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EXECUTIVE SUMMARY OF THE THESIS

Dual Modulator based SSB Transmitter for Optical Metro and Access Networks

LAUREA MAGISTRALE IN TELECOMMUNICATION ENGINEERING - INGEGNERIA DELLE TELECOMUNICAZIONI

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1. Introduction

In the metro and access optical network it is mandatory to minimize as much as possible costs, energy consumption and complexity of the used devices, that necessarily leads to the employment of a simple technology. For this reason, the most exploited approach nowadays is the Intensity Modulation-Direct Detection (*IM-DD*), as to say that just the light intensity is used for the information encoding at the transmitter and the receiver is constituted by a single-ended photodiode, where the optical signal directly impinges. Along with this, the used signals are mainly Dual Sideband (*DSB*) signals, since they are extremely easy to be produced. Nevertheless, there is an ongoing traffic increase, due to the development and diffusion of audiovisual applications (*e.g.* film streaming), real-time applications (*e.g.* videocalling and online gaming), etc. . . . This huge data and bandwidth demand needs a proper technology to be managed with a good performance. Unfortunately, the IM-DD solution is limited by some factors that do not let to obtain any relevant improvement with the current apparata. In particular, the frequency selective power fading induced by the optical fiber chromatic dispersion during the signal propagation is the most detrimental effect acting in an IM-DD system. On the other hand, in these kind of networks is mandatory to minimize the previously listed device features, making coherent detection exploitation not feasible. During last years the research has focused its attention in finding possible sustainable solutions for the metro and access network improvement. Lots of proposals have been developed both on the transmitter side and on the receiver side.

For the transmitter, the main ideas concern both the physical structure and the coding. Speaking of the transmitter architecture, the most remarkable proposals have been the employment of Directly Modulated Lasers (*DMLs*) and Electro-Absorption Modulators (*EAMs*) ([1], [2]), since they reduce the energy consumption, are quite tiny and can be realized in semiconductor technology, which means that they can be integrated easily. Moving to the coding, the main studies have been aimed to adapt transmitting algorithms used in the RF communications to the optical communications. The main examples are the use of the Alamouti coding and of the DFT-Spread pre-coding for optical fiber

communications.
For the receiver, instead, the most remarkable results have been achieved keeping a DD scheme and then working on the Digital Signal Processing (*DSP*) part with suitable algorithms. The main example in this context is the Kramers-Kronig (*KK*) algorithm with its improvements. This procedure is able to improve the DD performance since we can reconstruct the impinging optical field (amplitude and phase) without a coherent receiver.

2. The dual modulator scheme

Among all the research proposals to improve the performance of an IM-DD system, we have examined the so called dual modulator scheme. This architecture is very simple, as it is composed by a cascade of a DML and an Intensity Modulator (*IM*) driven with different signals, as shown in Figure 1. Theoretically speaking, the idea behind the dual modulator scheme is quite simple. First, we directly modulate the laser output, so that it behaves both as a light source and as a phase modulator thanks to its chirp, which is described by the expression

$$\Delta f(t) = \frac{\alpha_{DML}}{4\pi} \cdot \left\{ \frac{1}{P_{out}(t)} \frac{dP_{out}(t)}{dt} + \kappa P_{out}(t) \right\} \tag{1}$$

where $\Delta f(t)$ is the instantaneous frequency shift, α_{DML} is the laser linewidth enhancement factor, $P_{out}(t)$ is the laser output power and κ is the laser adiabatic chirp factor. Then, an intensity modulation is performed by the IM modulator. This is needed to eliminate the undesired amplitude modulation made by the DML (unavoidable if we want to exploit its chirp) and, at the same time, to improve the signal amplitude/intensity modulation. Despite these simple features, the dual modulator approach is extremely interesting: it allows to use the Discrete Multi Tone (*DMT*) modulation with Single Sideband (*SSB*) signals (that are DSB signals where one of the two bands around the carrier is suppressed). The DMT modulation is a high level intensity modulation able to transfer a huge amount of information thanks to its features. First, a DMT signal is basically a superposition of N orthogonal sinusoids (named subcarriers), so it's like having N parallel channels. These channels do not interfere one with the others thanks to the Cyclic Prefix (*CP*) exploitation. Then, even more important is the DMT water filling nature, that results in the bit loading and power loading strategies. They allows to use a suitable modulation (so to encode the information) and to allocate the power subcarrier by subcarrier depending on the channel state at each frequency: the better the channel the more information encoded and the more power allocated. These three DMT characteristics lead to a capacity in the order of 3-4 (or even more) times the signal bandwidth. Therefore, a SSB DMT signal is very attractive for the metro and access network because, even keeping in an IM-DD system framework, it overwhelms the power fading issue and, at the same time, transmits a huge amount of information. The dual modulator scheme has been already studied in the research, but constituted by a Distributed Feedback (*DFB*) laser combined with an EAM ([1], [2]), two components easy to be integrated. However, we believe that an interesting alternative can be a dual modulator scheme constituted by a Vertical Cavity Surface Emitting Laser (*VCSEL*) and a Mach-Zehnder (*MZ*) modulator. The reasons are the following ones:

