OFDM IN MOBILE SATELLITE SYSTEMS[1]

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abstract

Wireless multimedia communications require the selection of a suitable modulation-access technique. OFDM is a potential candidate in the design of such future generation mobile systems; it offers flexibility in bandwidth management, and potential good information protection against the severe degradations induced by the channel on signals characterized by large bandwidths. These attractive features have led to the adoption of OFDM in the design of a wireless LAN, which at the network layer is ATM (project ACTS-MEDIAN). The possibility of interfacing local with satellite networks seems challenging, although OFDM performance over the satellite channel remains to be tested. The present paper reports results of analyses on synchronization issues which show that while satellite-OFDM is in all cases a feasible hypothesis, LEO systems are favoured with respect to GEO, due to the lower delays they introduce.

Introduction

The first commercial satellite telecommunication systems have made large use of frequency modulation (FM). This was the case, for example, in the INTELSAT satellites (1965) operating for telephone communications between Europe and the USA. The choice of FM was motivated by the possibility of improving the received signal-to-noise ratio (SNR) by modifying the modulation index. This last property is very important in satellite systems, which, as well known, are power limited. However, in analogue FM the amount of information which can be transfered in the time and frequency unit is low, i.e. analogue FM is characterized by low spectral efficiency.

The low spectral efficiency of analogue FM systems motivated the development of digital modulation techniques, especially in view of applications using power limited systems, such as mobile communication systems. Several digital modulation schemes have been developed and are in use at the present time. The selection of one method over another depends upon performance requirements such as the Bit Error Rate (BER) in the presence of multipath fading, cochannel interference, and intersymbol interference. The most famous and widely used digital modulation techniques are Quadrature Amplitude Modulation (QAM) and Phase Shift Keying (PSK); this last is widely adopted in mobile terrestrial and satellite systems because of its reliability over the distorting channel. For example, in the North-American IS-54 mobile terrestrial system and in the Japanese PDC, $\pi/4$-QPSK is used. Another famous and very-well-performing modulation technique is Frequency Shift Keying (FSK); one of its dialects, GMSK which stands Gaussian Minimum Shift Keying, is used in GSM.

In satellite communications, the non-linearities generated at the transmitters by the High Power Amplifiers (HPA) which operate close to the saturation point, induce the use of constant envelope modulated signals. In addition, due to the random phase, non coherent demodulation is favoured. FSK modulation schemes with phase differential detection (FSK-PDD) or with partial response (FSK-PRS), such as in GSM, obey these requirements. However, these modulation techniques usually introduce higher ISI. Korn [1] showed that in the Satellite Mobile Channel (SMC) the probability of error can be analytically derived and does not tend to zero when SNR tends to infinity. In other words, there is a minimum under which the residual error does not go.

As regards the selection of the multiple access technique in relation to the modulation scheme adopted, traditional digital modulation methods harmonize with both TDMA and CDMA systems. An interesting investigation which has resulted in continuous and growing interest in the scientific community is the analysis of traditional digital modulation schemes imbedded in multi-carrier access based systems (FDMA family), such as Orthogonal Frequency Division Multiplexing (OFDM). OFDM turns out to be an appealing modulation-access technique which offers:

1. flexibility: the occupied band can be easily varied according to the data rate. This is an important factor in systems providing multimedia services.
2. robustness: the fading effects can be made less severe. This is an indispensable feature in satellite mobile channel communications.
3. good encoding of the information: in case of rapidly varying channels, such as the mobile channel, this is a challenging property. The reason for this appealing characteristic is the possiblity of selectively protect the information making thus

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fading effects less severe.

These reasons make OFDM a potential candidate in the design of future mobile systems. It offers the possibility of transmitting high data rates with good protection against the severe distortions on the large signal bandwidth.

However, when using OFDM over the satellite channel, a problem arises which is not present in the indoor environment: large delay, and consequently increased difficulty in synchronization. While in the indoor environment, delays are small since small distances must be covered, in the satellite channel, important delays are present; different users must synchronize to different carriers and errors can be tolerated only to a limited extent. Needless to say, the amount of error which can be tolerated depends upon guard bands; the larger the guard bands, the larger the synchronization errors can be. However, the larger the guard bands, the lower is the advantage of using OFDM over a more traditional FDM technique.

