High Quality Audio Services Over a L-Band Satellite Link using COFDM with Soft-Decision

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Abstract — The choose to perform a C-OFDM modulation directly by satellite makes the design of cost-effective new communication scenarios possible, in periods in which satellite communications call for a higher penetration in everyday services provision, avoiding the high costs of terrestrial - segment infrastructures to make the satellite signal exploitable by mobile users in urban environments. This paper focuses on the analysis of the performances of a C-OFDM-based communication scheme for the provision of a high quality and scalable bit rate radio signal over satellite links and exploitable in urban environments. Due to these preambles, the almost unemployed specifically satellite-oriented Mode-III of the DAB standard is considered, in conjunction with the design of an high-effective receiver based on soft-decision schemes, in cohabitation with almost very spread terrestrial DAB services.

The degradations due to propagation and signal distortions introduced by the payload are also taken into account in the analysis of the transmission system.

Index Terms — Satellite DAB, L-Band, C-OFDM, OBO, Soft-Receiver

I. INTRODUCTION

A very actual trend in satellite communication research is the investigation over new features and services able to be competitive and economically attractive with regard to whom derived from the huge spreading of terrestrial communication / dissemination networks [1]. In this challenging scenario, the well-known coverage and broadcast capabilities of geo-stationary satellite systems find new alliances with very spread techniques in order to provide broadcast services according with growing demand for very high quality and reliability. Numerical techniques are replacing the analogical ones even in very common every-day services like radio (T-DAB) or television (DVB-T) diffusion in urban environments, by means of terrestrial distribution networks using multipath- counteracting modulation such as Orthogonal Frequency Division Multiplexing (OFDM). In such an urban environment, satellite services have been often provided by means of a regeneration - performed in the ground segments - of the satellite signal into an OFDM-modulated one. Scope of the present paper is to evaluate the performance of a satellite transmission performed directly with COFDM modulation for the provision of High Quality audio broadcasting service in a very fading-affected area such as the urban one. The most attractive advantage in modulating directly in COFDM is the possibility to avoid further economic charges related with a terrestrial communication infrastructure for the provision of satellite services. In this context, a great interest arises for the design of new receiver devices able to obtain high performances even in very fading-affected environment.

II. C-OFDM OUTLINE

Coded Orthogonal Frequency Division Multiplexing (COFDM) is a very commonly used technique particularly suited in heavy-affected multi-path propagation environment, such as the urban one, in which multiple reflections of the same wave against buildings and obstacles generate interference at receiver side. Reflections provide delayed and magnitude-scaled copies of the direct wave, in such a way that the resulting signal in reception results to be deeply weakened.

The main feature in the COFDM technique is the possibility to divide huge bit streams into a set of smaller streams each of them modulating a single sub-carrier, in such a way to transform high bit rates into slower ones. In this way, the corresponding symbol duration (T_s) becomes larger than the delay spread of the transmission channels, making possible to avoid inter-symbol interference - caused by channel selectivity and multi-path propagation - simply by means of the insertion of a temporal guard interval (T_g) [6] between the transmission of two adjacent symbols.

Hence, C-OFDM results to be a scheme characterized by implicit interference-counteracting properties, since it performs a spreading of the overall information over a set of frequencies, in this way taking the selectivity of the fading into account as an advantage.

Let’s consider a set of N sub-carriers,

\[ \Psi_k(t) = e^{j2\pi f_k t}, t \in [(k-1)T_u, kT_u], k = 1..N \] (1)

the orthogonality (2) of the sub-carriers makes the overlapping of sub-carrier - related spectra feasible,

\[ \frac{1}{T_u} \int_0^{T_u} \Psi_i(t)\Psi_j(t) = \delta_{ij} \] (2)

(where \( \delta_{ij} = 1 \) if \( i = j \), \( \delta_{ij} = 0 \) otherwise), since the demodulation of a single carrier is performed simply by multiplying the whole signal by the frequency.

The fact that a large amount of frequencies is involved does
not call for the necessity to have a considerable number of modems to be utilized in reception: it can be demonstrated that the sequence of modulated complex symbols $c_i$ can be obtained at transmission side as the Inverse Discrete Fourier Transform (IDFT), which just needs the chief sub-carrier to be managed at physically layer.

$$s(t) = \sum c_i e^{j2\pi f_i t}$$

Fig. 1: Scheme of the OFDM Transmitter.

At the same manner, at receiver side, everything is managed by means of a DFT.