- a VCSEL is tinier than a DFB laser and is a constantly evolving device thanks to the research (Next-Generation VCSELs operating in the optical fiber C-band with wider bandwidth and lower noise are expected to be available in the next years);
- the MZ modulator, in the proper conditions, performs better than an EAM, not introducing any chirp contribution.

Obviously, the VCSEL and the MZ choice has also its cons (for example, a VCSEL is a little more unstable than a DFB laser and the MZ can be not so easy to be integrated as an EAM). In the next sections we discuss this new proposal. In particular, in Section 3 we develop the theory for a DMT SSB signal generation in the

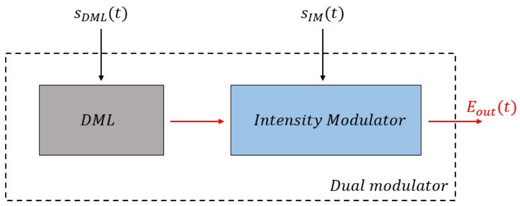

Figure 1: *Dual modulator generic scheme.*

new DML-MZ scheme and we verify it in Section 4; then, in Section 5, we compare the performance among different dual modulator solutions by means of a Matlab® simulator.

3. Simulator implementation

In this section we discuss the fundamental theory for the SSB signal generation in the DML-MZ scheme. We start from the simple case of a single sinusoid as modulation signal and then we move to the more complex DMT case.
For the single sinusoid discussion, conceptually speaking, we apply exactly the same steps followed in [1] (for the DFB-EAM dual modulator) to find the new SSB generation conditions for the DML-MZ dual modulator architecture. The first remark we have to do is that the IM modulator field transfer function is now a cosine, so we must bias the MZ with a voltage $V_B = V_\pi/2$ (V_π being a device parameter) to exploit the approximately linear region of the intensity transfer function. The second comment is that, if we want to avoid the MZ chirp, we must operate in the push-pull configuration, so the arms' driving signals have to be $V_1(t)$ and $V_2(t) = V_B - V_1(t)$.In the end, we get to the SSB conditions

$$m_{MZ} = m_{PM}/\pi \tag{2}$$
$$\Delta = 0 \tag{3}$$

where m_{MZ} and m_{PM} are the MZ amplitude modulation index (the corresponding of m_{EAM} in [1]) and the DML phase modulation index respectively and Δ is a phase shift.
Starting from this result, the single harmonic theory can be generalized to the complex case of a DMT signal, as this latter one is a sinusoids and cosinusoids superposition. The basic model is presented in [2] and applied to the DFB-EAM dual modulator. The block diagram of the procedure that should be followed for the SSB optical signal generation in the DML-MZ scheme is represented in Figure 2. First of all, we must remark that we have to work in the small signal regime. We don't describe each step of the algorithm (a detailed explanation can be found in [2]), but we focus on the main blocks, highlighted in Figure 2. The first operation that we discuss is the digital filtering, performed both on the DML signal and on the MZ signal and whose goal is exactly the generation of a SSB signal in the optical domain. The two filters that allow to obtain such result for a DMT signal are characterized by the frequency responses

$$H_{SSB,DML}(\omega) = \frac{2\pi}{\alpha_{DML} \cdot \sqrt{1 + \left(\frac{\kappa P_0}{\omega}\right)^2}} \tag{4}$$

