Burst Timing Synchronization for OFDM – Based LEO and MEO Wideband Mobile Satellite Systems

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I. ABSTRACT

A burst timing offset estimation method is examined in fast time varying frequency selective fading channels for broadband orthogonal frequency division multiplexing (OFDM)–based systems. The estimation is obtained in the presence of Gaussian noise and Rayleigh or Rice multipath fading. Two formats for the OFDM training symbol and the corresponding timing metrics are proposed and compared with respect to their estimation performance and improvement is succeeded [7]. The performance is evaluated by computer simulation in terms of estimation variance. The synchronization in the OFDM system is examined by setting as parameters the number of subcarriers, the signal–to–noise ratio (SNR) and the high Doppler shift present in LEO/MEO satellite communications.

II. INTRODUCTION

The utilization of satellite networks based on low earth orbit (LEO) and medium earth orbit (MEO) satellites constitutes one of the most promising technological solutions to attain reliable and economically efficient mobile and personal telecommunications on a global scale. LEO and MEO satellites, while maintaining the important characteristics of geostationary earth orbit (GEO) satellites, such as wide coverage area and direct radio path, feature a number of additional advantages that are essential to the provision of mobile multimedia services. These advantages of LEO and MEO satellites, which originate from their lower altitude as compared to GEO satellites, include the short propagation delay, the low propagation loss and the high elevation angle at high latitudes. A direct consequence of these advantages is that the tight delay requirements of multimedia applications are more easily met. In addition, low-power hand-held terminals are less demanding and more cost effective. Therefore, LEO and MEO satellite based communications systems are foreseen to play a significant role as they can naturally provide cost-effective access to the global multimedia infrastructure in cases where cable network cannot be established, e.g., in aeronautical and navigational applications and in areas where their terrestrial counterparts require high deployment cost and, in general, inefficient utilization [9].

In LEO and MEO satellite based mobile wideband communications systems, except for using code division multiple access (CDMA), which would constitute a natural extension of the terrestrial air interface employed in third generation (3G) terrestrial mobile communications systems, the use of OFDM has recently attracted considerable attention as an alternative to CDMA. However, the use of OFDM [1] as a candidate modulation technique for LEO and MEO satellite communications systems has not yet been thoroughly investigated.

Although OFDM has numerous advantages, including efficient implementation by the IFFT (Inverse Fast Fourier Transformation) and the FFT at the transmitter and receiver side, respectively, and the use of low-complexity channel estimation and equalization techniques [2][3], it requires accurate timing synchronization in order to preserve the orthogonality among the subcarriers after the application of the FFT at the receiver. Especially in the case of packet switching, where fast carrier and timing synchronization, low receiver implementation complexity and low training overhead per packet for synchronization purposes are required, timing synchronization can become one of the most serious problems for the complete OFDM-based system.

Among the proposed timing synchronization techniques, in [5] the training symbol that is used is an m-sequence synchronization burst that is correlated at the receiver with locally generated one. In cases of large frequency offset between the receiver and transmitter oscillators, large frequency Doppler shift and phase noise [4], this method would not achieve accurate timing estimation. In [6], using a training symbol with two identical halves is one of the most efficient in terms of receiver complexity and robustness. By modifying the format of the training symbol, Minn and Bhargava [7] succeeded in eliminating the plateau that appears in the timing metric in [6], thus reducing the timing offset estimation variance.

However, in these papers, the channel was assumed to be a static frequency selective channel, which clearly is not the case for LEO and MEO mobile satellite systems. Motivated by the above, in this paper we examine the problem of timing synchronization in LEO and MEO satellite OFDM–based systems, simulating a time varying frequency selective fading channel which includes the effects of high frequency Doppler shift always present in LEO and MEO satellite communications [10].

III. SYSTEM DESCRIPTION

III.1 OFDM System Design

The baseband OFDM signal in time domain at the transmitter side is given by

$$x_{m,n} = \sum_{k=0}^{N-1} X_{m,k}\, exp(j2\pi\, kn/N) \tag{1}$$

where $X_{m,k}$ is the modulated data that loaded at the k^{th} subcarrier of the m^{th} OFDM symbol. In (1) n denotes the n^{th} time sample within an OFDM symbol, $0 \leq n \leq N-1$, and N is the number of subcarriers. After attaching the cyclic prefix (CP) the serial data is transmitted.

