Distribution of OFDM radio signals over optical fiber

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Abstract – In this paper, we will study, via simulation, several transmission schemes of OFDM radio signals over optical fiber, in order to evaluate their main advantages and limitations. We will start by studying the transmission of 2 OFDM channels at 8GHz and 60GHz, consideringseveral types of optical modulation: Double Sideband (DSB), Vestigial Sideband (VSB) and Double Sideband-Carrier Suppressed (DSB-CS). Then, we will proceed to assess the transmission of a few OFDM channels, generated according to the standards MB-OFDM UWB (ECMA-368) and 60GHz WPAN (ECMA-387).

I. INTRODUCTION

In the last decades, there has been a constant evolution of wireless systems, with the emergence of new communications standards such as 3G, 4G, WiMax, etc. The transmission of such signals over fiber can bring many benefits, due to the fiber's high bandwidth, low attenuation and immunity to electromagnetic interference. The transmission of RF signals over optical fiber can be made at its original frequency, reducing complexity at the transmitter and receiver.

This article aims to compare several optical modulation scenarios for the distribution of OFDM signals, in the microwave and mm-wave frequency bands, using the software VPI Transmission Maker. OFDM is one of the most commonly used modulation formats in wireless systems that require high transmission rates, due to its multi-carrier nature, which makes it robust to multi-path effects. This type of modulation is used in WLAN systems (e.g. WiFi), WMAN (e.g. WiMax), WPAN (e.g. MB-OFDM UWB), mobile communication systems (e.g. 3GPP LTE) and digital video broadcasting (e.g. DVB-T, T-DMB, ISDB-T, DVB-H).

We also analysethe transmission of multiple channels modeled according to the standards MB-OFDM UWB (ECMA-368) and 60GHz WPAN (ECMA-387). These standards were developed for WPAN applications with high bandwidth and transmission rates, which can be in the hundreds of Mbps on the ECMA-368 standard, and in a few Gbps on the ECMA-387 standard.

II. OFDM SIGNALS' TRANSMISSION

A. GENERATION OF THE OFDM CHANNELS

To create the 2 OFDM channels at 8 and 60GHz, westarted by generating 2 OFDM channels at the intermediate frequency of 1GHz, and then up-convert them using 2 oscillators at the frequencies of 8 and 60GHz (see Fig 1). The OFDM channels, with bitrate of 1Gbps, are composed by 16 subcarriers, occupying 295MHz bandwidth, modulated using 16QAM. At the input of the optical modulator (point A in Figure 1), we obtain two channels in electrical DSB, with the carriers at 8 and 60GHz, and side bands at, 7 and 9GHz, and 59 and 61GHz. This transmission scheme was chosen in order to enable the comparison of the configurations studied below, since there are some limitations in the simulator modules. The OFDM signal generator and analyzer, require the same frequency in order to operate correctly, so it wouldn't be possible to use them in the DSB-CS configuration,without the use of an intermediate frequency, because as we will see in D, the carrier suppression generates frequency duplication at the optical-to-electrical conversion.

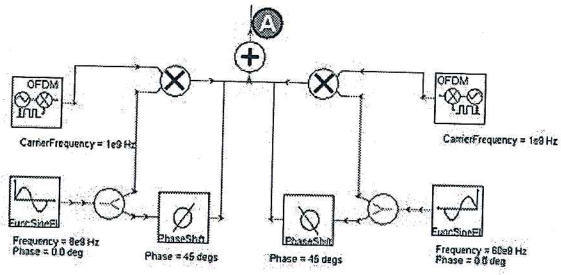

Figure 1–Generation of the channels at 8 and 60GHz.

B. OPTICAL DSB CONFIGURATION

The channels generated in II, go through a driver block, which varies the amplitude and bias of the RF signal. The signal was biased at the MZM quadrature point, to obtain optical amplitude modulation. By varying the amplitude of the signal, we also vary its power and modulation index at the MZM output. The amplitude modulation will generate a DSB optical spectrum on the output of the MZM. The MZM used in the simulations is a normalized MZM, with input values between 0 and 1. The laser diode has an average power of 0dBm, 10MHz linewidth, and an emission frequency of 193.1THz.

The optical fiber used is a standard SMF, with dispersion of 17ps/nm/km, at the laser's wavelength, with a slope of $0.08ps/nm^2/km$ and attenuation 0.2dB/km. At the receiver we use a PIN with responsivity of 1A/W, thermal noise of $1\times10^{-11}A/\sqrt{Hz}$ and without bandwidth limitations. After the optical-to-electrical conversion at the PIN, both channels are filtered and down-converted to the IF frequency, and the OFDM analyzer measures their EVM.

The optical transmitter and receiver are illustrated in Figure 2 and 3.

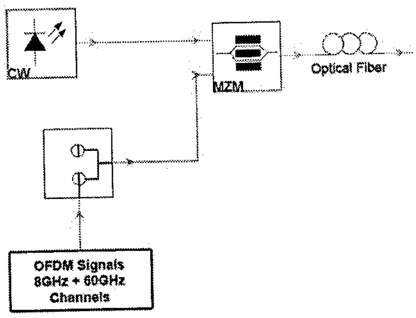

Figure 2 –Optical modulation.