$$H_{SSB,MZ}(\omega) = e^{j \cdot \left[\frac{\pi}{2} - \arctan\left(\frac{\kappa P_0}{\omega}\right)\right]} \tag{5}$$

for the DML and the MZ respectively, where P_0 is the laser Continuous Wave (CW) power. These functions have been obtained starting from (2) and (3). Actually, in [2] we have the application of just one filter on the DML signal, but the filtering operation is conceptually clearer if we separate the amplitude and the phase terms. The other passage that should be taken into account is the signals subtraction. In this case, it can be demonstrated that the coefficients necessary in the subtraction $c_1 \cdot s_{MZ}(t) - c_2 \cdot s_{DML}(t)$ (s_{DML} and s_{MZ} being the DML and MZ driving signals) are

$$c_1 = V_\pi \tag{6}$$
$$c_2 = \frac{V_\pi}{2} \frac{\bar{m}_{DML}}{\bar{m}_{MZ}} \tag{7}$$

where $\bar{m}_{DML}$ and $\bar{m}_{MZ}$ are the signals Root Mean Square (RMS) amplitude modulation indices for the DML and the MZ respectively. By performing a first order approximation of the output field allowed by the small signal regime, we get that

$$E_{out}(t) \simeq \sqrt{P_0/2} \cdot [1 + \pi \bar{m}_{MZ} s(t) + \\ + \pi \bar{m}_{MZ} \tilde{s}(t)] \tag{8}$$

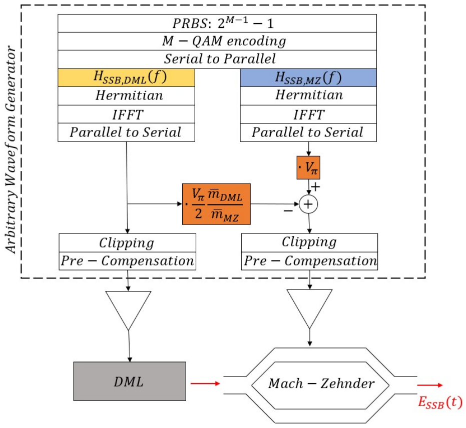

Figure 2: *Generation algorithm for the SSB DMT optical signal.*

Parameter	DFB	VCSEL
α_{DML} [-]	2.7	3.8
κ_{DML} [GHz/mW]	10	15.2
$\Delta\nu_L$ [MHz]	1	5

Table 1: *DFB laser and VCSEL parameters used in the simulations.*

where $s(t)$ is the original DMT signal without any manipulations and $\tilde{s}(t)$ is its Hilbert transform. This result represents exactly the definition of SSB signal.

4. SSB generation validation

After the developments of the theoretical model for the generation of a DMT SSB signal, it's important to understand the performance of the DML-MZ architecture. Before proceeding with the simulations, we must fix the used parameters' values, which will be valid both in this section and in Section 5. For the DMLs, we set $P_0 = 5mW$ and a bandwidth $B_L = 17GHz$ as common parameters, while the remaining ones are shown in Table 1 ($\Delta\nu_L$ is the laser linewidth). For the MZ and the EAM, we fix an identical bandwidth equal to $B_{IM} = 20GHz$. We also define the linewidth enhancement factor $\alpha_{EAM} = 0.5$ ([1]) for the EAM and a π-voltage $V_\pi = 5V$ for the MZ ([3]). Finally, the DMT signal is a *20 GHz bandwidth* signal constituted by *255 subcarriers* with a spacing $\Delta f = 78.23MHz$ and a CP length more or less equal to the 2.1% of the symbol length.

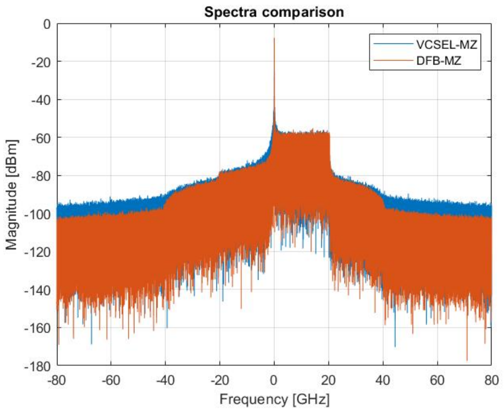

Figure 3: *DMT SSB optical signal spectra for the VCSEL-MZ dual modulator (blue) and for the DFB-MZ dual modulator (orange).*

