SC-OFDM, a Low-Complexity Technique for High Performance Satellite Communications

Damien Castelain*, Cristina Ciochina-Duchesne† and Julien Guillet‡
Mitsubishi Electric R&D Centre Europe - 1 allée de Beaulieu – CS 10806 – 35708 Rennes Cedex 7, France

and

Fumihiro Hasegawa§
Mitsubishi Electric Information Technology R&D Center - Kamakura, Kanagawa 247-8501, Japan

Single-Carrier Orthogonal Frequency Division Multiplexing (SC-OFDM) is a transmission technique particularly suitable for satellite transmission due to its low envelope variations and to the advantages brought by its natural compatibility with zero roll-off. Moreover, low complexity per-carrier equalization is possible in the frequency domain. This paper proves the high performance of SC-OFDM transmission over satellite in different use cases and compares this performance with state of the art techniques such as DVB-SX transmission.

I. Introduction

IN the world of broadcasting, the past 20 years have been marked by the wide acceptance of the milestone standards in the family of Digital Video Broadcasting (DVB) that become the reference for transmission over terrestrial, cable and satellite communications. Development of DVB standards is conducted by an international industry-led consortium of around 250 broadcasters, manufacturers, network operators, software developers, regulatory bodies and others in over 35 countries, called the DVB Project. Firstly directed towards digital television, DVB standards now fix the framework of data, sound and multimedia broadcasting world-wide.

Among the variety of applications covered by the DVB standards, satellite transmission is one of the most representative fields. The DVB-S[1] system for digital satellite broadcasting (1993), based on Quaternary Phase Shift Keying (QPSK), is still used by many satellite broadcasters around the world for direct-to-home television services. The European analogue switch-off and the increasing spectrum scarcity issues triggered the development of a second generation satellite broadcasting standards DVB-S2[2] (2005) directed towards broadband satellite applications, including broadcast, interactive services, satellite news gathering (SNG), etc... The more spectrally efficient DVB-S2 offers increased capacity by using higher modulation orders (16 and 32 Amplitude Phase Shift Keying (APSK)), adaptive modulation and coding and a very powerful forward error correction (FEC). Designed constellations are transmitted over a classical Single Carrier/Time Division Multiplexing (SC-TDM) waveform with roll-offs 20%, 25% or 35%. DVB-S2 was rapidly adopted by the global satellite broadcasting and telecommunications industries, and is currently the most widely spread standard in the satellite market, targeting applications such as High Definition TV (HDTV) broadcasting, professional video distribution, cellular backhauling, military and government satellite communications, broadband VSAT (Very Small Aperture Terminal), etc...

Following the Commercial Requirements issued by its Commercial Module in October 2012, the DVB group started to work towards the post-DVB-S2 era in 2013. Two parallel initiatives were launched in the DVB-S2 group.[4] The first one aimed at the development of an evolution of the DVB-S2 specification, including fine-tuning the

* Chief Scientist, Communications Technology Division, d.castelain@fr.merce.mee.com. Not a Member.
† Research Engineer, Wireless Communications Systems, Communications Technology Division, c.ciochina@fr.merce.mee.com. Not a Member.
‡ Research Engineer, Wireless Communications Systems, Communications Technology Division, j.guillet@fr.merce.mee.com. Not a Member.
§ Researcher, Wireless Transmission System Group, Wireless Communication Technology Dept., Hasegawa.Fumihiro@bk.MitsubishiElectric.co.jp. Not a Member.

technical specification without fundamental changes to the complexity and structure of the current DVB-S2 standard. The result of this initiative is the newly emerged DVB-S2X specification, considered as an extension of DVB-S2 and published in March 2014 as a DVB bluebook.[3] It will be published by ETSI as the second part of the DVB-S2 specification[2] (ETSI EN 302 307 part 2, with DVB-S2 being part 1). DVB-S2X provides several additional technologies and features, such as higher order modulations (64, 128 and 256APSK) dimensioned for linear or non-linear channels, additional reduced roll-off (5% and 10%), finer modulation and coding granularity, very low SNR (signal to noise ratio) support enabling mobile (land, sea, air) applications, channel bonding and super-frame option. Since these improvements result in significant gains in capacity and flexibility of broadband interactive satellite networks, basically all relevant providers for professional satellite transmit and receive equipment announced their support for the new specification.[5]

