. The correlator output power is

$$\begin{aligned} P[k] &= (y[k] + \sum_{i=1}^{L} n_I[k-i+1]a[L-i+1])^2 \\ &\quad + (y[k] + \sum_{i=1}^{L} n_Q[k-i+1]a[L-i+1])^2. \end{aligned}$$

When $y[k] \neq 0$, the random variable $P[k]$ has a non-central Chi-square distribution, whose probability distribution function is [10]

$$\Pr\{P[k] <= \eta\} = 1 - Q(\frac{2|y[k]|}{\sqrt{LN_0}}, \sqrt{\frac{2\eta}{LN_0}}). \tag{11}$$

The classic method uses (11) as the likelihood function for detection. When timing of the signal is unknown, the detector has to run all the time until it declares the presence of a signal. Therefore, a sidelobe in the auto-correlation function of the signal can cause early detection. Assume the auto-correlation function has the highest sidelobe at $k = S$. The probability of early detection caused by the sidelobe is

$$\Pr\{P[S] \geq \eta\} = Q(\frac{2|y[S]|}{\sqrt{LN_0}}, \sqrt{\frac{2\eta}{LN_0}}). \tag{12}$$

When automatic gain control (AGC) is employed in practice for a QPSK system, the probability of early detection caused by the sidelobe is

$$\Pr\{P[S] \geq \eta\} = Q(\frac{2|y[S]|}{\sqrt{LN_0}}, \sqrt{\frac{4\eta(1+\sigma^2)}{LN_0}}). \tag{13}$$

Let $\eta = (aL)^2$, $0 < a < 1$. The probability of early detection can be written as

$$\Pr\{P[S] \geq \eta\} = Q(\frac{2|y[S]|}{\sqrt{LN_0}}, 2a\sqrt{\frac{L(1+\sigma^2)}{N_0}}). \tag{14}$$

B. CFAR

Assume there is a sidelobe in the autocorrelation of the unique word at $k = S$ with $y[k = S] = H$. Using CFAR, the likelihood function $\Lambda[k = S]$ can be written as

$$\Lambda[k = S] = \frac{A}{\sum_{i=1}^{L} |r[S-i+1]|^2}. \tag{15}$$

where $A = (H + \sum_{i=1}^{L} n_I[S-i+1]a[L-i+1])^2 + (H + \sum_{i=1}^{L} n_Q[S-i+1]a[L-i+1])^2$. Let $E = \sum_{i=1}^{L} |r[S-i+1]|^2$, $E_I = \sum_{i=1}^{L} |\Re\{r[S-i+1]\}|^2$ and $E_Q = \sum_{i=1}^{L} |\Im\{r[S-i+1]\}|^2$. The denominator in (15) can be written as

$$E = E_I + E_Q \tag{16}$$

where

$$E_I = \sum_{i=1}^{L}(a[S-i+1] + n_I[S-i+1])^2 - \sum_{i=S+1}^{L} 2a[S-i+1]n_I[S-i+1] + (S-L)$$

and

$$E_Q = \sum_{i=1}^{L}(a[S-i+1] + n_Q[S-i+1])^2 - \sum_{i=S+1}^{L} 2a[S-i+1]n_Q[S-i+1] + (S-L).$$

In [5], it is shown that the likelihood function for the event of a miss using CFAR can be converted to a random variable of the F-distribution, which requires the numerator and the denominator to be independent. The fundamental skill in [5] is to apply the fact that the noise at the correlator output is independent to each of its element minus the averaged noise, i.e.,

$$E\{(\sum_{i=1}^{L} a[i]n[i])(a[k]n[k] - \frac{1}{N}\sum_{i=1}^{N} a[i]n[i])\} = 0 \tag{17}$$

where $n[i]$ and $n[j]$ are i.i.d. AWGN. Let

$$S_1[k] = \sum_{i=1}^{L}(a[L-i+1]n_I[k-i+1] - \frac{1}{L}\sum_{j=1}^{L} a[L-j+1]n_I[k-j+1])^2$$

and

$$S_2[k] = \sum_{i=1}^{L}(a[L-i+1]n_Q[k-i+1] - \frac{1}{L}\sum_{j=1}^{L} a[L-j+1]n_Q[k-j+1])^2.$$

Let

$$X_1[k] = \sum_{i=1}^{L}(\Re\{r[k-i+1]\})^2 - \frac{1}{L}(\sum_{i=1}^{L} a[L-j+1]\Re\{r[k-j+1]\})^2$$

and

$$X_2[k] = \sum_{i=1}^{L}(\Im\{r[k-i+1]\})^2 - \frac{1}{L}\sum_{i=1}^{L} a[L-j+1]\Im\{r[k-j+1]\})^2.$$

