TWO-STATE CDMA RECEIVER FOR SHARED UPLINK SATELLITE CHANNEL

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Abstract

Most of future packet satellite systems are characterized by an high speed downlink channel broadcasted from the earth service gateway and a shared, low speed, return channel from each user equipment. In this paper a CDMA technique is proposed for return channel access mechanism. CDMA is interference limited rather than noise limited. The research for new methods to reduce interference and increase efficiency lead us to formulate a signaling method where fast impulsive silence states are mapped on zero-energy symbols. The theoretical formulation of the optimum receiver is reported and the probability of error for a generic linear CDMA receiver is derived. In particular, conventional and decorrelating two-states CDMA detector probability of errors are calculated. Numerical comparisons between two-states and traditional one-state CDMA conventional receivers are reported in the paper.

Keywords

CDMA System Performance, System Capacity Analysis and Optimization, Receiver and Transmitter Design, Signal Processing Applications in Telecommunications, Multiple Access Techniques.

I. INTRODUCTION

The natural evolution of packet satellite networks operating on DVB technology is to employ a complete connection via satellite allowing the end users to transmit on a shared satellite channel.

Most of present proposals for return channel are referring to MF-TDMA technology as multiple access mechanism [?]. The geo-stationary constellation, characterized by long propagation delays and a deep attenuation, has a negative impact on the complexity of user's equipment since accurate synchronization and a slot reservation mechanism are required.

The TDMA access method imposes a preconfigured hard limit on the number of users on the channel, even if the users are transmitting a moderate throughput each.

An asyncronous CDMA access is here proposed as an alternative for the return channel. The asynchronous access has the advantage of a reduced complexity at the user terminal and allows a soft limit on the maximum number of users in the same carrier. The return portion of the satellite network can be temporarily overloaded at the expense of a soft degradation of the global quality of service thus facilitating the statistical increase of the number of served users.

In order to increase the number of users the multiple access interference level has to be limited. The proposal in this paper is to exploit the discontinuos nature of the user information sources to increase the efficience of the return channel.

The idea of a discontinued transmission has been exploited starting from the second generation of terrestrial personal communication systems with the DTX feature in the GSM standard [?], [?], [?]. It also has been included in the recent 3GPP specifications with the "compressed mode" operation [?]. Both this methods, however, implies signaling to anticipate the silence segments. The frequent insertion of fast silence periods, however, results in intolerable signaling overhead.

Voice activity detectors are designed to exploit the natural pauses in the speech flow to reduce the transmitted power and, consequently, battery life. Transmission silences are modelled as two states Markov chain where the average silences last for seconds [?]. In this case a signaling mechanism at frame level is sufficient. There are however some information sources, like fast variable rate video coders or fast impulsive data sources that require a tight signaling to follow the fast content variations.

Those considerations lead to the development of the transmission scheme presented in this paper. The basic idea is the extension of the traditional informative symbol set with a *zero energy* symbol. The silence symbols are integrated with the informative ones and delivered to the radio link layer for transmission [?]. The end-to-end signaling between the applications can be avoided and the radio layer does not need to receive any explicit *transmit on/off* commands from higher layers.

The proposed reception scheme has also the property of being able to receive common single state transmissions. In this case, the silence symbols thresholds collapse to 0 and the receiver degenerates in a traditional single state receiver.

The advantages of the proposed solution can be summed up in the following list:

- the reduction of the average transmit power from a CDMA terminal, obtained by employing silence symbols, reduces the interference on other users,
- the radio layer need not to be integrated with the silence state management function of the application layer,
- silence symbols allow very short traffic bursts and a great variety of fractional bit-rates without increasing the MAI level.

The paper has been organized as follow: in section II the proposed two-states communication strategy is described and the optimum detector is derived. Section III reports the probability of error for the two-states conventional detector and the probability of false alarm for a two-states CDMA communication system. Numerical results and conclusions are shown in Section IV and Section V, respectively.