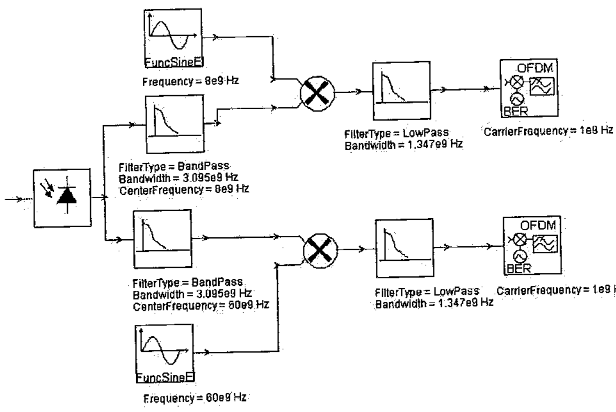

Figure 3 – Receiver.

In order to calculate an optimal value for the amplitude of the RF signal at the MZM input, we fixedthe fiber length, and changing the amplitude, we observe the minimum EVM value at receiver. This optimization was done, since for high amplitude values of the RF modulating signal, the distortion at the MZM output is high, because of its nonlinear response, while, for low values, the optical power of the channels at the MZM output is low. For 5km of fiber, we obtained a mean value of amplitude of 0.1Vpp. In Figure 4 and 5, we can see the values of EVM, for both channels, versus the length of the optical fiber. We also present the limit value of EVM forthe ECMA-368 standard [1], so we can make a better comparison between the configurations.

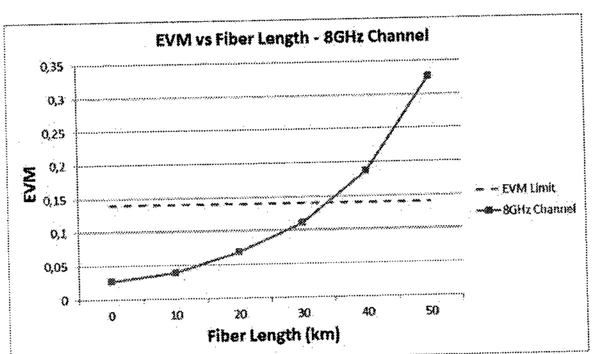

Figure 4 – EVM of the channel at 8GHz vs.Fiber length.

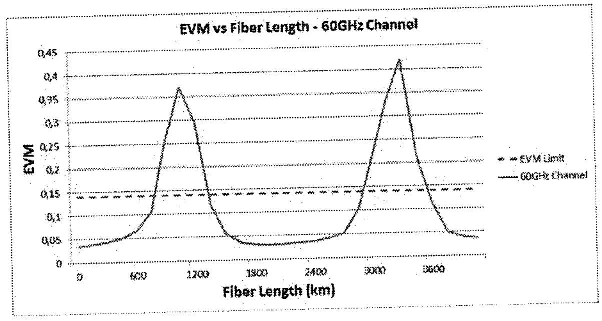

Figure 5 – EVM of the channel at 60GHz vs.Fiber length.

The optical transmission in DSB, introduces some problems in the signal optical-to-electrical conversion at the PIN, due to the phase shift between the two optical sidebands, causing a loss of RF power in the received electrical signal. This power loss, called fading, has minima, with period dependent of the sidebands spacing and chromatic dispersion, being problematic for transmission of signals at high frequencies. For signals at 60GHz, using SMF fiber with dispersion of 17ps/nm/km, we get the first minimum at about 1km, while for signals at 8GHz this value increases to 61km. By using fiber with a lower dispersion parameter, e.g. 2.7ps/nm/km, we can increase the minimum of the channel at 60GHz to about 6km.

In fig.5, we can see the effect of fading on the reception quality of the channel at 60GHz, limiting the maximum distance to less than 1km, while the channel at 8GHz has a maximum distance of 34km. Suppressing one of the sidebands of the DSB spectrum, i.e. transmitting the optical signal in VSB, we can eliminate the fading effect. Another different method is to suppress the optical carrier [2].

C. *OPTICAL VSB CONFIGURATION*

In this configuration, we used an optical filter, after the MZM, in order to suppress the lower sideband of the DSB spectrum (see Fig.6). Thus, we eliminate the fading effect, at the cost of having a reduction of RF power at the receiver, due to the referred sideband suppression. The reception scheme is identical to the previous one.

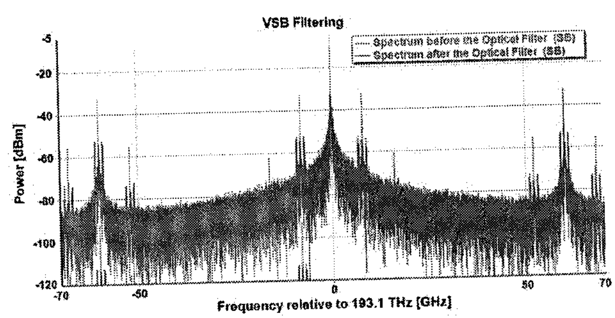

Figure 6 – Optical DSB and VSB spectra.