The second initiative towards the post-DVB-S2 within the DVB group aimed at so called "green-field" satellite technologies[4] opening the way to disruptive technologies going beyond the boundaries of DVB-S2, such as new modulation and coding, new waveforms such as, e.g., faster than Nyquist[4,6] or Single-Carrier Orthogonal Frequency Division Multiplexing (SC-OFDM), new receiving algorithms for joint detection, decoding and equalization, interference mitigation, framing and pilot optimization. These next generation technologies are still under study and evaluation within the group.

In this paper, we concentrate on the performance of SC-OFDM, one of the proposed waveforms for future evolutions in satellite communications. This technique has been largely investigated in the past years and achieved maturity with its inclusion in recent standards. Under the name SC-FDMA (Frequency Domain Multiple Access), it is successfully implemented for the uplink of the Long Term Evolution (LTE) of UMTS (Universal Mobile Telecommunications System), issued by 3GPP (Third Generation Partnership Project) and already in commercial use since 2009. In the satellite world, SC-OFDM has been adopted as one of the waveforms for the satellite profile of DVB-NGH (New Generation Handheld)[7,8] since 2011, and acknowledged as a promising technique for future developments of DVB-RCS Return Channel Satellite. Moreover, the International Telecommunication Union-Radiocommunications sector (ITU-R) recently issued its Recommendations[9] for the satellite component of the IMT-Advanced radio interface(s) where both validated air interfaces rely on SC-FDMA-based waveforms.

The paper is organized as follows. After the analysis of the principles of SC-OFDM in Section II, Section III will review the system model and will set the framework of the comparison between SC-OFDM and the current DVB-S2/S2X waveform, SC-TDM. In depth performance assessment is conducted in Section IV, followed by conclusions drawn in Section V.

II. SC-OFDM for Satellite Communications

SC-FDMA waveform[10] has become very popular lately, especially since its adoption for the uplink air interface of 3GPP LTE and the recent attention it benefits from in the satellite world. In a 3GPP LTE context, SC-FDMA represents not only the uplink waveform but also the multiple access scheme, the users sharing the uplink channel in the frequency domain by being allocated different groups of localized subcarriers like in a classical Orthogonal Frequency Division Multiple Access (OFDMA) system. In systems where there is no user specific multiple access (e.g. DVB-NGH) SC-FDMA with full spectral allocation was called SC-OFDM in order to stress out the broadcasting aspect and clarify the fact that SC-FDMA is only used as a waveform, and not as a multiple access scheme. In the following, we will thus refer here to SC-OFDM waveform as the support of point-to point or point-to-multipoint transmission via satellite, in the forward (e.g. broadcasting) or the return (e.g. SNG contribution) link.

SC-OFDM can be easily implemented in the frequency domain under the form of discrete Fourier Transform (DFT)-precoded OFDM waveform, possibly with an appended cyclic prefix (CP), as depicted in Fig. 1.

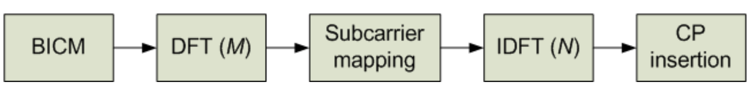


Figure 1. SC-OFDM waveform generation.

Bit interleaved coded modulation (BICM) symbols (e.g. X-APSK symbols) are grouped in blocks of M symbols and are precoded by an [MxM] DFT matrix. The M-sized output vector is then mapped onto M contiguous carriers represented by M out of N inputs of the inverse DFT. N-M guard subcarriers are inserted at band edges on the remaining inputs. After an N-point Inverse Discrete Fourier Transform (IDFT), an N_{CP}-length CP may be inserted. In systems where the transmitted signal experiences a multipath frequency selective channel, the role of the CP is to absorb the channel delays and thus eliminate the interference between successive SC-OFDM symbols. In satellite scenarios, where the channel is essentially line of sight with practically no frequency selectivity, the insertion of a CP is not mandatory.