II. CDMA Two-States Reception

With the proposed scheme, the general base-band transmission signal of the kth user is:

$$s_k(t) = \sum_{n=-\infty}^{n=\infty} s_k(t)^{(n)} \tag{1}$$

$$s_k(t)^{(n)} = A_k m_k^{(n)} b_k^{(n)} g_k^{(n)}(t - nT_s) \tag{2}$$

where

$$g_k^{(n)}(t) = \sum_{i=1}^{G} c_k^{(n)}(i) p(t - iT_c)$$

and

T_s is the symbol time,

T_c is the chip time,

$G = T_s/T_c$ is the processing gain,

$A_k = \sqrt{E_k}$ the transmitted amplitude for user k,

$p(t)$ is the complex valued chip waveform due to pulse shaping filter,

$c_k^{(n)}$ is the kth normalized spreading code of user k referred to nth symbol interval,

$m_k^{(n)}$ is the **mask** symbol which assumes one of the two possible values $\{0, 1\}$. It determines the state of the transmitter in the n-th time interval: *Talk* or *Silent*.

$b_k^{(n)}$ is the informative symbol transmitted during the n-th interval, chosen among the symbol alphabet of the chosen modulation (e.g. for a BPSK signaling $b_k^{(n)} \in \{-1, 1\}$) . It has no significance when the transmitter is in the *Silent* state.

TABLE I
BPSK+ SIGNALING

Symbol	Transmitter state	Informative symbol
q_0	Talk	0
q_1	Talk	1
q_2	Silent	n.a.

The received signal $r(t)$ expresses the observable part of the transmission chain. The received signal can be seen as:

$$r(t) = \sum_{k=1}^{K} s_k(t) + n(t) \tag{3}$$

where $n(t)$ is the the white gaussian noise with zero mean and variance σ^2.

The unknown mask and symbol transmitted by the user over the transmission channel can be grouped in the two-state information symbol $q^{(n)}$ defined as:

$$q^{(n)} = m^{(n)} b^{(n)} \tag{4}$$

where we have dropped here the k index for simplicity. The **optimum detector** [?], for a given set of transmitted two-state symbols will choose the symbol $\hat{q}^{(n)}$ corresponding to the largest *posterior probability* based on the observation of $r(t)$ (MAP criterion). Formally:

$$\hat{q}^{(n)} = \arg\max_q P\left(q|r(t)^{(n)}\right) \tag{5}$$

We can assume that the two-states are alternating independently from the informative stream, constituted by M equally probable symbols. This leads to:

$$P\left(q_{talk}\right) = \frac{P\left(talk\right)}{M} \tag{6}$$

$$P\left(q_{silence}\right) = 1 - P\left(talk\right) \tag{7}$$

where $P\left(talk\right)$ is the absolute probability of a talk symbol. The two-state symbol q is thus possibly one of the equally probable M informative symbols or the single "silence" one. The transmission model described above needs a more complex performance characterization with respect to the traditional one. The receiver is characterized by a general *probability of error* which is specialized in:

- probability of false detection of a *silence state*, $P_{e,sil}$
- probability of symbol error conditioned to a talk state, $P_{e,symb}$.

In the special case of a BPSK+ (the "plus" symbol indicates the presence of a "silent" state) operating on a AWGN channel, the optimum receiver is defined by the following thresholds:

$$\theta_{0,2} \doteq \frac{\sigma^2}{\sqrt{E}} \ln \frac{P\left(q_2\right)}{P\left(q_0\right)} + \frac{\sqrt{E}}{2} \tag{8}$$

$$\theta_{1,2} \doteq \frac{\sigma^2}{\sqrt{E}} \ln \frac{P\left(q_1\right)}{P\left(q_2\right)} - \frac{\sqrt{E}}{2} \tag{9}$$

Where the symbols are labelled as in table I, and E is the talk symbol energy.