By performing the simulations with the DMT signal algorithm, we obtain the spectra represented in Figure 3. We can immediately notice that the developed model works independently by the employed DML, since we get a more or less constant OSSR value equal to $20dB$ both for the DFB and for the VCSEL. We can also see that the only difference between the two results is the different phase noise contribution, that for the VCSEL is slightly higher than for the DFB. From this generation point of view, this is not a big issue, since we have suppressed the Lower Sideband (LSB, that is the negative spectrum band) with respect to the Upper Sideband (USB, that is the positive spectrum band) as we wanted. On the other hand, this may become so at the receiver. Together with this result, we have also to take into account that we want a transposition as accurate as possible of the DMT signal from the electrical to the optical domain. Performing the simulations, we can observe that we satisfy this requirement too. Actually, looking at the whole signal there is inevitably some distortion, but the waveform keeps almost unchanged.

5. Dual modulator application

After having verified that the DMT SSB signal generation works correctly, we study the dual modulator impact on the current metro and access network. We will subdivide this analysis in two parts: first we focus on the transmitted capacity as a function of the propagation distance; then we compare the VCSEL-MZ dual modulator with another type of SSB transmitter architecture, based on the cascade of a DML and an Optical Filter (OF) (the scheme is described in Subsection 5.2).

5.1. Transmitted capacity vs distance

To understand how much effective a SSB signal is with respect to a DSB one as a function of the propagation distance, we take into account just the dual modulator architecture, but we consider all the four combinations that can be built with a DFB laser, a VCSEL, an EAM and a MZ. We set the received power equal to $-3dBm$. The detection algorithm used at the detection stage is the usual DMT detection procedure in case of DD with a target Bit Error Rate (BER) equal to $4.6 \cdot 10^{-3}$. Considering our framework, we

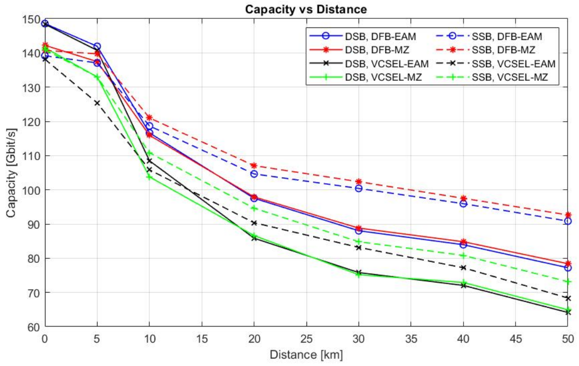

Figure 4: *Transmitted capacity as a function of the propagation distance in the DSB and SSB case for every dual modulator structure.*

have set the distances $[0, 5, 10, 20, 30, 40, 50]km$ and the final result of the various simulations is shown in Figure 4. From this picture, we can deduce three conclusions:

- the SSB signal guarantees higher capacity with respect to the DSB one, in particular when the propagation distance increases. The reason is clearly visible in Figure 5: the photocurrent spectrum in the DSB case is characterized by big dips, which represent the power fading effect. These dips imply that a certain number of subcarriers is not available, something that does not happen at all in the SSB case;
- the DFB laser returns better results than the VCSEL. This is due to the VCSEL broader linewidth (Table 1), that affects the low-frequency subcarriers. In a certain sense, we have previously foreseen this result when we commented the comparison between the optical spectra in Figure 3;
- once we fix the DML, the MZ modulator shows better results than an EAM, even if the performance of the two is quite close. The cause is the MZ lack of chirp.

This discussion shows that a MZ allows to obtain a slightly better performance than an EAM (especially when a VCSEL is used) and, in particular, that the DFB laser outperforms the VCSEL, owing to this latter one's larger linewidth. However, we remark that the Next-Generation VCSEL with lower phase noise is coming, so it's likely that the VCSEL-MZ dual modulator will have basically the same performance as the DFB-MZ one.