In the present paper, OFDM synchronization in a satellite system is examined. The synchronization technique will be described in section 2 after a summary of the OFDM technique (section 1). The simulation of an OFDM mobile satellite system was implemented by inserting the OFDM module in a more general system in which the access method was a PRMA-based technique. The simulation experiment will be described in section 3. Finally, results of simulation will be reported in section 4. We will show how OFDM behaves in satellite systems with different guard bands. Since the extension of the guard band will be found to be strictly related to the acceptable delay, we shall show results of simulation of LEO systems which have low delays and compare the requirements to the case of GEO systems which have significant higher delays. Finally, we shall attempt to give a conclusive discussion on the hypothesis of using OFDM over the LEO/GEO-satellite channel.

1.Description of the OFDM technique over the satellite mobile channel

As highlighted by Weinstein and Ebert [2], the mo-demodulation in an OFDM system can be implemented by digitally-based FFT circuits. The scheme of an OFDM system which uses DSP techniques is shown in Fig.1. OFDM allows the transmission of several signals over several carrier frequencies. A coder generates a group of N symbols out of a group of K bits. These symbols are indicated by $a_{m,k}$ with $m=0,\dots,N-1$ where k indicates the block number. Each symbol belongs to an alphabet A of L elements. Thus, each symbol carries $\gamma = \log_2 L$ bits. The duration of each block is T. Each symbol modulates a sub-carrier using a modulator (for example, QAM), as shown in Fig.2. The carrier frequencies are spaced by Δf and distributed around f_c. Consequently, one can write:

$$f_m = m\cdot\Delta f - \frac{N}{2}\cdot\Delta f \qquad with\ m=0,\dots,N-1 \tag{1}$$

The binary rate at the coder output is $N\cdot\gamma/T$ where T must be shorter than the $g_T(t)$ of the QAM modulator.

The complex envelope for the output of the OFDM modulator, s(t), is:

$$\underline{s}(t) = g_T(t)\sum_{m=0}^{N-1} c_m \exp[j2\pi\cdot f_m\cdot t]\cdot g_m = \sum_{m=0}^{N-1} c_m\varphi_m(t) \tag{2}$$

which is periodic with period $T_s = 1/\Delta f$, except for $g_T(t)$.

In order to evaluate the bandwidth of $s(t)$, suppose that $g_T(t)$ is rectangular with duration equal to T. The Fourier transform of $\underline{s}(t)$ is:

$$\underline{S}(f) = \sum_{m=0}^{N-1} c_m G_T(f - f_m) \tag{3}$$

which has an infinite band. If we assume that $G_T(f)$ has an effective band limited to $\pm M\cdot\Delta f$ (M integer) out of which the amplitude of the spectrum can be neglected, then $\underline{S}(f)$ can be limited to $(N+2M)\cdot\Delta f$. If over N symbols, the first and the last M are "neutral" (corresponding to the origin of the QAM constellation) then the bandwidth of $\underline{S}(f)$ is: $B = N\cdot\Delta f$ although the useful band is: $B_u = (N-2M)\Delta f$. Note that if B is the bandwidth of $s(t)$, then the sampled version of $s(t)$ is:

$$\underline{s}_k = \underline{s}\left(t = \frac{k}{N\cdot\Delta f}\right)$$

$$= \exp(-jk\pi)g_T\left(\frac{k}{N\cdot\Delta f}\right)\sum_{m=0}^{N-1} c_m \exp\left(j2\pi\frac{m\cdot k}{N}\right) = (-1)^k\cdot g_T\left(\frac{k}{N\cdot\Delta f}\right)\cdot C_k$$

$$C_k = \sum_{m=0}^{N-1} c_m \exp\left(j2\pi\frac{m\cdot k}{N}\right) \tag{4}$$

$for\ k = 0,\dots,N-1$

Eq.4 is the discrete inverse Fourier transform of $c_m = \{c_0,\dots,c_{N-1}\}$ of period N. Thus, the N modulators can be replaced by an FFT^{-1} circuit on the N complex C_k derived by the a⇒c association in the QAM. Once the C_k are computed, one obtains the $s(t)$ sample weighted by the $g_T(t)$ sample.