In Fig. 7, we can observethe results using a meanvalue of amplitude of 0.2Vpp forthe modulating RF signal (obtained by optimization at 10km of fiber). We can see that the fading effect on the channel at 60GHz disappeared, thus, obtaining a big improvement in this channel. The maximum distance of the channel at 8GHz also increased, as in the previous case the first fading minimum was around 61km, despite having a worst performance in the first kilometers.

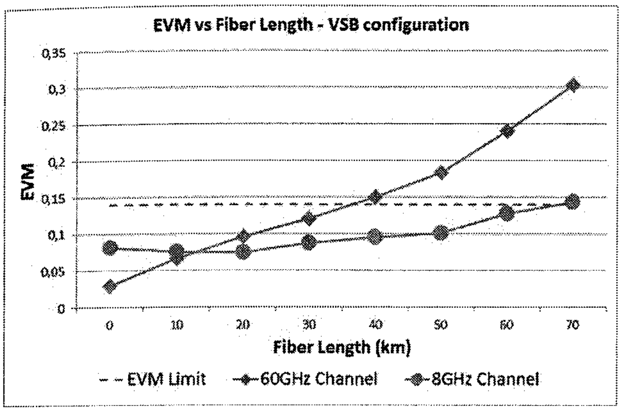

Figure 7 – EVM of both channels vs.Fiber length.

D. *OPTICAL DSB-CS CONFIGURATION*

In this configuration, we suppressed the optical carrier, after the MZM (see Fig.8 and 9). Due to the suppression of the optical carrier, at the receiver, a large number of spectral components will show up at the PIN output, from the different beatings between the different components at its input. Thus, the channel frequency will be duplicated, and because of this, we send the channels, at the transmitter, at 4 and 30GHz, in order to receive them at 8 and 60GHz, as intended.

A major problem of this configuration is that doubling the frequency would also affect the OFDM channel, doubling its bandwidth, thus making this configuration undesirable. Because of this problem, we sent the electrical carriers to serve as a reference value in the PIN, i.e. they are sent with over 10dB of power than one of the sidebands of the DSB electrical spectrum, in order to receive, at the PIN, the beatings between the carriers and OFDM channels, while the beatings between OFDM channels would have a much lower power.

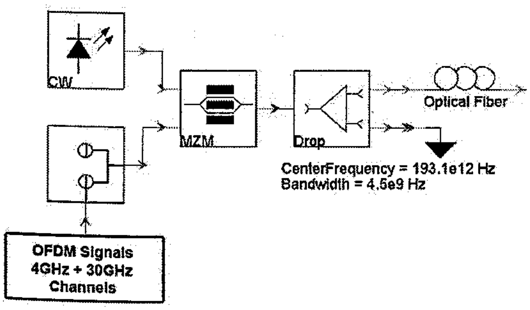

Figure 8 –DSB-CS transmitter.

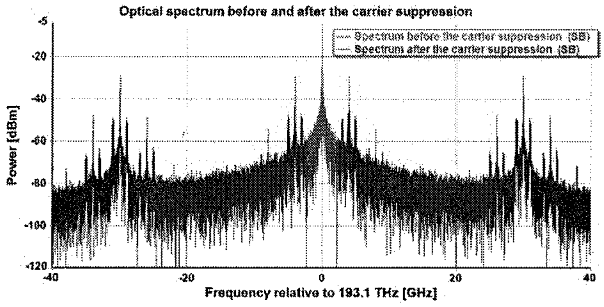

Figure 9 – Optical spectra before and after the optical carrier suppression.

Using now a mean value of amplitude of 0.25Vpp (value obtained by optimization at 10km) in the modulating signal, we can observe the following results for both channels (Fig. 10). The channel at 8GHz shows a better behavior, while the channel at 60GHz shows a high increase in its EVM after 30km.

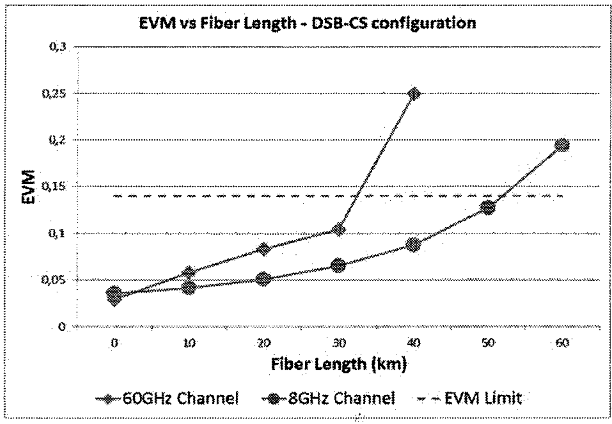

Figure 10 – EVM of both channels vs.Fiber length.