It is worth noting that the higher is the number $N$ of the sub-carriers involved in the modulation scheme, the closer will be the frequencies spread over the spectra; this can cause particular problems as far as the Doppler effect is concerned, in condition of high speed mobility. Anyway, a Doppler counteracting feature of COFDM scheme concerns with the fact that the higher $N$ gets, the lower is the bit rate, the lower is the bandwidth related to each carrier.

![Diagram](image)

III. SATELLITE – DAB STANDARD

Digital Audio Broadcasting (DAB) [2] provides support for high quality audio transmission in terrestrial as well as satellite environment for users in mobility with no needs for directional antennas; furthermore, general-purpose digital multiplex capabilities are also foreseen in DAB standard, in such a way that a sound service shall be equipped with information data.

These assumptions allow for new scenarios as far as sound broadcasting is concerned, due to the possibility of exploiting very high quality sounds and value-added services in very hard mobility environment; moreover, due to the rate scalability allowed by DAB, satellite intrinsic coverage capability could carry very far-away media as well as small radio networks signals, opening new market opportunities.

DAB uses OFDM with Differential Modulation and foresees the possibility to choose among four utilization modes depending on frequency, frame duration and transmission environment. These modes share the common feature to be characterized by an overall bandwidth equal to 1.5 MHz, and they mainly differentiate in their capabilities to cope with the Doppler effect experienced by the transmission platform the transmission is performed in.

In particular, DAB – mode III addresses transmission features as far as satellite environment is concerned; the usage of 192 carriers is foreseen, each carrying 16 kbps, with frequency inter-spacing equal to 8 KHz in the range of 1.5 - 3 GHz (L-band), whereas the others are mainly dedicated to terrestrial transmission environments. Table II summarizes the values of parameters for each Mode, where:

- $s$ = number of OFDM symbols per frame
- $N$ = carriers involved in ODFM modulation
- $T_f$ = frame duration
- $T_u = $ inverse of frequency-spacing between carriers
- $T_g = $ guard time

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mode I</th>
<th>Mode II</th>
<th>Mode III</th>
<th>Mode IV</th>
</tr>
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<tr>
<td>$S$</td>
<td>76</td>
<td>76</td>
<td>153</td>
<td>76</td>
</tr>
<tr>
<td>$N$</td>
<td>1536</td>
<td>384</td>
<td>192</td>
<td>768</td>
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<td>96 ms</td>
<td>24 ms</td>
<td>24 ms</td>
<td>48 ms</td>
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<tr>
<td>$T_u$</td>
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<td>250 µs</td>
<td>125 µs</td>
<td>500 µs</td>
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<tr>
<td>$T_g$</td>
<td>246 µs</td>
<td>62 µs</td>
<td>31 µs</td>
<td>123 µs</td>
</tr>
</tbody>
</table>

IV. THE POWER AMPLIFIER

No-regenerative transponders, in which an amplification and a frequency shift are only performed, are often foreseen in the project of a satellite communication system. As far as the amplification is concerned, two different kinds of devices (High Power Amplifier – HPA) are in turn usually involved: the Solid State Power Amplifier (SSPA) [7] and Traveling Wave Tube Amplifier (TWTA). In the following, the case of a TWTA is considered.

In this device, input signal modulates the speed of an electrons stream, in such a way to make an electron density variation to evolve according to an electron speed variation; the former translates back into a more-powerful electromagnetic signal before the electrons are collected at the electrode.

TWTA affects both signal amplitude and phase with non-linear distortions which can be modeled by means of an AM/AM conversion function and a AM/PM one, respectively.

A very widely spread way used for modeling these transfer characteristics is provided by means of the utilization of the distortion model proposed by Saleh, who introduced an approximation [5] with the following functions:

$$g(A) = \frac{\alpha_A A}{(1 + \beta_A A^2)}$$
$$\phi(A) = \frac{\alpha_A A^2}{(1 + \beta_A A^2)}$$

where $A$ is the magnitude of the input signal.

The $g(A)$ and $\phi(A)$ functions represent the normalized forms of the above mentioned AM/AM and AM/PM functions; they are shown in Fig. 2 and Fig. 3, where the following parameters have been chosen:

$\alpha_A = 2.2433$, $\beta_A = 1.2433$, $\alpha_\varphi = 2.0277$, $\beta_\varphi = 1.6201$. 
A very important parameter involved in the operative specifications of a satellite on-board power amplifier is the Output Back-Off (OBO), defined as in (5), where $P_{\text{sat}}$ is the maximum power the amplifier can provide (Saturation Power) and $P_o$ represents the actually level coming out of the amplifier.