As for the demodulator, it is necessary to have a set of functions $\psi_k(t)$ orthogonal to the $\varphi_k(t)$:

$$\int_0^T \varphi_m(t)\cdot\psi_k^*(t)dt = \begin{cases}1 & 0\le m=k\le N-1\\ 0 & m\ne k\end{cases} \tag{5}$$

If the $\psi_k(t)$ exist, and indicating by $r(t)$ the received signal, one has:

$$\int_0^T \underline{r}(t)\cdot\psi_k^*(t)dt = \sum_{m=0}^{N-1}\hat{c}_m\int_0^T\varphi_m(t)\cdot\psi_k^*(t) = \hat{c}_k \tag{6}$$

The receiver is a bank of correlators. There must be block synchrony; $\psi_k(t)$ must be temporally alligned to $\varphi_k(t)$.

As regards the application of OFDM to satellite systems, the SMC can be represented by the Rice model with parameter $k=P_s/P_d$ (ratio between direct and diffuse components). As well known, this includes the case of Gaussian channel (k=∞) and of Rayleigh channel with one path (k=0). In the SMC, it is appropriate to have $g_T(t)$ and $g_R(t)$ as the raised cosine.

In a satellite multi-users mobile communication system, the different signals in one OFDM block can be thought to be associated to a single mobile unit; these signals are characterized by different delays and Doppler frequencies, and are also affected by different temporal and frequency offsets which can cause interference with users located in the same coverage area. Consequently, there is a strong need for synchrony between mobile stations. This problem will be analyzed in the next section. If U indicates the number of mobile stations served by the satellite, the i^th^ transmitted signal (i=0,...,U-1) has the following base-band expression:

$$\underline{s}_i(t)=\sum_{k=-\infty}^{\infty}\underline{x}_i(t-dt_i-kT)\cdot\exp\left[j2\pi\cdot(df_i+f_{c_i}-f_0)\cdot(t-dt_i)\right] \quad (7)$$

$$\underline{x}_i(t)=g_T(t)\exp\left(-j2\pi\frac{N}{2}\Delta ft\right)\cdot\sum_{n=0}^{N-1}c_n\exp(j2\pi n\Delta ft) \quad (8)$$

Since a raised-cosine is used (with roll-of α), then $\Delta f=(1+\alpha)/T_U$ and since the OFDM signal bandwidth is $B=N\cdot\Delta f$ the carrier of the i^th^ channel is $f_{ci}=f_0+i\cdot B$. The terms dt_i and df_i represent the temporal and frequency offsets of the i^th^ user with respect to the mobile user i=0. At the i^th^ channel output, the received signal is:

$$\underline{r}_i(t)=\sqrt{2P_{c_i}}\,\underline{s}_i(t)+\sqrt{P_{d_i}}\,\underline{s}_i(t-t_{d_i})\exp(-j2\pi f_{D_i}t)\xi_i(t)+n(t) \quad (9)$$

i.e. the sum of direct and diffuse components, and of gaussian white zero-mean noise. The diffuse component takes into account the delay t_{di} and the Doppler shift f_{Di}. Focusing on user 0, after filtering through $g_R(t)$, the received signal is:

$$\underline{r}(t)=\sum_{i\in U}\sqrt{2\cdot P_{c_i}}\,G_{c_i}(t)+\sum_{i\in U}\sqrt{P_{d_i}}\,G_{d_i}(t)\cdot\xi_i(t)+n_o(t) \quad (10)$$

$$G_{c_i}(t)=\sum_{k=-\infty}^{\infty}\left\{\exp\left(-j2\pi\frac{N}{2}\Delta ft\right)\sum_{n=0}^{N-1}c_n\exp(j2\pi n\Delta ft)\right\}g_{c_i}(t-kT)$$

$$G_{d_i}(t)=\sum_{k=-\infty}^{\infty}\left\{\exp\left(-j2\pi\frac{N}{2}\Delta ft\right)\sum_{n=0}^{N-1}c_n\exp(j2\pi n\Delta ft)\right\}g_{d_i}(t-kT)$$

$$g_{c_i}(t)=\left\{g_T(t-dt_i)\exp\left[j2\pi(f_{c_i}-f_0+df_i)(t-dt_i)\right]\right\}*g_R(t)$$

$$g_{d_i}(t)=\left\{g_T(t-dt_i-t_{d_i})\exp\left[j2\pi(f_{c_i}-f_0+df_i-f_{D_i})(t-dt_i-t_{d_i})\right]\right\}$$
$$*\,g_R(t) \quad (11)$$

As for $n_O(t)$, it is a gaussian zero-mean noise, with autocorrelation

$$R_{n_o}(\tau)=N_o\int\left|G_R(f)\right|^2\cdot\exp(j2\pi\cdot f\cdot\tau)df \quad (12)$$

Note that the shape of the received signal for user 0 includes the contributions of the other units.