We may also use other transmitter as an alternative, in order to avoid the use of the narrow optical filter, using 2 MZM instead (see Fig.11). This configuration is explained in more detail in [3]. We can see in Fig.12 that the results obtained with this configuration, using the mean value of 0.2Vpp in the amplitude of the modulating the RF signal, are very similar to the ones of the configuration using the optical filter, with the exception of the slight EVM degradation in the channel at 8GHz, due to the worst suppression of the optical carrier.

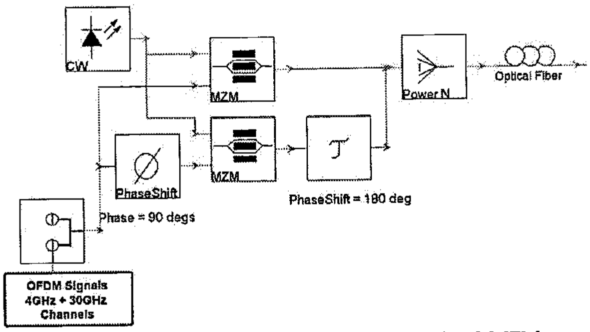

Figure 11 – DSB-CS transmitter using 2 MZM.

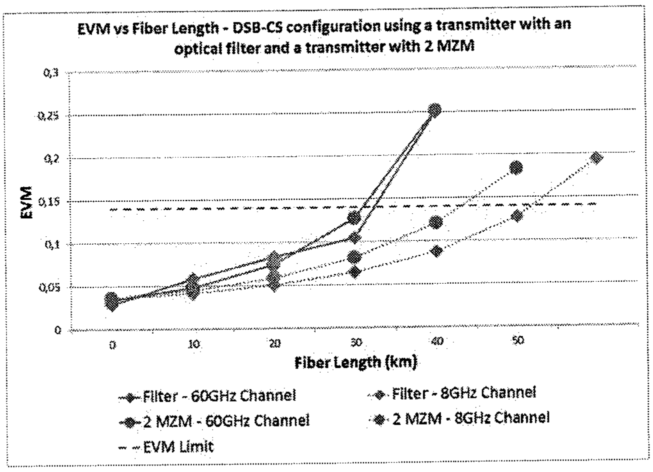

Figure 12 – EVM of both channels vs.fiber length, for both transmitters.

E. CONFIGURATIONSCOMPARISON

We begin by pointing out that the DSB-CS configuration has the great disadvantage of requiring the transmission of the electrical carrier, with higher power than the OFDM channels, which is very problematicdue to the RF power limitations at the optical modulator input. In the VSB and DSB configurations, this procedure is not necessary. However, the DSB-CS configuration has the advantages of reducing the complexity in the generation of the RF signals, because we send the channels at half the frequency, reducing also the bandwidth requirements at the transmitter's components.

When chromatic dispersion doesn't limit the performance of the system, the DSB configuration is the best option, due to its simplicity as well as having the advantage, compared to the VSB and DSB-SC configurations, of receiving greater RF power in the optical-to-electrical conversion, since in the VSB case, one of the bands is suppressed, while in the DSB-CS case, the energy received in the PIN's input is divided fora large number of spectral components. For RF frequencies of a few GHz, it can still be used for a few tens of kilometers, and we can increase this distance using optical fiber with lower dispersion e.g. a dispersion parameter of 2.7ps/km/nm allows the transmission of signals at 60GHz for about 6km, so it may be a good solution in the transmission of mm-waves signals on short-distance communications, like in access networks. In terms of optical bandwidth, it will be nearly 2 times greater than forthe VSB and DSB-SC configurations, which may be relevant in DWDM systems, e.g. forthe transmission of RF signals at 60GHz it wouldn't allow the use of the 100GHz window.

Next, we will compare the performance of the optical transmission, VSB and DSB-SC, in terms of their sensitivity to the attenuation and dispersion of the fiber. In Fig.13, we can see the performance of both configurations, when optical fiber affected only by attenuation is used, i.e. there's no dispersion. We observed that the VSB configuration has a better performance: although the channels have a lower optical power at the PIN input, because in the DSB-CS configuration we send more RF power (the average amplitude of the modulating signal is 0.25Vpp instead of 0.2Vpp of the VSB configuration). This happens because of the high number of spectral components generated at the PIN, in the DSB-CS configuration, which reduces the RF power of the desired channel.