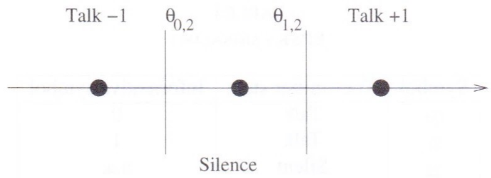

Fig. 1. BPSK+ Decision Regions

	Rx q_0	Rx q_1	Rx q_2 (silence)
Tx q_0	Correct	Error	False Alarm
Tx q_1	Error	Correct	False Alarm
Tx q_2	False Alarm	False Alarm	Correct

TABLE II
THE SET OF SYSTEM STATES

The decision regions for the described receiver, with h being the observable metric, are described by:

$$\begin{cases} h < \theta_{1,2} & \text{the symbol } q_1 \text{ is selected} \\ \theta_{1,2} \leq h < \theta_{0,2} & \text{the symbol } q_2 \text{ is selected} \\ \theta_{0,2} \leq h & \text{the symbol } q_0 \text{ is selected} \end{cases} \quad (10)$$

The decision regions are represented in Fig. 1.

III. Error and False Alarm Probability

After each received symbol, the proposed *two states* reception scheme belongs to one of the possible states derived from the combination of both the transmitter and the receiver ones. This concept is explained in Table II. The columns represents the possible receiver decisions while the rows enumerate the transmitter symbols. The elements inside are called "conditions" of the whole reception system (i.e. transmitter + receiver).

The **False Alarm** condition is met when the Talk/Silence status is misinterpreted. An **Error** occurs when the transmitter is in the Talk state but the symbol is not correctly detected. The **Correct** condition is self explanatory.

In order to provide the two states receiver with a performance index suitable for a comparison with the traditional reception, we consider the *generalized probability of error* or P_{eg} defined as:

$$P_{eg} = \Pr(\text{Error}|\text{Talk}) \cup \Pr(\text{False Alarm}|\text{Talk}) \quad (11)$$

The cited index takes into account all the potential errors the receiver may commit when the transmitter is in the talk state. It should be noted that the two state system provides more information than the traditional "always on" reception, the additional information is transmitted at the expense of a reduced noise margin for the decision regions. This fact makes the comparison with the traditional system a difficult task.

In this section an estimate of the P_{eg} is computed for the:

- conventional detector,
- decorrelating detector.

The two-states probability of error of the kth active user when $N_z = z < K$ users are in the silent state, is:

$$P_k^{(2s)}(P_{talk}, N_z) = Prob\left\{(\mathbf{LR})_{kk} > \Phi | b_k = -1, P_{talk}, N_z\right\} = \sum_{\mathbf{b}\in(-1,0,1)^K, b_k=-1} Prob\left\{(\mathbf{LR})_{kk} > \Phi | \mathbf{b}, P_{talk}, N_z\right\} \cdot Prob\left\{\mathbf{b} | b_k = -1, P_{talk}, N_z\right\} \quad (12)$$

where $\mathbf{R}$ is the cross-correlation matrix whose generic element is $\mathbf{R}_{kj} = \sqrt{E_k}\sqrt{E_j}\int_0^{T_s} c_k(t)c_j(t)dt$, $\mathbf{L} \in \mathbb{R}^{K\times K}$ is a generic linear transformation, e.g., for the conventional CDMA receiver results simply $\mathbf{L} = \mathbf{I}$, where $\mathbf{I}$ is the identity matrix. The term $\Phi = \theta_{0,2}\sqrt{E_k} = \sigma^2 \ln\left(\frac{P(q_2)}{P(q_0)}\right) + \frac{E_k}{2}$ represents the energy threshold that implies the detection of the erroneous symbol assuming that $b_k = -1$ has been transmitted.