2.Multi-user synchronization in OFDM

Synchronization issues vary in the up- or down-link. Having a good synchronization in the down-link is easier since the different signals all originate at the same source. In the up-link, the signals originating in the different units have different delays due to multipath. In addition, the spectra are widened and shifted by the Doppler.

Consider the up-link. Suppose that the OFDM channels are in a band W between the frequencies fs and $fs+W$. The algorithm described was first presented by Wei and Schlegel [3]; W is divided into Q sections which are interspaced by a "guard interval" B_G. Since the OFDM signal bandwidth is $B=N\cdot\Delta f$, one has (in each section) $N_c=(W/Q)-2B_G/B$ channels, one for each mobile station.

The separation of the spectrum into sections can be obtained by using pilot tones (fq_0 , fq_1 , ..., fq_Q) used for synchronizaton. Each section is identified by two adjacent tones. The satellite broadcasts (fq_0 , fq_1 , ..., fq_Q) and the mobile alligns its transmission to the carrier of its OFDM channel.

In case of a non-distorting channel and of absence of Doppler shifts, if the i^th^ channel of the n^th^ section is assigned to the j^th^ mobile unit, then the carrier frequency of the j^th^ unit is given by:

$$f_{c_j}=\frac{\left(f_{q_{n+1}}-f_{q_n}\right)}{\frac{W}{Q\cdot B}}\cdot i+f_{q_n}+B_G \quad (13)$$

If the N_C users of the n^th^ section are capable of accurately estimating the synchronization tones which delimit the n^th^ section, then they are synchronized to their carrier frequencies.

In the case of a real channel, multipath fading and Doppler effects affect the estimation of the synchronization tones. Note that due to the relative speed v_j of the j^th^ station a frequency f sent by the satellite, is received as:

$$f'=f\cdot\left(1\pm\frac{v_j}{c}\right) \quad (14)$$

in which $f\cdot(v_j/c)$ represents the Doppler shift f_D .

We examine now the method used by the mobile to estimate the pilot tones and correct the Doppler. The j^th^ mobile receives the synchronization tones relative to section n , $f'q_n$ e $f'q_{n+1}$ (while the satellite transmits fq_n and fq_{n+1}):

$$f'_{q_{n+1}}-f'_{q_n}=\left(f_{q_{n+1}}-f_{q_n}\right)\cdot\left(1\pm\frac{v_j}{c}\right) \quad (15)$$

from which one has:

$$\left(1\pm\frac{v_j}{c}\right)=\frac{Q}{W}\cdot\left(f'_{q_{n+1}}-f'_{q_n}\right) \quad (16)$$

Thus, the mobile can compute the Doppler $(1\pm v_j/c)$ and derive the correct synchronization tones which are:

$$f'_{p_k}=\frac{f'_{q_k}}{\left(1\pm\frac{v_j}{c}\right)^2}=\frac{f_{q_k}}{\left(1\pm\frac{v_j}{c}\right)} \qquad k=n,n+1 \quad (17)$$

If in the up-link, the carrier associated to the j^th^ mobile, $f'c_j$, is associated to the m^th^ channel of the n^th^ section, then the mobile unit generates the carrier $f'c_j$ by using the estimated synchronization tones $f'p_j$ and one has:

$$f'_{c_j} = \frac{\left(f'_{p_{n+1}} - f'_{p_n}\right)}{\frac{W}{Q \cdot B}} m + f'_{p_n} + B_{G_i} \tag{18}$$