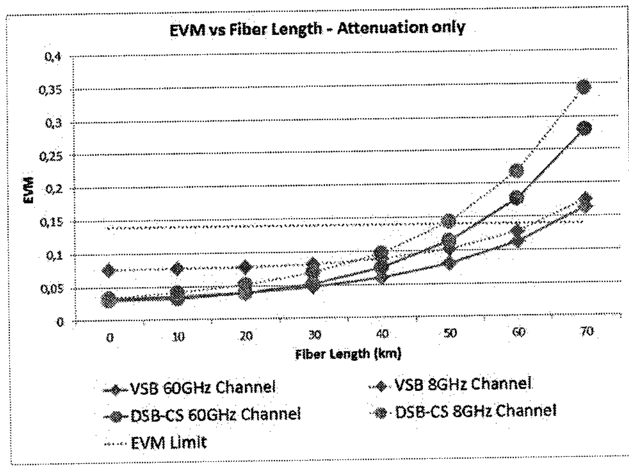

Figure 13 – EVM of the VSB and DSB-CS configurations, using optical fiber only affected by attenuation.

Next, we can see, in Fig.14, the results obtained when using optical fiber only affected by dispersion of 17ps/nm/km at the laser's wavelength. The increase in the EVM, of the channel at 8GHz, with the distance, is relatively small compared with the increase of the channel at 60GHz. This happens because of the lower frequency of the channel at 8GHz, thus it's less affected by chromatic dispersion. The channel at 60GHz, in the DSB-CS configuration, presents a better behavior than in the VSB case, since the signal is sent over the optical fiber at half of the final frequency. After 30km, there's a sudden increase of the EVM, in the DSB-CS configuration, due to the phase shift between the two sidebands of the electrical signal, which originates, in the PIN, a loss of power in the 60GHz channel. In Fig.15, we see this effect in one of the electrical sidebands of the channel at 8GHz, for 2 different values of IF frequencies (using optical fiber only affected by chromatic dispersion). We can see, that for 30GHz (with a 1GHz IF),the decrease in the received power of one of the electrical sidebands, starts to be relevant, causing this sudden increase of EVM, observed in fig.14.

In terms of performance, the transmission of OFDM channels at 60GHz, in VSB, seems to be the best option. In this setting, we don't need to send the electrical carrier that will work as a reference value in the PIN, providing greater power of the OFDM channels to the optical modulator's input. In the DSB-CS configuration, the high number of spectral components,which appear at the optical-to-electrical conversion, makes it more sensitive to the fiber's attenuation. However, the transmission in DSB-CS, is less sensitive to the dispersion effects of the fiber, that may become useful in systems limited by this factor. The multiplication in the RF signal frequency can also be seen as a benefit, allowing the use of oscillators at lower frequencies, which reduces the bandwidth requirements of the transmitter's components.

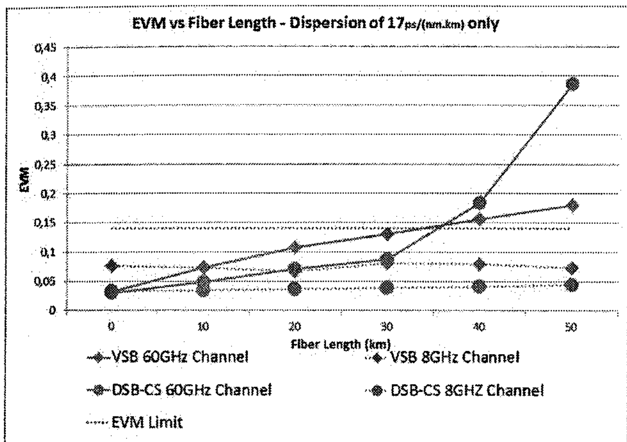

Figure 14 – EVM of the VSB and DSB-CS configurations, using optical fiber only affected by dispersion.

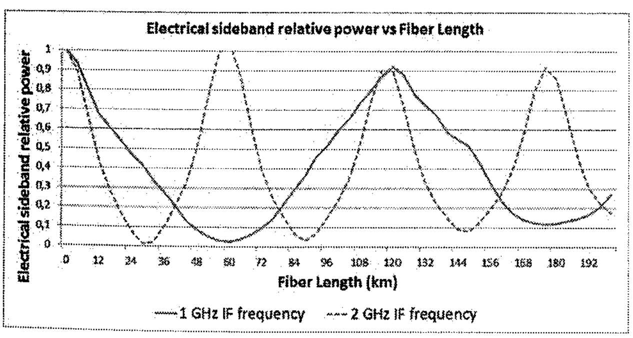

Figure 15 – Power of one of the electrical sidebands vs.Fiber length, using fiber only affected by dispersion.

F. *OPTICAL FREQUENCY MULTIPLICATION*

In this section we will use OFM at the transmitter, multiplying the frequency, of the generated electrical signals, by two. This method reduces the bandwidth requirements of some components in the transmitter, which for very high frequencies, e.g. in the mm-wave band, can be very useful.

To obtain this duplication, in frequency, at the transmitter, we will operate the MZM in a nonlinear regime, biasing the modulating signal at Vπ, which will maximize the second-order distortion components, and minimize the first-order ones (see Fig.16).