The second term of (12) is the probability to have $N_z = z$ users in the silent state among the K total users:

$$Prob\left\{\mathbf{b} | b_k = -1, P_{talk}, N_z\right\} = \binom{K-1}{z} P_{talk}^{K-1-z}(1 - P_{talk})^z \quad (13)$$

The first term of (12) is the probability of error of a two-state receiver when a certain transmission pattern $\mathbf{b}$ is sent:

$$Prob\left\{(\mathbf{LR})_{kk} > \Phi | \mathbf{b}, P_{talk}, N_z\right\} = Q\left(\frac{(\mathbf{LR})_{kk} - \sum_{j\neq k}(\mathbf{LR})_{kj}b_j - \Phi}{\sqrt{(\mathbf{LRL}^\top)_{kk}}\sigma}\right) \quad (14)$$

where $\top$ denotes the transpose operation. Without loss of generality, we have suppose here that the $N_z = z$ interfering users in silent state are the last z among the total K users.

Thus, the general expression for the average P_{eg} for a generic two-states CDMA linear receiver is:

$$P_{eg}^{(2s)} = \sum_{\mathbf{b}\in\{-1,0,1\}^{K-1}} \binom{K-1}{z} P_{talk}^{K-1-z}(1 - P_{talk})^z \cdot Q\left(\frac{(\mathbf{LR})_{kk} - \sum_{j\neq k}(\mathbf{LR})_{kj}b_j - \Phi}{\sqrt{(\mathbf{LRL}^\top)_{kk}}\sigma}\right) \quad (15)$$

The MAI term in (15) can be upper bounded by

$$\begin{aligned}\sum_{j\neq k}(\mathbf{LR})_{kj}b_j &\leq \sum_{j\neq k}\max_j\left((\mathbf{LR})_{kj}\right)b_j \\ &= \max_j\left((\mathbf{LR})_{kj}\right)\sum_{j\neq k} b_j \\ &\leq \max_j\left((\mathbf{LR})_{kj}\right)N_{nz}(\mathbf{b}) \\ &= \rho(\mathbf{L})N_{nz}(\mathbf{b})\end{aligned} \quad (16)$$

where:

$$\rho(\mathbf{L}) = \max_j\left((\mathbf{LR})_{kj}\right)$$

$$N_{nz}(\mathbf{b}) = \sum_{j\neq k}|b_j|$$

The term $N_{nz}(\mathbf{b})$ represents the number of instantaneous active users for a given interference symbols pattern $\mathbf{b}$. By substituting (16) in (15) we drop the dependence on the specific interference pattern and thus the generalized probability of bit error for a two-states CDMA linear receiver results:

$$P_{eg}^{(2s)} \leq \sum_{z=0}^{K-1} \binom{K-1}{z} P_{talk}^{K-1-z}(1 - P_{talk})^z \cdot Q\left(\frac{(\mathbf{LR})_{kk} - (K-1-z)\rho(\mathbf{L}) - \Phi}{\sqrt{(\mathbf{LRL}^\top)_{kk}}\sigma}\right) \quad (17)$$

A. P_{eg} for the conventional detector

In order to get the probability of error for a two-states CDMA conventional receiver it is enough to substitute $\mathbf{L} = \mathbf{I}$ in Eq. (17):

$$P^{(2s)}_{eg,conv} \leq \sum_{z=0}^{K-1} \binom{K-1}{z} P_{talk}^{K-1-z} (1 - P_{talk})^z \cdot Q\left(\frac{E_k - (K-1-z)\rho - \Phi}{\sqrt{E_k}\sigma}\right) \tag{18}$$

where $\rho = \max_j\{|\mathbf{R}_{kj}|\}$ is the maximum element in the cross-correlation matrix.

Analogously, the probability of error of a traditional one-state conventional detector can be written as [?]:

$$P^{(1s)}_{e,conv} \leq Q\left(\frac{E_k - (K-1)\rho}{\sigma\sqrt{E_k}}\right) \tag{19}$$

The numerical comparison between eq. (18) and eq. (19) is reported in the Section IV.

B. P_{eg} for the decorrelating detector

The probability of error for the two-states CDMA decorrelating detector is obtained by substituting in equation (17) the linear transformation:

$$\mathbf{L} = \mathbf{X}^{-1}$$

where $\mathbf{X}$ is the normalized correlation matrix whose generic element is $\mathbf{X}_{kj} = \int_0^{T_s} c_k(t)c_j(t)dt$. Thus, it follows that $\mathbf{R} = \mathbf{W}^{1/2}\mathbf{X}\mathbf{W}^{1/2}$ where $\mathbf{W} = diag\{E_1, ..., E_K\}$.