Roll-off can optionally be easily implemented in the frequency domain, after DFT precoding, at subcarrier level by the means of low complexity frequency domain processing. Nevertheless, SC-OFDM is by its nature compatible with zero roll-off. When employed, the roll-off controls both the excess bandwidth and the envelope variations of a signal. While high roll-off values reduce the signal's peak to average power ratio (PAPR), they also increase the excess bandwidth, which penalizes the system's performance due to either frequency mask filtering issues, or to increased inter-channel interference in multiple channels per transponder scenarios. In these cases, the natural compatibility of SC-OFDM with zero roll-off is an advantage.

The major drawbacks of OFDM and of most of its precoded counterparts are the high PAPR and the sensitivity to phase noise. In the particular case of SC-OFDM, DFT precoding restores the low envelope variations of the resulting waveform. SC-OFDM has low single-carrier-like PAPR, variable on the function of the applied roll-off.[11] SC-OFDM has in fact the same PAPR as classical SC-TDM at the same roll-off. It also has similar robustness to phase noise as it will be shown hereinafter.

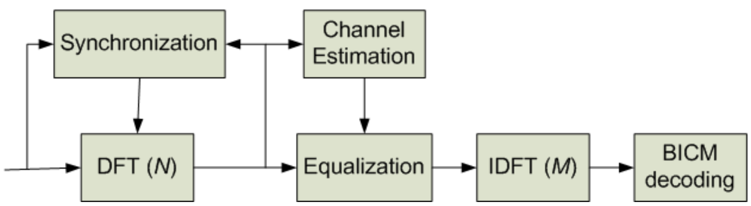


Figure 2. SC-OFDM receiver.

At the receiver side, SC-OFDM receiver, depicted in Fig. 2, performs low-complexity equalization in the frequency-domain at subcarrier level, allowing an important reduction of the number of required operations with respect to time-domain equalization.

Time-domain implementations of SC-OFDM are also possible both at the transmitter and receiver sides. Nevertheless, less complex frequency domain implementations are usually preferred in practice.

III. System Model

Let us consider transmission over a transparent satellite transponder as depicted in Fig. 3. At the ground transmitter (terrestrial gateway, SNG van, etc), a signal is generated incorporating modulation and coding (MODCOD) symbols representing the data to be transmitted, physical layer headers and possible pilot symbols.