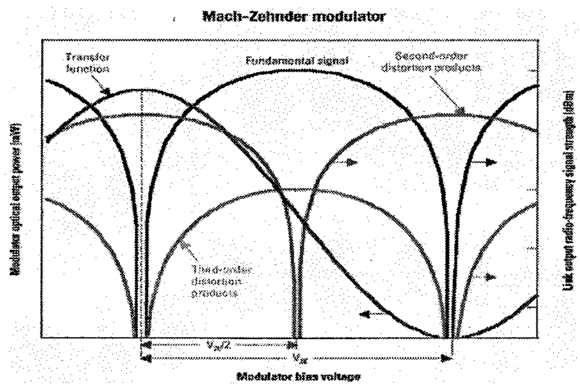

Figure 16 – MZM waveforms [3].

In this section, we will only transmit the channel at 60GHz, which will be generated at 30GHz. The multiplication that happens at the MZM, would also affect the OFDM channel, doubling its bandwidth, as was observed in the optical-electrical conversion of the DSB-CS configuration. Therefore, these settings also require that we send a reference value, which in this case is the 60GHz carrier. In Fig.17, we can see the results, with and without OFM, for the DSB configuration, using fiber dispersion of 2.7ps/nm/km. In Fig.18, the results for the VSB configuration, and finally, in Fig.19 the results for the DSB-CS configuration, which in this case produced a frequencyquadruplication, so the channel was generated at 15GHz.

In our simulations we obtained positive results regarding the use of OFM in RoF systems, since the behavior of the curves of EVM for the situations with and without OFM, are very similar. Of course, the OFDM channel is being transmitted in electrical DSB, so that the multiplication in the MZM doesn't modify it. Without OFM, in the DSB and VSB settings, we can send the channel directly, aswe'll do in the next study.

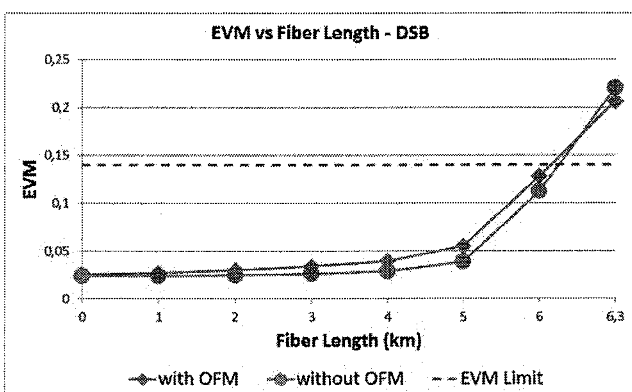

Figure 17 – EVM of the DSB configuration, with and without OFM, using optical fiber with dispersion of 2.7ps/nm/km.

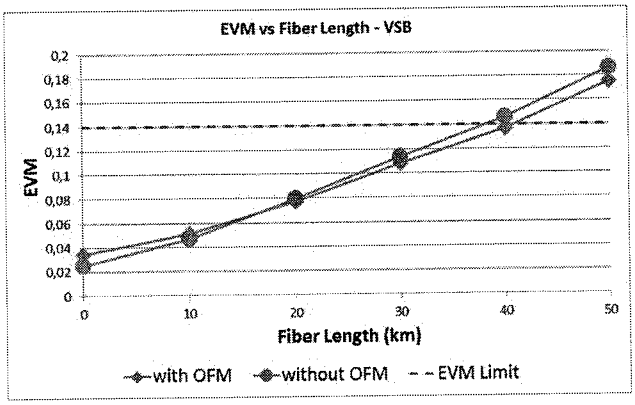

Figure 18 – EVM of the VSB configuration, with and without OFM, using optical fiber with dispersion of 17ps/nm/km.

III. TRANSMISSION OF ECMA-368 AND ECMA-387 SIGNALS

The WiMedia MB-OFDM (ECMA-368) standard allows transmissions in the 3.1-10.6GHz band, which is divided into 14 channels of 528MHz (see fig.20). Each channel is composed by 122 subcarriers, which can be modulated QPSK or DCM, depending on the bitrate[1]. In our scenario, we consider the transmission of 5 consecutive channels, measuring the EVM of the middle channel with center frequency of 5.544GHz. In this section, the channels are generated directly to the final frequency without frequency up-conversion, since we will not use the DSB-CS this time. In fig.20 and 21, we can see the channels, and the transmitter and receiver used in the simulations (in the DSB case). The OFDM channels used in the simulation have a bitrate of 500Mbps and 128 subcarriers, QPSK modulated.

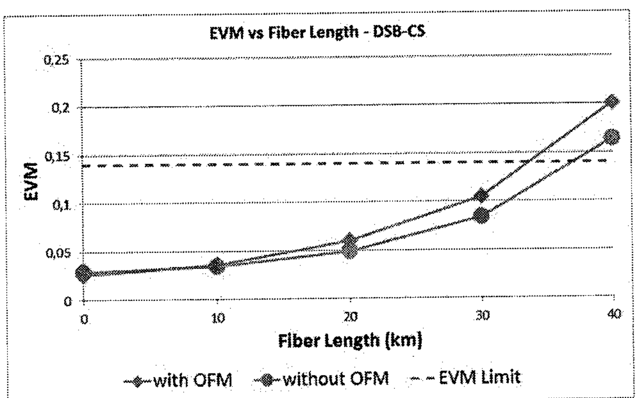

Figure 19 – EVM of the DSB-CS configuration, with and without OFM, using optical fiber with dispersion of 17ps/nm/km.