It can be shown that for $L > k \geq 1$

$$X_1[k] = (1 - \frac{1}{L})\sum_{i=1}^{L} n_I^2[k-i+1] - B + Y_1[k] \tag{18}$$

where $B = \frac{1}{L}\sum_{i=1}^{L}\sum_{j=1, j\neq i}^{L} a[L-i+1]a[L-j+1]n_I[k-i+1]n[k-j+1]$, and $Y_1[k] = k - \frac{y[k]^2}{L} + \sum_{i=1}^{k} 2a[L-i+1]n_I[k-i+1] - \frac{H}{L})\sum_{i=1}^{L} 2a[L-i+1]n_I[k-i+1]$. When $k = 0$ in the case of false alarm, or $k = L$ in the case of a miss, the following is true

$$S_1 = X_1 \tag{19}$$

and

$$S_2 = X_2. \tag{20}$$

Then, the likelihood function using CFAR can be written as

$$\frac{P[k]}{S_1[k] + S_2[k]} = \frac{\Lambda}{1-\Lambda} < \frac{\zeta}{L-\zeta} \tag{21}$$

while the left hand side has the F-distribution [11]. This is why the results in [5] hold to evaluate the probability of a miss.

Unfortunately, when $1 < k < L$, (19) and (20) do not hold. We also tried to orthogonalize the noise samples in each channel by grouping them as two groups, i.e.,

$$\bar{n}_I[i] = a[L-i+1]n_I[S-i+1] - \frac{1}{S}\sum_{j=1}^{S} a[L-j+1]n_I[S-j+1] \tag{22}$$

for $S \geq i \geq 1$ and

$$\bar{n}_I[i] = a[L-i+1]n_I[S-i+1] - \frac{1}{L-S}\sum_{j=S+1}^{L} a[L-j+1]n_I[S-j+1]$$

for $L > i \geq S+1$. It can not convert the likelihood function to a random variable of F-distribution either. Therefore, the method in [5] can not be used to derive the probability of early detection.

For PTP, the detection aperture has the maximum length of 30 symbols. The simulation results are shown in Table I. Each point is obtained by running at least 10^6 packets. It can be seen that the probability of early detection using CFAR is below 10^{-6} when the normalized threshold is greater than 0.1. For the classic method, the probability of early detection drops faster than the probability of false alarm in Fig. 1, when the threshold increases; When the normalized threshold $\eta \geq 0.2$, the probability of early detection is lower than the probability of false alarm.

The maximum detection aperture of the CONUS signal is ten symbols, one third of that for PTP. When the detection aperture decreases, the probability of early detection also decreases using CFAR, while it is not changed using the classic detection method.

For the beacon signal, there is no detection aperture. Simulation was also performed for the beacon detection. The simulation results are shown in Table II. Comparing with Fig. 1, the probability of early detection is about 10 times of the probability of false alarm. One can conclude that when the packet signal timing is completely unknown, the probability of early detection is much larger than the probability of false alarm. Therefore, the packet detector should be designed to jointly minimize the probability of early detection and the probability of a miss.

TABLE I

PROBABILITY OF EARLY DETECTION FOR THE PTP UW OF 108 SYMBOLS, QPSK, EB/NO=1.9DB, DETECTION APERTURE = 30 SYMBOLS.

Threshold	Probability (CFAR)	Probability (Classic)
0.08	0.000000	0.956688
0.1	0.000000	0.592939
0.15	0.000000	0.016558
0.2	0.000000	$5.8 * 10^{-5}$

TABLE II

PROBABILITY OF EARLY DETECTION FOR THE UW OF 108 SYMBOLS, QPSK, EB/NO=1.9DB, WITH OPEN DETECTION APERTURE FOR THE BEACON.

Threshold	Probability (CFAR)	Probability (Classic)
0.08	0.002788	1.0
0.1	0.0001946	0.9984146
0.12	1.87×10^{-5}	0.9322847
0.14	1.3×10^{-6}	0.5486533

6. CONCLUSIONS

The classic detection method can achieve an overall probability of packet loss lower than 10^{-9} for QPSK, Eb/No=1.9dB, $|UW| = 108$. The recommended detection threshold normalized is 0.6. The CFAR detection method can give an overall packet loss rate lower than 10^{-9} for QPSK, Eb/No=1.9dB, $|UW| = 108$. The recommended detection threshold normalized is 0.5. The results in this paper can be used by system designers to choose the right detection method and evaluate the performance of packet detection in onboard switching broadband IP satellite networks.

ACKNOWLEDGMENT

The work was supported in part by the NSF under Grant CNS-0435341 and US ARO under Grant W911NF-04-1-0267.

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