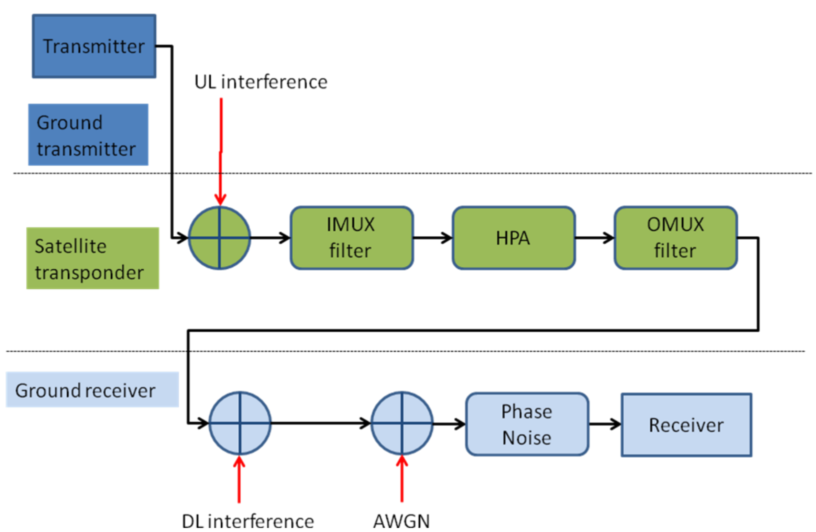


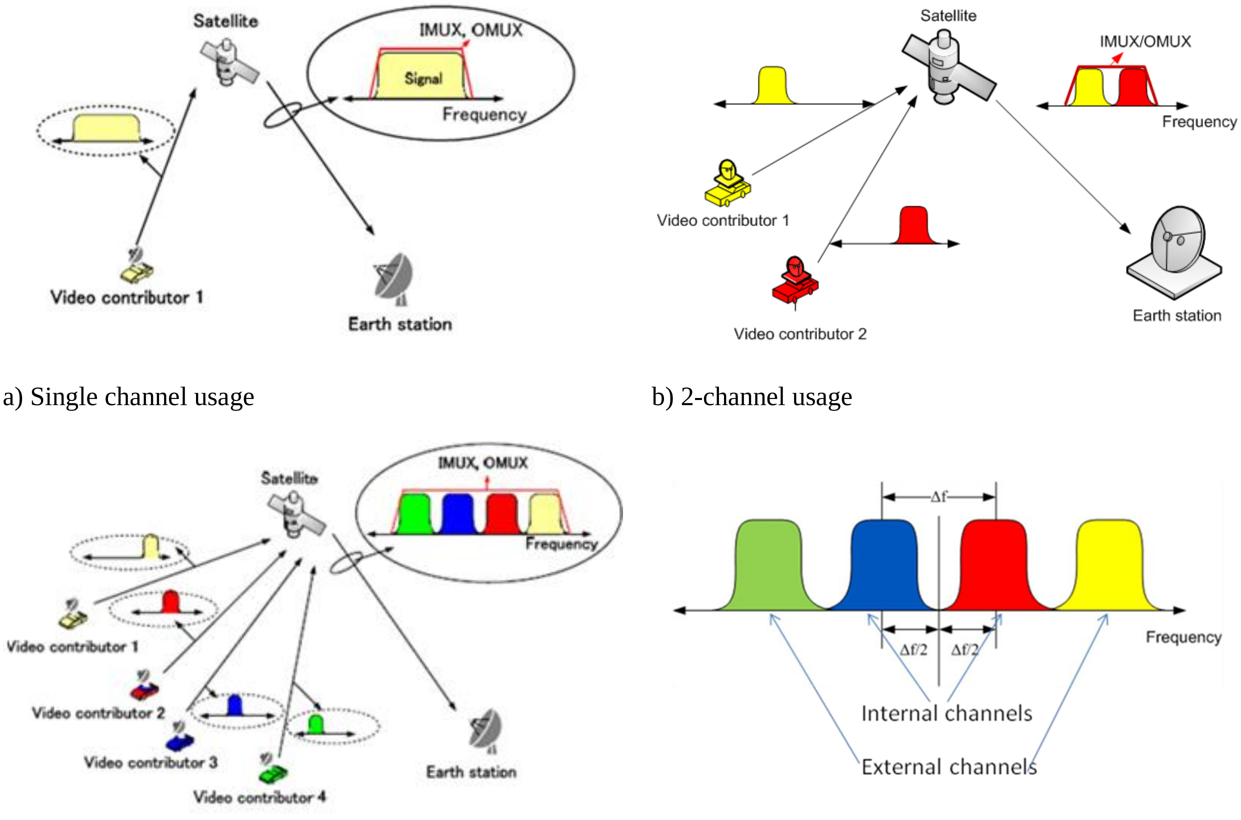
Figure 3. System model.

This signal modulated and framed either as described in the DVB-S2/S2X specifications[2,3] to obtain a SC-TDM transmitted signal, or as described in Fig. 1 to obtain a SC-OFDM signal. The signal is then transmitted onto the current carrier to the satellite transponder. Uplink (UL) interference is also modeled by simulating adjacent carrier transmission.

The transponder is composed of an input filter (IMUX) selecting the current carrier, a high power amplifier (HPA) representing the non-linearity on board of the satellite and an output filter (OMUX) who reduces the out-of-band emission due to the spectral regrowth after the HPA.

At the ground receiver, the useful signal is corrupted by adjacent downlink (DL) interferers, additive white Gaussian noise (AWGN) and phase noise. The receiver is either a time-domain SC-TDM receiver with fractional equalization or a SC-OFDM receiver with frequency domain per carrier equalization as the one depicted in Fig. 2.