III.2 Channel

The OFDM signal is transmitted over a discrete frequency selective fading channel with the following channel impulse response (CIR)

$$h_{m,n} = \sum_{l=0}^{L-1} h_{m,l,n}\, \delta(n - \tau_l) \tag{2}$$

where $\tau_l = l \cdot \tau$ with L the total number of paths and τ is the path time delay between two successive bins, δ is the Dirac–delta function and $h_{m,l,n}$ is the time varying complex path gain. The maximum delay spread is $T_{max} = \tau \cdot (L-1)$.

III.2.1 Rayleigh Frequency Selective Fading Channel

The Rayleigh channel is modelled using (2) together with

$$h_{m,l,n} = \frac{1}{\xi} exp(-\frac{\tau_l}{W}) \cdot a_{m,l,n} \cdot exp(j2\pi\, \phi_{m,l,n}) \tag{3a}$$

$$\xi = \sqrt{\sum_{k=0}^{L-1} exp(-\frac{\tau_k}{W/2})}. \tag{3b}$$

In (3), W is the decay factor, $\phi_{m,l,n}$ are uniformly distributed, $a_{m,l,n}$ are Rayleigh distributed with autocorrelation function $R_a(\tau) = J_0(2\pi \cdot f_D \cdot \tau)$, where $J_0(\cdot)$ is the zero–order modified Bessel function of the first kind and f_D is the maximum Doppler frequency that depends on the wavelength λ and the velocity u mainly of the satellite.

III.2.2 Rice Frequency Selective Fading Channel

In the case of Rice frequency selective fading channel, in (2) $h_{m,0,n}$ is set to A which is a constant attenuation factor of the specular component. Assuming that the power of the non–specular specular component is σ^2 the Rice factor is obtained as:

$$K(dB) = 10 \cdot log(\frac{A^2}{2\sigma^2}). \tag{4}$$

Independently of the channel, the received signal is given by

$$y_{m,n} = exp(j2\pi n \frac{\Delta F}{N}) \cdot \sum_{l=0}^{L-1} h_{m,l,n} \cdot x_{m,n-\tau_l+\varepsilon} + w_{m,n} \tag{5}$$

where $w_{m,n}$ denotes the additive white Gaussian noise (AWGN), ΔF is the normalized to the subcarrier spacing frequency offset and ε is the timing offset.

IV. TIMING SYNCHRONIZATION TECHNIQUE

IV.1 Proposed Training Symbol Format

All the training symbols that are generated are N samples long. To generate a training symbol, a group of four parts with $[A\ A\ -A\ -A]$ format is considered [7]. This basic group is used to create training symbols that consist of more groups (G). We combat the time dispersive nature of a rapidly changing channel by using training symbol formats that consist of one ($G = 1$) $[A\ A\ -A\ -A]$ and two ($G = 2$) $[A\ A\ -A\ -A\ B\ B\ -B\ -B]$ groups respectively. A and B represent signals of length $L = N/(4G)$ generated by $N/(4G)$ point IFFT of $N_u/(4G)$ length modulated data of a PN sequence padded with zeros. The other parts in each group are just copied and a negative sign is set where it should. In fast time varying channels the identical parts in every group should be next to the other. Training symbols with more groups are presented in [8].

IV.2 Technique Description

At the receiver side, to detect the existence of the OFDM training symbol in the received signal, the timing metric is calculated. The estimation, by using the timing metric, is to be done each time a sample is received. By detecting a peak in the timing metric, the receiver estimates the first sample of the OFDM synchronization symbol. The following two timing metrics $M_2(d)$ will be considered.

IV.2.1 One Group Timing Metric

The timing metric $M_2(d)$ is given by (6)

$$M_2(d) = \frac{\mid P_2(d) \mid^2}{R_2^2(d)} \tag{6}$$

$$P_2(d) = \sum_{k=0}^{S} \sum_{m=0}^{L-1} r^*(d + 2Lk + m) \cdot r(d + 2Lk + m + L) \tag{7}$$