The OBO plays a very important role in dimensioning a satellite telecommunications system: in fact, in order to exploit all the power available from a HPA, it is strongly recommended to have

$$OBO = 10 \log \frac{P_{\text{sat}}}{P_o}$$  \hspace{1cm} (5)$$

OBO as low as possible. On the other side, it is worth noting that very strong in-band as well as out-of-band interferences could arise from utilizing high levels of power – that is, very low level of OBO: in fact the non-linearity characterizing satellite amplifiers generate inter-modulation products both in the transmission and the adjacent bands, creating in-band interference as well as affecting frequency-adjacent transmissions.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{AM_PM_characteristic.pdf}
\caption{TWTA AM / PM characteristic}
\end{figure}

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\includegraphics[width=\textwidth]{AM_AM_characteristic.pdf}
\caption{TWTA AM / AM characteristic}
\end{figure}

\section{The Transmission System}

The reference scenario focuses on the simulation of the reception of a satellite broadcast signal taking the mobility of the user and the multipath-shadowing into account (e.g., a car equipped with an ad-hoc receiver moving along an urban environment).

The signal is transmitted by a terrestrial fixed transmitter Base Station which performs a D-QPSK | COFDM modulation in Ku-Band; a no-regenerative satellite operates a frequency-shift in such a way to convert the downlink stream into an L-Band one.

Finally, a Rice – Rayleigh channel models the hybrid downlink satellite / urban environment physical channel.

\subsection{The receiver}

The receiver equipment is mainly composed by a non-directional receiver antenna, an OFDM receiver, a Differential-QPSK (DQPSK) constellation symbol estimator, a soft-output QPSK demodulator and a soft-decision Viterbi decoder.

The OFDM receiver performs complementary operations of OFDM transmitter acting as a Digital Signal Processor (DSP) performing demodulation by means of a Fast Fourier Transform (FFT), as described in Section II.

The next block considered in the receiver chain (see Fig. 4) is the DQPSK Estimator, for which two different estimation functions have been in turn implemented: the Hard Estimator (HE) and the Soft Estimator (SE).

The HE performs an evaluation $\hat{u}_i(k) = e^{j\phi_i}$ of the sequence generated by DQPSK modulator by processing the output $z_i(k)$ streaming out from the OFDM receiver $z_i(k) = |z_i(k)|e^{j \phi_i}$ according to the following maximum likelihood phase decision rule:

$$\phi_i = \min_{m=-4,-3,...,3,4} \{ \phi_m \} \hspace{1cm} (6)$$

where $\phi_m = e^{jm\pi/4}$, $m=-4,3,...,3,4$ are phases of DQPSK constellations symbols.

In the second case, the SE is realized by means of the (complex) non-linear function described in (7),

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Receiver_processing_chain.pdf}
\caption{Receiver processing chain}
\end{figure}

$$\hat{u}_i(k) = \frac{\sum_{m=0}^{7} p_m e^{-(\text{Re}[z_i^{(k)}]c_m + \text{Im}[z_i^{(k)}]s_m)/\sigma}}{\sum_{m=0}^{7} e^{-(\text{Re}[z_i^{(k)}]c_m + \text{Im}[z_i^{(k)}]s_m)/\sigma}} \hspace{1cm} (7)$$

where $p_m = c_m + js_m = e^{j m\pi/4}$, $m=0,1,...,7$ are the DQPSK constellations symbols and $\sigma$ is a parameter controlling the softness of the decision, in such a way that the greater is $\sigma$, the softer is the decision [4]; in the following the value $\sigma = 0.007$ has been considered.

After a DQPSK / QPSK conversion, a soft-output QPSK demodulator converts the incoming data into a format suitable
to be processed by the soft-decision Viterbi decoder; that is, the demodulator converts the received data signal into a real signal by interlacing its imaginary and real parts, normalizing this real signal by dividing by its running standard deviation, multiplying by -1 and finally performing a 4-bit quantization of the normalized data.

The soft-decision Viterbi module decodes the input signal by performing two distinct actions: as a first step, it makes a 4-bit soft decision of encoded data generated by the convolutional encoder from the input signal; finally, the estimated sequence is decoded according to the trellis used by the convolutional encoder utilized on the transmitting side of the system.