We consider the professional use case scenario of video contribution and distribution. One or several video contributors share the same transponder, making either simple or multiple channel usage. The cases of one, two and four contributors are represented in Fig. 4 a), b) and c) respectively. Channel spacing is denoted Δf as in Fig. 4d).



a) Single channel usage b) 2-channel usage

c) 4-channel usage d) Channel spacing for multiple channel usage

Figure 4. Video contribution and distribution use case.

IV. Performance Evaluation

In order to compare the performance of SC-OFDM with the performance of the SC-TDM waveform used in DVB-S2/S2X, we will set a simulation framework corresponding to DVB-S2/S2X scenarios described in the ETSI EN 302 307 specification.[2,3]

A. Simulation Parameters and Methodology

The system model described in Section III is implemented with typical parameters drawn from the DVB-S2/S2X specification, as detailed in the following.

MODCODs are chosen among S2 and S2X MODCODs. Here, we employed QPSK4/5, 8PSK3/4, 16APSK3/4, 32APSK3/4, 64APSK132/180, 128APSK3/4 and 256APSK3/4, all with normal frame length (64800 low-density parity-check (LDPC) coded bits per codeword). We employed physical layer headers and framing parameters as in DVB-S2 for both SC-TDM and SC-OFDM. For SC-OFDM, we considered one single SC-OFDM symbol per frame and omitted the CP.

Simulations are performed both on a linear and a non-linear channel and consider a reference transceiver bandwidth of 38MHz. Carrier spacing is 40MHz. The linear channel is indicated in the following by the absence of a HPA (IMUX/OMUX filtering is existent). The non-linear channel employs a linearized travelling wave tube amplifier. IMUX/OMUX filter models and linearized HPA characteristics are extracted from the DVB-S2 specification.[2] For the phase noise (PN), we used the critical mask described in annex H.8 table H.4 of the DVB-S2X specification.[3]

At the receiver side, we consider ideal frequency synchronization. Time synchronization is genie-aided (based on correlation with the transmitted signal, ideally supposed as known). We employ linear minimum mean square error (MMSE) equalization using long term auto-correlation and cross-correlation coefficients computed through a genie-aided approach. The SC-TDM receiver employs a fractional time domain equalization implemented in the time domain with a N_{taps}=41 taps finite impulse response filter with an oversampling rate *ovs*=2. The SC-OFDM receiver employs a frequency domain equalizer with one coefficient per subcarrier. Phase noise estimation and correction is realistic, based only on Start of Frame sequence and pilot resources of S2 frame. We used a simple method reduced to a piecewise linear interpolation between reference resources.[12] For both waveforms, phase noise compensation is performed after equalization, at symbol rate.

Performance is evaluated as following.

In a first step, in non-linear channels, for each MODCOD we determine an optimum functioning point of the HPA. Let us define the input/output back-off (IBO/OBO) as the measured power ratio (in dB) between the input/output signal power and the HPA's saturation level. We test a large range of IBO values and for each such value we represent the MODCOD's performance under the form of packer error rate (PER) versus CSat/*N*, where CSat is the signal power at the output of the IMUX and *N* is the AWGN level at the input of the receiver measured in the reference bandwidth of 38MHz. CSat/*N* is thus representative of the signal-to-noise ratio (SNR) at the input of the receiver, plus a penalty caused by OBO and OMUX filtering. We choose the HPA optimum functioning point (corresponding to a couple (IBO_{opt}, OBO_{opt})) as the one maximizing the performance for a target PER=10^{-3}. Here, maximizing the performance means minimizing CSat/*N*. All following simulations for each MODCOD are considered as being performed at its optimal IBO_{opt}.