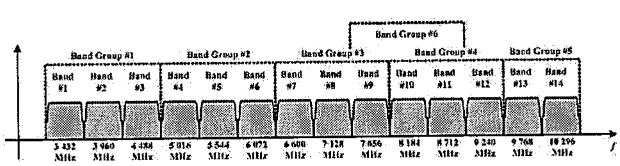

Figure20 –ECMA-368 channels[1].

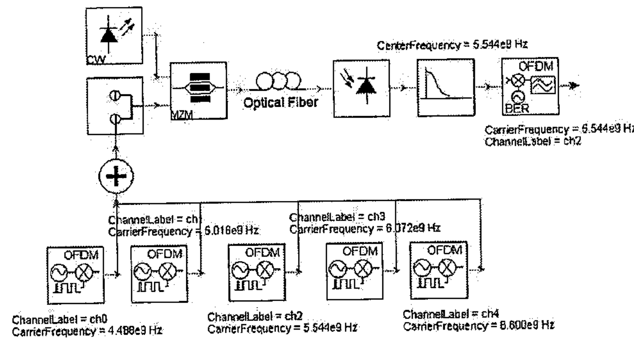

Figure 21 – ECMA-368 transmission system.

Next, in Fig.22, we can see the results for both the configurations studied. The VSB configuration is done using an optical filter.

We can observe in that figure that the VSB transmission shows better results for fiber lengths above 35km, as the transmission of DSB is affected by fading in the PIN. A sinusoid of 5.544GHz, transmitted over fiber with dispersion of 17ps/nm/km at 1550nm, would have the first fading minimum at 124km, so we have a quick increase of EVM when approaching this value. For a sinusoid of 10.296GHz, corresponding to the center frequency of the last channel of the standard, in the same situations, we would have the first minimum at 35km, degrading the performance of this channel.

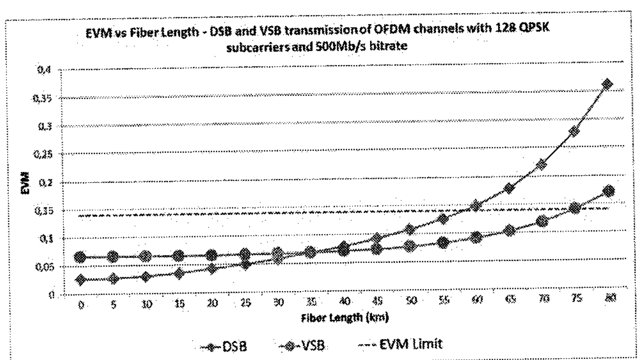

Figure 22 – EVM of both configurations, using optical fiber with dispersion of 17ps/nm/km.

The ECMA-387 standard, used for 60GHz WPAN applications, defines four channels with separation of 2.160GHz, in the 57-66GHz frequency band[4], as we see in the following figure.

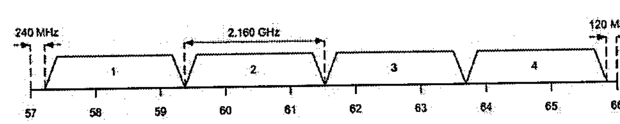

Figure 23 – ECMA-387channels[4].

The channels are defined by many operating modes. The OFDM modes are composed by a total of 512 subcarriers, which can be modulated according to one of the following constellations - QPSK, 16QAM, QPSK-UEP, UEP-

16QAM - depending on the mode of operation. Transmission rates can range from 1.008Gbps to 4.032Gbps [4]. In our scheme, we will send the four OFDM channels, centered in accordance with the standard (58.320GHz, 60.480GHz, and 62.640GHz 64.800GHz) with a transmission rate of 4 Gbps each, and a total of 512 subcarriers modulated 16QAM. The second channel is analyzed at the receiver.

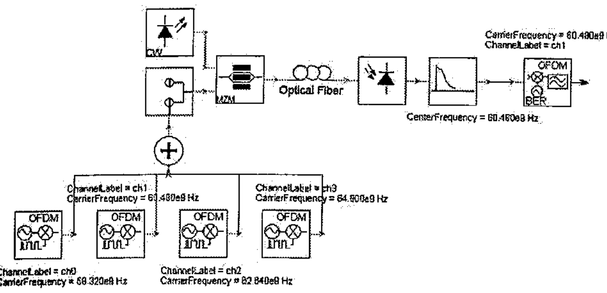

Figure 24 –ECMA-387 transmission system.