B. Simulation design.

As discussed in Section IV, an over-dimensional amplification provides in-band interference; such a situation is responsible of in-band extra noise which demands for more transmitted power in order to be counteracted. We can measure such a surplus as the difference between the target $E_b/N_o$ in the case in which the effects of TWTA are taken into account and the $E_b/N_o$ in the case in which no distortions due to amplification are affecting the transmitted signal – that is, considering the case of an ideal linear amplification; in the following, we are denoting such a surplus as the $E_b/N_o$ Degradation ($E_b/N_o$ Degr). The target $E_b/N_o$ is defined as the requested target to achieve a BER equal to $10^{-4}$; it has been studied that such a BER defines the threshold of audibility for DAB services [9].

$$E_b / N_o \text{Degr}(OBO) = E_b / N_o (OBO) - E_b / N_o \text{lin} \bigg|_{\text{BER}=10^{-4}}$$ (8)

The higher is the amplification of the TWTA, the greater are the in-band distortions, the greater is the degradation experienced by the system; in order to solve the trade-off between an efficient utilization of the on-board power amplifier and the level of distortions arising from a high amplification, the Total Power Degradation (TPD) function [3] is introduced according to (9). Since the distortion level depends on the amplification, the TPD results to a function of OBO.

$$TPD(OBO) = OBO + E_b / N_o \text{Degr}(OBO)$$ (9)

By minimizing the TPD function, the optimum OBO is evaluated, that is the optimal output power is defined.

A further scope of the simulation is the evaluation of the robustness of the link while varying the conditions of the air channel; an evaluation of the necessary $E_b/N_o$ for different value of K will be drawn, in order to compare the availability of the service to be exploited in different environments characterized by different level of multipath.

Finally, some considerations about the reliability of the link according to different speeds for the mobile receivers are formulated.

In these two last analysis a comparison between the two above discussed DQPSK estimation scheme will be taken into account.

VI. SIMULATION RESULTS

1) Total Power Degradation Analysis: as shown in Fig. 5, if the amplifier working point moves away from the saturation power level of the amplifier (i.e. the OBO gets higher and higher), a lower level of $E_b/N_o$ surplus is needed to compensate for in-band extra - noise due to the inter-modulation products.

![Fig. 5 Eb/No Degradation vs OBO behavior.](image)

The trajectory of the TPD function - as depicted in Fig. 6 - shows that the optimal OBO minimizing the TPD is equal to 3.

![Fig. 6 The minimum for the trajectory of Total Power Degradation function is reached in correspondence of OBO = 3.](image)

i.e. the operating point is situated at about the middle of the amplifier power characteristic. Such an OBO ensures the lowest provision of extra – power in transmission while providing an efficient utilization of the on – board amplifier.

2) Channel Analysis: the results of the simulations have been carried out in the case of an optimized on-board amplification (i.e. considering an OBO equal to 3). Fig. 7 reports the results at the varying of the channel.

Since the audibility threshold is given by a BER equal to
$10^4$, an overall $E_b/N_0$ ranging from 10 up to 14 results to be sufficient to guarantee good performance as far as DAB provision is concerned even in environment affected by very strong multipath fading; moreover, since a transmitted power margin equal to six provide very small out-of-service link events [8], low levels of received power allows for keeping the quality of the transmission acceptable in good channel conditions even for $E_b/N_0$ target ranging from 4 to 8.

Fig. 7 also demonstrates that the SE works better than the HE does; in particular, in all the cases in which the link is not characterized by a very fading condition, it results to be the very best choice between the two considered estimation functions.

3) Doppler Analysis: as far as the evaluation of the Doppler effect is concerned, a set of different speeds allowed for the mobile receivers are taken into account (such as $v_a=3$ Km/h, $v_1=50$Km/h and higher). As soon as the mobile speed rises from $v_a$ up to $v_1$, a Maximum Doppler Frequency Shift ($F_d$) equal to 5 Hz and to 93 Hz are respectively considered. The diagram in Fig. 8 shows that in the range of $E_b/No$ up to 12, the Doppler degradations do not particularly affects the transmission. The SE has stronger Doppler effect counteracting properties with regards to the HE: in particular at pedestrian speed the SE method provides excellent performance at low level for $E_b/N_0$.

VII. CONCLUSION AND FUTURE WORKS

In this paper, the performance exploitable in the deployment of satellite oriented DAB Mode – III has been considered taking into account non-linear amplifier distortions and high-effective receiver scheme.

It has been shown that mobile users with no need for very equipped receivers can exploit such high quality audio service in urban environments at almost any usual speed. Very good performances also in critic deep shadowing conditions are possible with low level of received power by means of the implementation of Soft technique for the DQPSK Estimator.

Specifications for mobile receivers in urban environment for high audio service provision by satellite COFDM signals (DAB) as well specifications for the on-board power amplifier have also been carried out.

The next steps of the research will involve the analysis of a frequency-adjacent multi-user environment, in order to evaluate the performance when out-of-band interferences are considered.

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REFERENCES