In a second step, modulation rate (R_s) (for all use cases) and channel spacing Δf (for multiple channel usage use cases) are optimized. This optimization is conducted separately for SC-TDM and SC-OFDM. For a same configuration the two waveforms may display different optimum (R_s, Δf) values. For each use case and for each waveform, optimization is conducted as following. For all MODCODs (at their respective IBO_{opt}) we test a range of different (R_s, Δf) values and we plot PER versus CSat/*N* performance. We identify the CSat/*N* values for a target PER=10^{-3} and the associated spectral efficiency and we plot, for each tested (R_s, Δf) couple, the variation of spectral efficiency (given by the different MODCODS) versus CSat/*N*. We choose the optimum $(R_s, \Delta f)_{opt}$ couple as the one overall maximizing the performance (i.e., minimizing CSat/*N* and maximizing the spectral efficiency). For multiple channel usage, simulation results show that, for all scenarios, the optimum carrier spacing Δf_{opt} equals the reference transponder bandwidth divided the number of used channels, i.e. Δf_{opt}=19MHz for 2-channel usage and Δf_{opt}=9.5MHz for 4-channel usage.

B. Performance Comparison

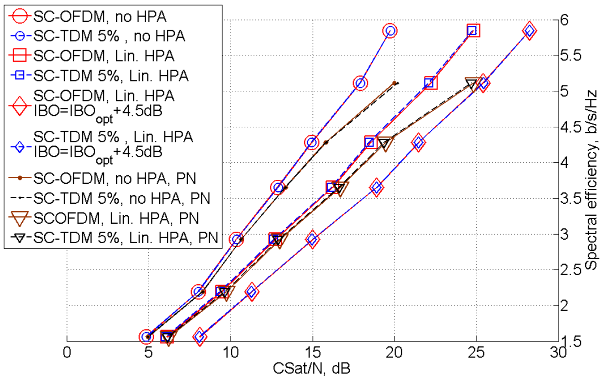
We have compared the performance of SC-TDM and SC-OFDM in various scenarios in terms of spectral efficiency versus CSat/*N*. The results of this comparison are depicted in Fig. 5 a)-f). Simulation results have shown that SC-TDM with higher roll-off factors (10%, 15%) is always outperformed by SC-TDM with 5% roll-off, and we thus decided to include only SC-TDM 5%. In the absence of phase noise, solid red curves and dotted blue curves represent the performance of SC-OFDM and SC-TDM 5% respectively, whereas round and square markers represent simulations over a linear and a nonlinear channel respectively. In the presence of phase noise, solid brown curves and dotted black curves represent the performance of SC-OFDM and SC-TDM 5% respectively, whereas dot and triangular markers represent simulations over a linear and a nonlinear channel respectively.

For a single channel usage, Fig. 5a) shows that SC-TDM 5% and SC-OFDM display almost equal performance, on linear and non-linear channels, operated at the optimum IBO_{opt} or at higher IBOs. The presence of phase noise degrades the performance of SC-TDM and SC-OFDM in a similar manner. The optimum modulation rate was found to be $R_{s\,opt}$=37 Mbauds for all simulated curves.

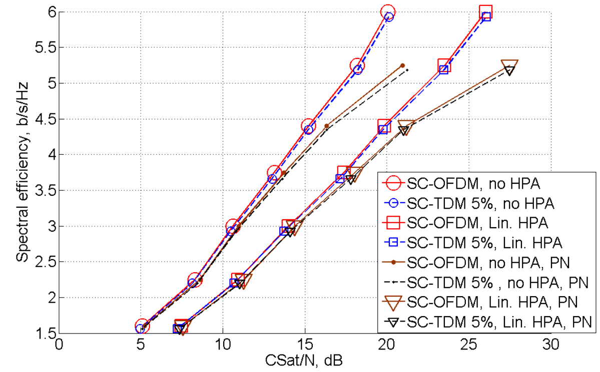
For a 2-channel usage, Fig. 4b) shows that SC-OFDM has a slight performance gain with respect to SC-TDM 5%. This gain is of around 0.2dB for high modulation orders (64APSK and higher), both in the presence or absence of PN. This difference is due mainly to the different inter-channel interference profile caused by the different roll-off values, SC-OFDM benefiting from the zero roll-off implementation. Here, Δf_{opt}=19MHz but optimum modulation rates differ for SC-OFDM ($R_{s\,opt}$=19 Mbauds) and SC-TDM ($R_{s\,opt}$=18,53Mbauds for 32APSK and lower, $R_{s\,opt}$=18,76Mbauds for 64APSK and higher).