$$R_2(d) = \frac{1}{2} \sum_{m=0}^{N-1} \mid r(d+m) \mid^2 \tag{8}$$

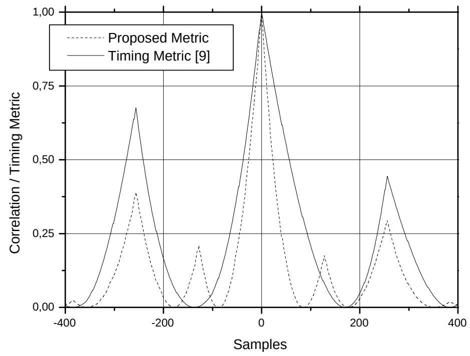
where $S = 2G - 1$ and $L = \frac{N}{4G}$. $P_2(d)$ is the correlation metric and $R_2(d)$ represents half symbol energy and it is included for normalization of the correlation metric. Dividing the correlation metric by the half symbol energy in (6) is useful, especially in fading channels for normalization. However, by applying (6), especially in the case of training symbols with more than one groups, too many peaks are present, which results in an increased estimation variance. The first metric that is proposed is just the correlation metric (7) in the case where $G = 1$. Fig. 1(a) presents the timing metric (6) and the normalized, by its maximum value, correlation metric (7). It is apparent in Fig. 1(a) that the correlation metric has shorter side lobes compared to the timing metric.

IV.2.2 Two Groups Timing Metric

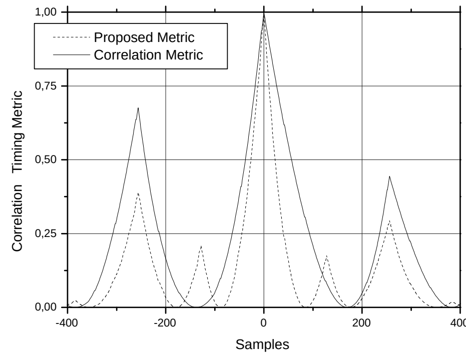
The second metric that is proposed is the product of the correlation metric $P_2(d)$ with the half symbol energy $R_2(d)$, divided by the product 's maximum value for normalization, in case $G = 2$:

$$M_2(d) = \frac{\mid P_2(d) \mid^2 \cdot R_2^2(d)}{M_2(d_0)\rfloor_{max}}. \tag{9}$$

In (9), d_0 is the received sample for which, neglecting the denominator, the $M_2(d = d_0)$ is estimated as maximum. Fig. 1(b) presents the proposed metric by using training symbols consisting of two groups ($G = 2$), compare to the timing metric of (6) where one group is used. In Fig. 1(b), the proposed timing metric is narrower around index 0 and shorter side lobes are obtained as well. Thus, it is expected to achieve better accuracy in timing offset estimation. The metrics in Fig. 1 were obtained for an OFDM system with $N = 1024$ IFFT points, under no noise and distortion condition, cyclic prefix $cp = 102$ samples, frequency offset $\Delta F = 0$ and QPSK modulation. In both proposed timing metrics, the timing offset estimation is to be done in a two–step procedure. In the first step, both correlation metric and half symbol energy are calculated and compared. If the half symbol energy is much greater than the correlation metric the received signal will be just noise. If the half symbol energy is comparable to correlation metric, the received signal will contain the training symbol. If the second one is the case, at the second step, the timing offset estimation algorithm is applied and the peak is estimated. It is mentioned that the receiver complexity is about the same as in [7].



(a) First proposed metric compared to the timing metric of [7].



(b) Second proposed metric compared to the timing metric of [7].

Fig. 1: Proposed Metrics compared to the timing metric of [7].

V. SIMULATION RESULTS AND DISCUSSION

A threshold in the correlation metric to half symbol energy ratio of 0.05 was set. In all 10000 simulation runs, the receiver detected the existence of the training symbol at the received data successfully. The parameters were the same with those that are presented next. Consequently, all metrics above can be used without need for normalization.

For the Rayleigh and Rice channels, we present the results by computer simulation using the first ($G = 1$ with (7)), in Fig. 2, and the second ($G = 2$ with (9)), in Fig. 3, proposed training symbol formats. The parameters for both simulated satellite channels are $L = 5$ *taps* with $f_D \cdot T_S = 0.13$, with T_S as OFDM symbol duration, $f_D = 5\ kHz$, $T_{max} = 1\ \mu s$, $cp = 2\ \mu s$ cyclic prefix, $\Delta F = 0$, QPSK modulation and 10000 simulation times run. In the case of the Rice channel Rice factor $K = 7\ dB$.