On the satellite side, the satellite receives the following carrier:

$$f_{c_j} = f'_{c_j}\left(1 \pm \frac{v_j}{c}\right) = \frac{\left(f'_{q_{n+1}} - f'_{q_n}\right)}{\left(1 + \frac{v_j}{c}\right) \cdot \frac{W}{Q \cdot B}} \cdot m + \frac{f'_{q_n}}{\left(1 \pm \frac{v_j}{c}\right)} + B_{G_i} = \tag{19}$$

$$= \frac{\left(f_{q_{n+1}} - f_{q_n}\right)}{\frac{W}{Q \cdot B}} m + f_{q_n} + B_{G_i}$$

This last expression is equivalent to the one examined in the case of an ideal channel, if i=m. Thus, since the terrestrial mobile unit derives its transmission carrier frequency from the synchronization tones received in the down-link, it is possible to correct the offset due to the Doppler if $f'q_0$, $f'q_1$, ..., $f'q_Q$ are correctly recovered.

3.Description of the simulated system

The OFDM synchronization has been simulated by writing a C software running on a Sun Worstation Spark 5. In the simulator, the satellite acts as the supervisor. The coverage area can be thought as composed by Q coverage sub-areas to which the entire resource is allocated (N channels). These channels are allocated on a bandwidth which is: $B_s = W/Q$

Since the satellite acts as the supervisor of the connection, it not only allows synchronization of the users but also checks the state of the different channels which can be either occupied by a transmitting user, or non-occupied. In the first case, the channel cannot be used until the user stops sending messages and disconnects. In the second case, the satellite must decide whether to assign the channel to the users making a connection request.

The resource management acted by the satellite is of a connection-oriented type based on FDMA. In order to limit collisions, a permission probability parameter is introduced. This parameter represents the probability of obtaining a channel when requested. If more than one user asks for connection simultaneously, some of the users will be allowed to access the channels, and others will not. Each user generates a casual number between 0 and 1. This number is compared to a permission probability threshold (typically 0.3). Only those users who emitted a number lower than 0.3 will be allowed to make a request for the resource. If more than one user has succeded in request, and only one channel is non-occupied, then the satellite might decide not to assign the channel to any of them. This is a typical case of collision. In the simulator, the state of the channels is checked by the satellite every 6 msecs, which implies that a given channel (if there is a request) will not stay non-occupied for a very long time.

The mobile users are supposed to be represented by statistical models of their activity. It is hypothesized that a user might be in a silence mode or conversation mode for a given average period of time and that the transition probabilities between two states are negative-exponentially distributed. If T_s and T_t indicate the durations of the silence and conversation modes, the transition probabilities are given by: $p_{st} = 1.0 - e^{-T/T_S}$ and $p_{ts} = 1.0 - e^{-T/T_S}$ where T=6 msecs, T_S=11.3 minutes, T_t= 2 minutes. The ratio $T_t/(T_s+T_t)$ indicates the average activity per user. With the selected times the activity is about 15%.

In order to communicate, the user must send a channel request. If the channel is obtained, the user goes in the reservation mode, and then tries to synchronize. An important parameter is T_{sync} which is the maximum time gap which the user can use in order to synchronize.

4. Results of simulation trials

4.1 The case of LEO

Results are presented in terms of average synchronization probability. This parameter is strongly dependent upon the guard band extension. In addition, it also depends upon the synchronization time allowed (the parameter T_{sync}). In the simulations, we have assumed that the ratio between number of users and number of channels be 5 to 1. The total number of users has been supposed to be 10000 while the number of channels is 2000. The average silence time is 2 minutes; the average conversation time is 12 minutes. The available bandwidth is 20 MHz in each direction. The waiting time before channel is assigned is 60 msecs. The LEO system considered assumes a distance between the satellite and the mobile of 780 km. The maximum mobile speed is 100 m/s. The satellite speed is 7462 m/s. The simulation considers the worst case, i.e. the satellite and the mobile travel in opposite directions. Results are presented in Fig. 3 in terms of average probability of correct synchronization as a function of used bandwidth and of maximum synchronization time T_{sync}. The results show that when T_{sync}>=600 msecs, the probability of correct synchronization is over 98% when the used bandwidth is below 89.2%. This data can be considered as a threshold, and a good dimensioning of the system would select an extension of the guard band which leads to <89.2% of bandwidth utilization and a maximum synchronization time equal to 600 msec.