For both single channel and 2-channel usage, the performance is highly degraded by the presence of the PN for both waveforms, especially for high modulation orders. For professional applications needing to employ such modulation orders it is recommended to use terminals with lower levels of PN, or to implement more effective PN correction methods than the basic methods employed in these simulations.

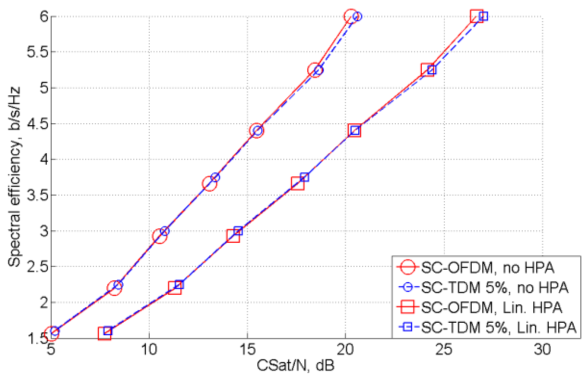
For a 4-channel usage, several configurations are possible (Fig. 5 c)-f)). We can anticipate from Fig. 4d) that inner and outer channels might have different behavior. Indeed, the interference profile caused by the presence of adjacent channels differs in function of the channel position in the transponder bandwidth.



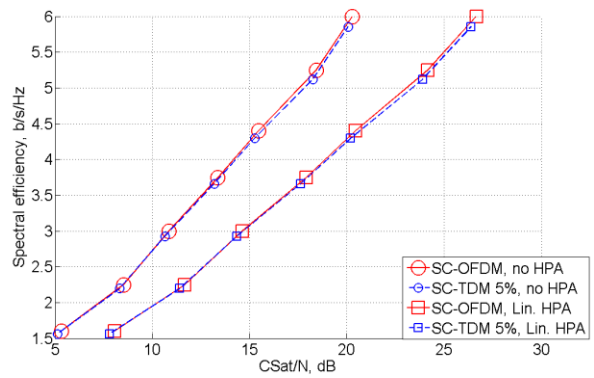
a) Single channel usage



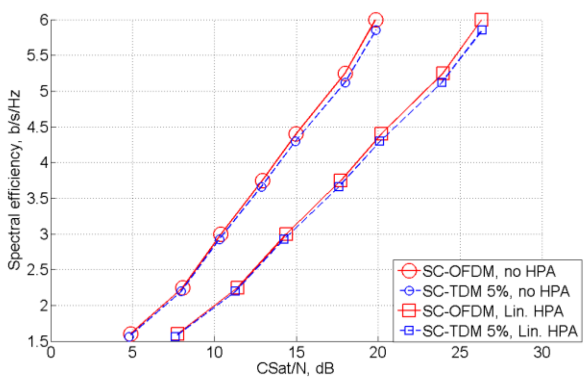
b) 2-channel usage



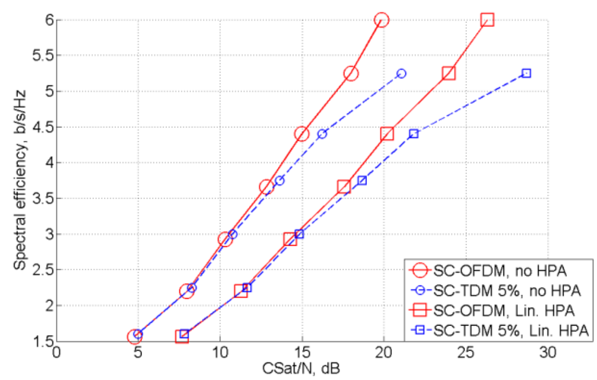
c) 4-channel usage: outer channels with optimized parameters



d) 4-channel usage: outer channels, parameters optimized for inner channels



e) 4-channel usage: inner channels with optimized parameters



f) 4-channel usage: inner channels, parameters optimized for outer channels

Figure 5. Performance comparison.