Using the same parameters for the multipath fading channels, excluding the maximum Doppler shift, we present in Fig. 4 the impact of the Doppler effect in timing synchronization performance by computer simulations using the training symbol with $G = 1$ and $G = 2$ groups, respectively.

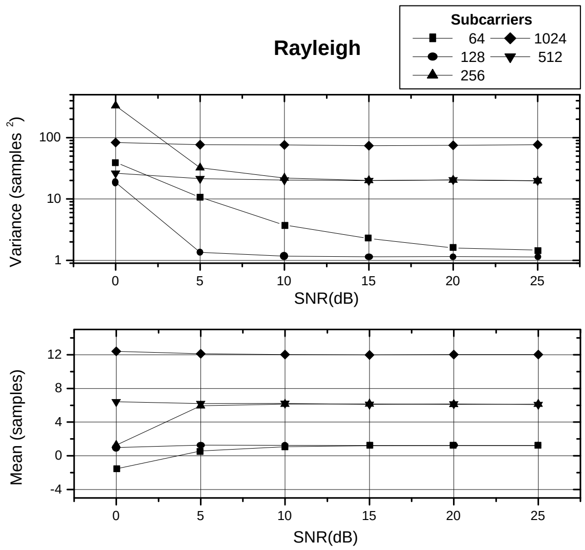
By observing the results in Figs. 2 – 4, together with the metrics presented in Fig. 1, we can note that:

- In the case of Rayleigh channel using both proposed metrics Fig. 2(a), 3(a) the mean value is constant while the SNR is increasing. The degradation due to ICI after the FFT can be easily avoided before removing the cyclic prefix and performing the FFT at the receiver, taking as first sample of the synchronization symbol the one that is pointed out by the algorithm with a constant timing offset. However, the variance of the timing estimator is decreasing while the SNR is increasing till a variance floor.
- In both Rayleigh and Rice channels where $G = 2$ the results are better than in the case where $G = 1$, as it is apparent from Figs. 2 and 3.
- In the case of Rice channel with Rice factor 7 dB using both proposed metrics, the mean value is near zero. The variance decreases while the SNR increases till a variance floor.
- A great advantage of using the proposed synchronization algorithms is the robustness over the Doppler phenomenon while the channel varies rapidly during one OFDM symbol, as it is apparent in Fig. 4.

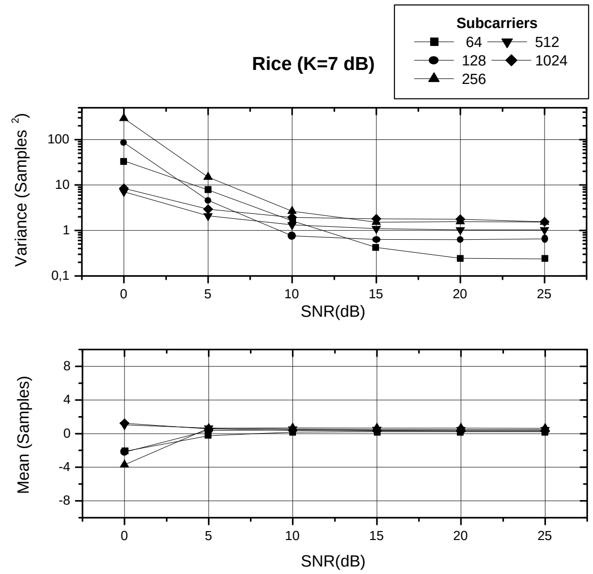
Finally, it is important to point out that in the simulations in the presence of frequency offset ΔF, there was no change in the performance of the timing offset estimator. Although the frequency offset seems not to be a problem in timing synchronization, it must be taken into account in the overall OFDM system design and compensate it together with the Doppler shift by channel estimation. Furthermore, various PN sequences were implemented to construct the training symbols in the simulations such as Gold and Kasami, however, marginal difference at the performance of the timing offset estimation were identified.