4.2 The case of GEO

The same hypotheses as in the LEO case are made in terms of number of users and channels. However, the distance between the satellite and the mobile is much bigger. The round-trip time is now 0.6 sec compared to the 12 msec of the LEO case. Thus, fewer synchronization attempts are possible in the same T_{sync}. Results are reported in Fig. 5 which shows that in order to have similar performance to the LEO case, the GEO system must have T_{sync}=24 sec which is an unaffordable time. The conclusion is that the used bandwidth must be decreased, to keep T_{sync} to reasonable values. Figure 4 shows that for T_{sync}=720 msecs the performance is adequate, with more than 95% of correct synchronization when the used bandwidth is below 88.48%. OFDM is still a valuable choice but does not present the great advantage as in LEO systems.

5. Conclusion

In this paper, the design of a satellite system using OFDM was examined. Results of simulation trials implementing a multi-user synchronization procedure show that in the case of LEO systems, the OFDM solution offers great advantage over traditional FDM, without introducing severe limitations due to synchronization errors. In the case of GEO systems, OFDM is still a valid alternative to FDM; however, propagation delays impose a limit which reduces the utilization of the available bandwidth.

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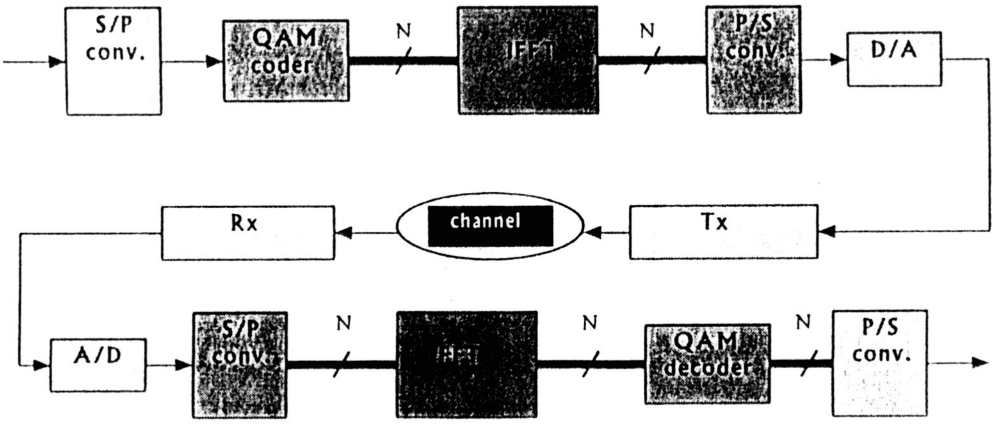

Figure 1 – Block diagram of an OFDM system using DSP techniques.