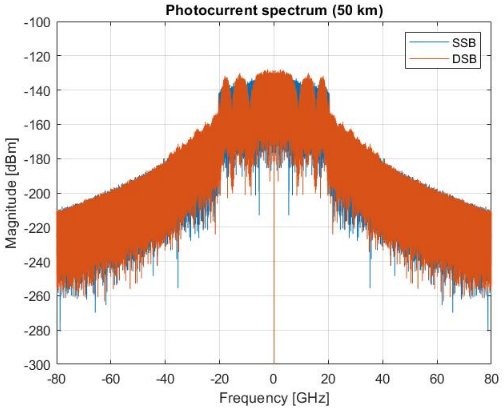

Figure 5: *Photocurrent spectrum after a 50 km propagation for a SSB signal (blue) and for a DSB signal (orange) It's a bit hidden but the SSB spectrum has a gradual power drop moving to high frequencies and does not show dips.*

5.2. Dual modulator vs OF SSB transmitter

Another working scheme for the SSB signal generation studied in the research is the DML-OF architecture, in particular the VCSEL-OF one ([4]). This solution scheme resembles the dual modulator one, shown in Figure 1, but there is an OF in place of the intensity modulator to achieve a SSB spectrum in an all optical way. The approach of such system is quite straightforward: we directly modulate the laser to generate a DSB signal and then we suppress the LSB by means of an optical filtering operation. Besides the conceptual simplicity, the filter employment is very critical for several reasons, especially for the filter tuning and stabilization.

It is interesting to compare the two working schemes, considering the VCSEL-MZ dual modulator and the VCSEL-OF solution in terms of transmitted capacity. The values for the VCSEL-OF scheme are recovered from [4]. In this work, an experimental evaluation was performed using a VCSEL having a $17GHz$-bandwidth and a DMT signal with the same parameters fixed in Section 4. Unfortunately, the reported values are limited to a $10km$ range. Moreover, a totally fair comparison between the solutions is a little bit difficult to be realized, because the simulated intensity modulator has a wider bandwidth than the VCSEL (in our case we have $20GHz$ for the MZ and $17GHz$ for the VCSEL), so the dual modulator scheme per-

	$C_{lost,\%}$ [%]		
D [km]	OF (SSB)	MZ, DSB	MZ, SSB
0	0	0	0
1	3.40	0.46	0.79
3	4.17	2.61	1.79
6	9.89	8.75	9.01
10	19.78	26.67	21.36

Table 2: *Transmitted capacity percent drop as a function of the propagation distance. In each case the DML is a* ***VCSEL***.

forms better for sure, in absolute terms. However, we can compare the two proposals from a capacity variation point of view, that is we compute the capacity percent drop with respect to the B2B case as a function of the distance and we compare these variations. In Table 2 we report these percent variations and, in both cases, the examined distances are $[0, 1, 3, 6, 10] km$. The table shows that the variation values are comparable in all three situations. In particular, the DSB case is the worst one, even if, for very low distances, the capacity percent drop is better or similar to the other two trends. For what concerns the SSB signals, the two solutions are very similar, limiting to the considered range. This conclusion, together with the intuitive huge capacity advantage in absolute terms and to the critical OF behaviour, leads to say that the dual modulator can be an effective solution for the metro and access network.

6. Conclusions

In this work we have investigated the dual modulator solution for the metro and access network improvement. Starting from the DFB-EAM dual modulator developed in the literature and we have proposed a similar dual modulator scheme, constituted by a cascade of a DML and a MZ, focusing especially on the use of a VCSEL source. We have developed all the theory for the modulation scheme to make a performance evaluation. We have demonstrated that, fixed the dual modulator as transmission scheme, SSB signals definitely outperform DSB signals because of the increased resilience to the power fading issue. This effect is more evident for a DFB laser than for a VCSEL due to the higher phase noise of this latter one. Moreover, the MZ modulator, thanks to its chirp lack, returns slightly better results than an EAM. Finally, we have compared (as best as we could) the VCSEL-MZ dual modulator and the VCSEL-OF solution, concluding that the dual modulator approach works better between the two. In fact, it guarantees a much higher capacity (typically due to the IM modulator bandwidth, larger than the VCSEL one) and the capacity percent drop is comparable, at least for the considered distances. Moreover, the employment of an IM modulator is less critical than an optical filter, since in this latter case we should care of its alignment, stabilization and other similar issues. All these results, together with the Next-Generation VCSELs development, allows to conclude that the VCSEL-MZ dual modulator can be a very interesting device for future applications.

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