The inner channels are suffering from a more important inter-channel interference, whereas the outer channels have a similar situation to the 2-channel usage channels. For these reasons, inner and outer channels do not have the same optimum functioning parameters. Δf_{opt}=9.5MHz for all simulated cases. For outer channels, optimum modulation rates differ for SC-OFDM ($R_{s\ opt}$=9.26Mbauds for 32APSK and lower, $R_{s\ opt}$=9.5Mbauds for 64APSK and higher) and SC-TDM ($R_{s\ opt}$=9.5Mbauds). For inner channels, $R_{s\ opt}$=9.5Mbauds for SC-OFDM and

$R_{s\ opt}$=9.26Mbauds for SC-TDM. When computing these optimum parameters, we assumed that all channels sharing a same transponder use the same (R_s, Δf) values. Thus, parameters optimizing the functioning of outer channels are not necessarily optimal for the inner channels sharing the same transponder and vice-versa.

Fig. 4 c) and d) show the performance of the outer channels functioning with (R_s, Δf) values optimized for the outer and respectively inner channels. Conclusions are similar to those drawn for the 2-channel usage scenario, SC-OFDM displaying a gain is of around 0.2dB for high modulation orders.

Fig. 4 e) and f) show the performance of the inner channels functioning with (R_s, Δf) values optimized for the inner and respectively outer channels. More sensitive to inter-channel interference, inner channels show a better robustness of SC-OFDM to this type of interference. When the inner channels function with their own optimized parameters as displayed in Fig. 4 e), SC-OFDM displays an advantage of around 0.4dB over SC-TDM 5%. Even though this effect is more important at high modulation rate, a slight advantage is present for all MODCODs. When the inner channels function with suboptimal parameters (computed for an optimal functioning of the outer channels) as displayed in Fig. 4 f), performance of SC-TDM is highly degraded, especially for high order modulations.

C. Complexity Issues

Let us compare the complexity of the SC-OFDM frequency domain receiver with the complexity of the SC-TDM current state of the art receiver. The only difference is given by the different structure of the equalizer, all other modules (synchronization, BICM decoding, etc.) being in all points identical.

For implementing a frequency-domain SC-OFDM receiver, the main complexity impact is given by the presence of a DFT and an IDFT module. For a transmission of M active subcarriers over a total of N existing subcarriers, the DFT/IDFT modules execute $M/2\cdot\log_2(M)+N/2\cdot\log_2(N)$ complex multiplications. Moreover, the frequency domain equalizer by itself corresponds to one multiplication per data carrier. Thus the frequency domain equalizer executes $(M/2\cdot\log_2(M)+N/2\cdot\log_2(N)+M)/M$ complex multiplications for each modulation symbol.

For the time domain implementation of SC-TDM receiver, there is no DFT/IDFT module, but the fractional equalizer executes $N_{\text{taps}}\cdot ovs$ complex multiplications.

For SC-OFDM we assume that the IDFT size N is around 10% higher than the number of active carriers M and that for hardware implementation reasons N is also a multiple of 2, 3 and 5. With the parameters used in this paper, we can compute an average number of complex multiplications per modulation symbol ranging from 16.81 for QPSK to 14.7 for 256APSK[**]. In implementations with several SC-OFDM symbols per frame, the DFT/IDFT size decreases and thus the complexity also decreases.

For SC-TDM with a 42 taps filter applied on the 2-times oversampled signal, 82 complex multiplications are needed for each modulation symbol, which indicates a complexity of the equalizer 5 to 6 times higher than for SC-OFDM.

V. Conclusion

This paper introduces the use of SC-OFDM (SC-FDMA with full allocation) in a satellite transmission context. Simulation results prove the high performance of SC-OFDM transmission over satellite single and multiple-channel per carrier professional use cases, in the presence and in the absence of phase noise. This performance is compared to state of the art techniques such as DVB-SX transmission and it is proven that SC-OFDM displays slightly better performance but also higher robustness and much lower complexity than SC-TDM 5%, the best performing DVB-SX waveform.

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[**] QPSK: 16.81; 16APSK: 15.76; 32APSK: 15.4208; 64APSK: 15.14; 128APSK: 14.87; 128APSK: 14.70 complex multiplications

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