VI. CONCLUSIONS

A burst timing offset estimation method was examined in two time varying frequency selective fading channels with parameters valid for LEO and MEO satellite channels. Two timing estimation metrics and formats of the OFDM

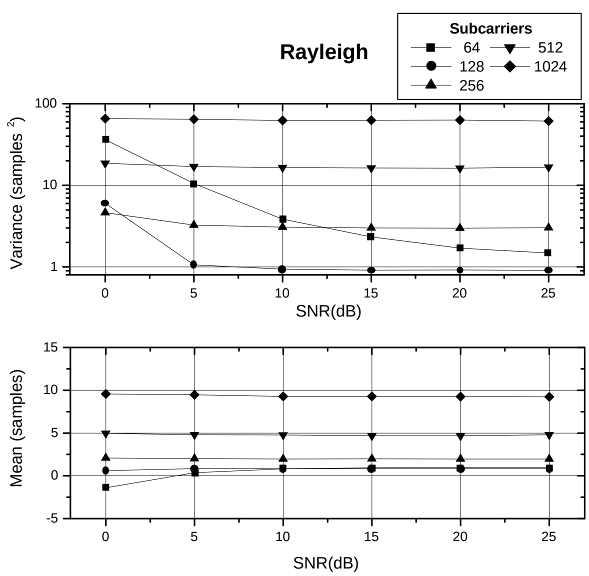


(a) Rayleigh channel.

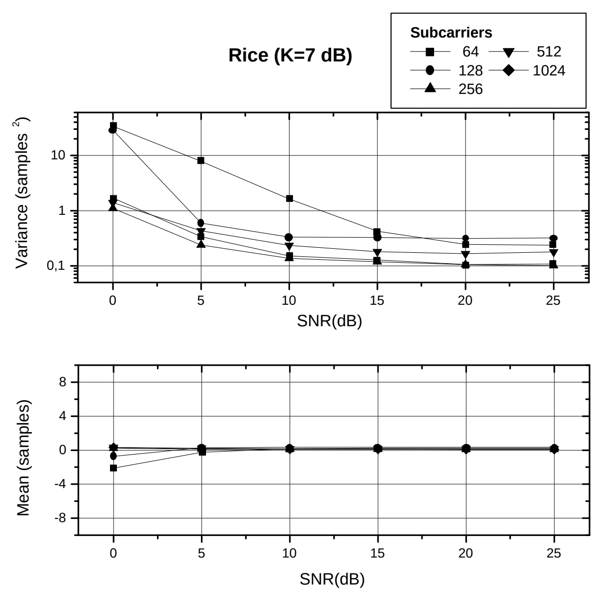


(b) Rice channel.

Fig. 2: Rayleigh / Rice frequency and time selective multipath fading channel ($G = 1$)

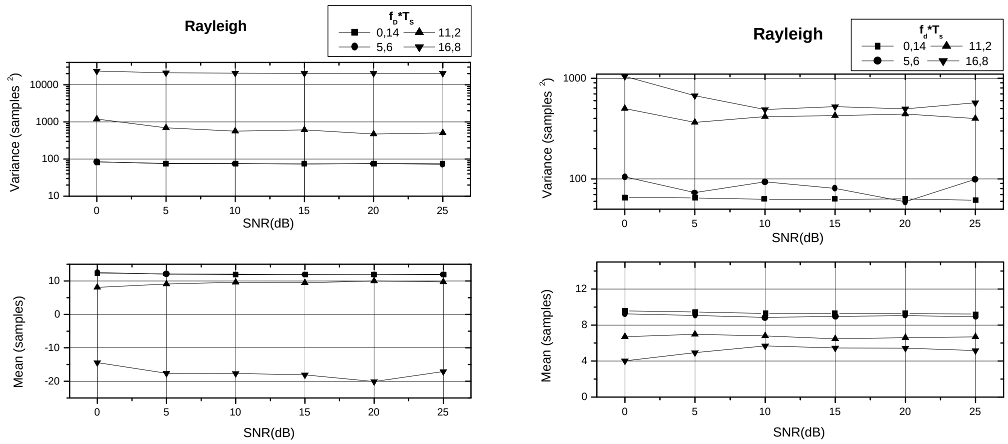


(a) Rayleigh channel.



(b) Rice channel.

Fig. 3: Impact Of Doppler Shift In Timing Synchronization



(a) *G=1.* (b) *G=2.*

Fig. 4: Rayleigh / Rice frequency and time selective fadings for $G = 1$ and $G = 2$.

training symbol were used and compared. Using the training symbol of two groups better performance was achieved than using that of one. In the case of Rayleigh channel the mean value is constant with SNR. In the case of Rice channel with Rice factor greater than 7 dB, perfect timing offset estimation is achieved. For realistic values of the Doppler shift, the performance of the timing offset estimation remains practically unchanged.

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