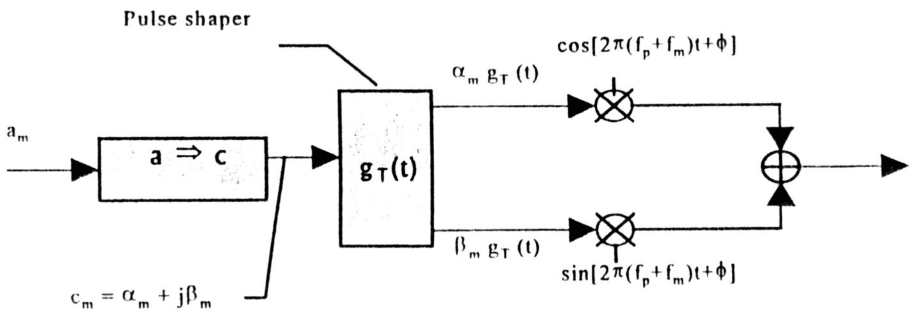

Figure 2 – Sub-carrier modulator

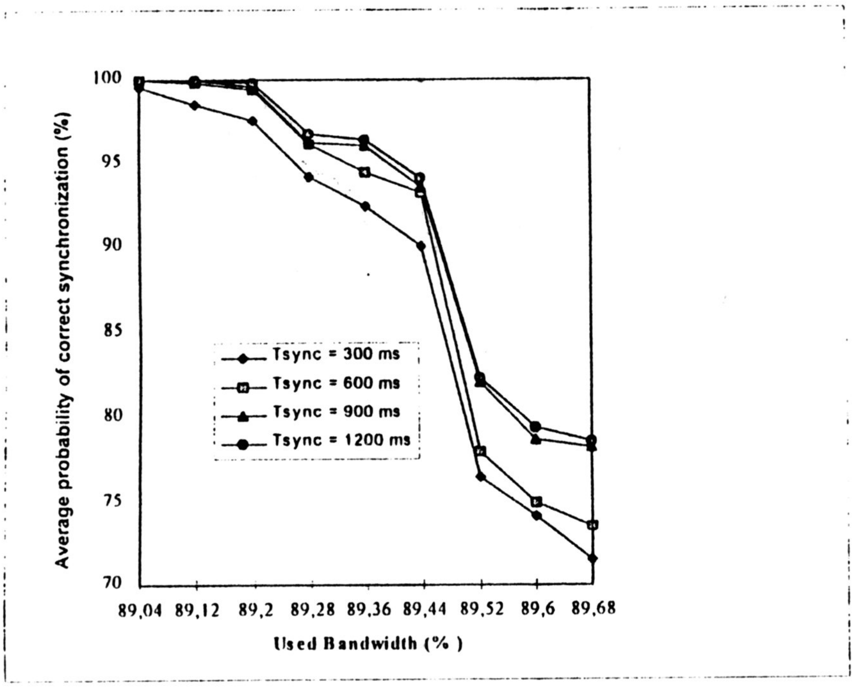

Figure 3 – Simulation results in the case of LEO

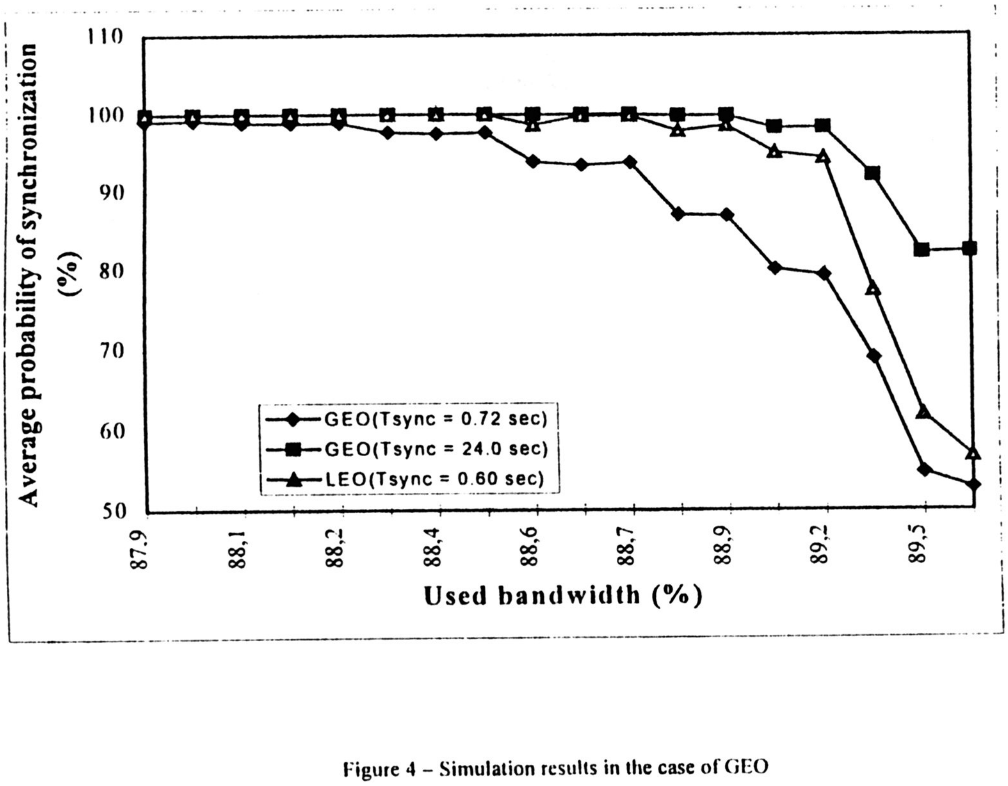

Figure 4 – Simulation results in the case of GEO