Below, we can see the results for both configurations. The limit of EVM, that we considered this time, was 11%, corresponding to the permissible EVM, in an ECMA-387 receiver, of the operating modes using a 16 QAM constellation with code rate of 2/3. In the DSB case, we can see the EVM peak again, as expected. Using fiber with dispersion of 17ps/nm/km this peak would be located at approximately 1km. The chromatic dispersion also becomes the limiting factor in the VSB transmission, obtaining a major improvement in the distance when using fiber with a lower value.

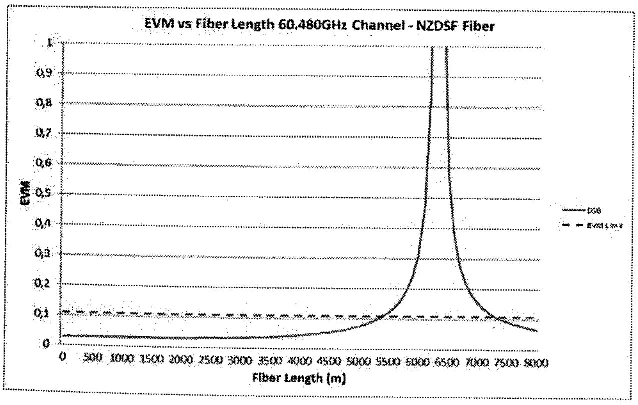

Figure 25 – EVM of the DSB configuration, using fiber with dispersion of 2.7ps/nm/km.

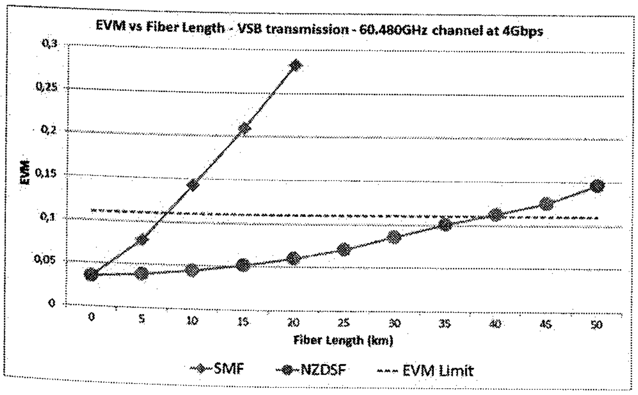

Figure 26 – EVM of the VSB configuration, using SMF with dispersion of 17ps/nm/kmand NZDSF with dispersion of 2.7ps/nm/km.

If we want to send signals of both standards on the same fiber, the approach, that seems to bring more advantages, would be to transmit the ECMA-368 channels in DSB and the ECMA-387 channels in VSB, reducing the complexity of the optical filter. The advantage of the VSB in ECMA-368 is only visible for distances greater than the possible distance for the ECMA-387 channels, so there's not a big benefit in sending all the channels in VSB.

IV. CONCLUSIONS

This article evaluates some scenarios for the transmission of OFDM signals over optical fiber. We saw that the transmission in DSB has the big problem of being very sensitive to chromatic dispersion in IM/DD systems, due to the fading effect that occurs in the optical-to-electrical conversion. However, it's the simplest and cheapest configuration, and should be used whenever possible. When the RF frequencies are very high, we can resort to using fiber with smaller dispersion in order to increase the possible distance.

When the problem of fading becomes critical, then we can resort to the suppression of one of the optical sidebands or, also, the suppression of the optical carrier. By removing the carrier, which generates duplication in the frequency of the spectral components that show up at the optical-to-electrical conversion, we are also directly affecting the OFDM channel, which must be avoided at all costs. A solution proposed, was to send the electrical carriers in order to serve as a reference value in the PIN. However, this limits the RF power that we can have on the optical modulation. The transmission of the channel at half the frequency is an advantage in terms of fiber dispersion, also reducing the requirements of bandwidth in the transmitter's components.

The VSB transmission becomes a good option for systems that require the transmission of high frequency signals for long distances.

We also observed that using OFM can be advantageous, although it also requires a reference component in the MZM, so the OFDM channel wouldn't be affected during the optical modulation, while operating the MZM in a non-linear regime.

In the transmission of multiple ECMA-368 channels, we could see that it can be done in DSB and VSB with positive results. The VSB transmission allows greater distances in systems where the limiting factor is not attenuation, but also requires a higher complexity at the transmitter due to the addition of the optical filter. Because of the high bandwidth occupied by the 14 channels, in the DSB configuration, we will receive the highest frequency channels with less power, making the transmission of lower frequency channels easier. The best configurationis dependent of a commitment between the desired distanceand the limiting effects of the system.

The transmission of the 4 ECMA-387 channelsis mainly limited by chromatic dispersion, because of the high-frequency channel and bitrate. The use of SMF fiber in an optical DSB transmission is not practical for a few kilometers of fiber, whereas e.g. with fiber dispersion of 2.7ps/nm/km, we obtain a substantial increase in the maximum allowed distance. Using NZDSF fiber in optical VSB transmission also becomes very advantageous when we want long distances. VSB transmission can also be used in SMF fiber, for a distance of a few kilometers.

REFERENCES

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