The result is:

$$P^{(2s)}_{eg,dec} \leq \sum_{\mathbf{b}\in\{-1,0,1\}^{K-1}} \binom{K-1}{z} P_{talk}^{K-1-z}(1 - P_{talk})^z \cdot Q\left(\frac{\sqrt{E_k} - \theta_{0,2}}{\sqrt{\mathbf{X}^{-1}_{kk}}\sigma}\right) \tag{20}$$

The previous equation has to be compared with the well-known probability of error of the CDMA single-state decorrelating detector [?]

$$P^{(1s)}_{eg,dec} \leq \left(\frac{1}{2}\right)^{K-1} Q\left(\frac{\sqrt{E_k}}{\sqrt{\mathbf{X}^{-1}_{kk}}\sigma}\right) \tag{21}$$

IV. Numerical Results

The dependence of the probability of error from the operating point of the proposed CDMA communication scheme has been analyzed; the same operating condition have been then applied to the conventional single-state receiver and the resulting performances compared to those obtained by the proposed two-states communication scheme.

The comparisons reported in this document, however, do not take into account the additional information available at the proposed receiver concerning the status of the transmitter. This additional information in a conventional receiver requires a signaling which has an impact on the overall performance. In this sense the results shown below are not completely fair to the proposed receiver as concerns the offered service.

In fig. 2 are reported the probabilities of error for the conventional two-states CDMA receiver, compared to the probability of error of the single-state receiver. The curves are reported for different values of the normalized cross-correlation index (ρ) and different values of $P(talk)$ (for the two-states receiver only). As shown, the low activity region ($P_{talk} < 0.5$) is characterized by a substantial improvement of the proposed transmission scheme over the traditional "always on" transmission. As the probability of a non-silence symbol increases, the increase of interfering power and the smaller decision regions for the non-silence information symbols introduce a degradation over the traditional reception schemes. As expected, in the low $P(talk)$

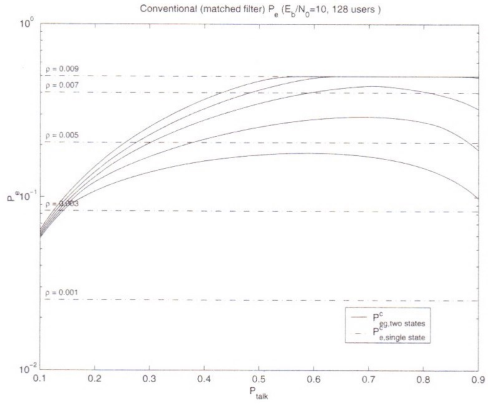

Fig. 2. P_{talk} and ρ influence on probability of error

region, the region of interest for the proposed receiver, the performances of the proposed scheme are significantly better than the traditional single-state receiver especially for high cross-correlation values. This result coupled with the lower power consumption, lead us to conclude that the proposed CDMA communication scheme is able to get practical advantages over the traditional CDMA communication systems.

V. CONCLUSIONS

In this paper is presented a new CDMA transmission scheme based on a variable energy symbols constellation called "two-states" transmission. A theoretic analysis shows the convenient use of the proposed signaling method in CDMA systems where MAI and complexity power are the dominant limiting factors. A detailed theoretical study has been conducted to express the exact probability of error applicable on every receiver that consists on a linear transformation, in particular the probability of error has been calculated for the conventional as well as the decorrelating detectors. Numerical performance evaluation and comparison based on the probability of errors of the conventional one-state and two-states receivers have been reported. The use of the silence symbol reduces MAI on the overall access scheme, thus allowing more users on the satellite return link. Hence, the proposed communication scheme is able to get practical advantages over the traditional single-state communication scheme, especially for "burst" data transfer.