SCM Optical Communication System Implementation without Optical Isolators

Luis M. M. Mendes¹ (lmendes@estg.iplei.pt)
Escola Superior de Tecnologia e Gestão, Alto Vieiro, Morro do Lena, P-2401-951 Leiria, Portugal

Henrique J. A. da Silva² (hjas@co.it.pt)
Instituto de Telecomunicações, Universidade de Coimbra, Pólo II, P-3030-290 Coimbra, Portugal

Abstract
This paper describes the design and performance of a sub carrier multiplexing (SCM) subsystem used in the optical links between base stations (BS) and the central node (CN) of a mobile communications system. The SCM subsystem uses the 1.91-2 GHz bandwidth, with the sub carriers modulated in phase shift keying (PSK). We demonstrate that there is no need of optical isolators allowing a substantial cost decrease for this kind of systems.

I. INTRODUCTION
One of the applications of SCM systems is in mobile systems where this technology is used in the optical link between base stations (BS) and the central node (CN) [1] [2]. For economical reasons, wavelength division multiplexing (WDM) must be used in order to establish a full-duplex link in only one fibre. Figure 1 shows the mobile communication system architecture.

Figure 1 – Mobile communication system architecture.

In this paper we describe the design of the downlink (CN to MS via BS) and present results that describe the performance of the system.

II. SYSTEM DESIGN
The functional diagram of the downlink is represented in Figure 2, where Tx is the optical transmitter, APC is the automatic power control subsystem, and Rx is the optical receiver.

Since this must be essentially a transparent optical link, the net gain must be equal to one. Because the sub carrier frequency is around 2 GHz, a careful choice of the components used was needed.

![Figure 2 – Block diagram of the implemented system.](image)

The target specifications of the SCM optical communication system are gathered in Table 1.

<table>
<thead>
<tr>
<th>SIGNAL NAME</th>
<th>TARGET SPECIFICATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFIN</td>
<td>Type</td>
</tr>
<tr>
<td>Carrier frequencies</td>
<td>Between 1912.5 and 1997.5 MHz (BW&lt;sub&gt;channel&lt;/sub&gt;=5MHz)</td>
</tr>
<tr>
<td>Power level</td>
<td>-20dBm/channel</td>
</tr>
<tr>
<td>OPT</td>
<td>Type</td>
</tr>
<tr>
<td>Optical wavelength</td>
<td>1550 nm</td>
</tr>
<tr>
<td>Optical power level</td>
<td>0 dBm ± 2dB (0.621 mW to 1.585 mW)</td>
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<tr>
<td>Optical modulation index</td>
<td>5%/channel</td>
</tr>
<tr>
<td>Rfout</td>
<td>Type</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>Between 1912.5 and 1997.5 MHz (BW&lt;sub&gt;channel&lt;/sub&gt;=5MHz)</td>
</tr>
<tr>
<td>Power level</td>
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</table>

In the following sections we describe the design of the system and present the results obtained in numerical simulations and test measurements performed.

¹ Assistant at Superior School of Technology and Business of the Polytechnic Institute of Leiria (ESTG-LEIRIA; researcher at IT-Coimbra).
² Associate Professor at the Department of Electrical Engineering, Faculty of Sciences and Technology, University of Coimbra; researcher at IT-Coimbra.
A. Laser driver

As shown in Figure 3, the laser driver may be divided into three different subsystems:

- Impedance matching circuit;
- Bias circuit;
- Laser circuit.

Figure 3 – Laser driver block diagram.

The impedance matching circuit is required to match the impedance seen by the signal source to 50 Ω. Besides providing the laser biasing current, the bias circuit is used to apply the signal current to the laser. The laser circuit also produces the feedback of the optical output for the automatic power control subsystem.

The laser chosen was the model FLD5F8LK of Fujitsu. This laser has a modulation bandwidth of 2 GHz, and its package includes a monitoring photodiode. The schematic of the laser driver is shown in Figure 4.

Figure 4 – Laser driver schematic.

We have used an attenuator of 9 dB to match the laser to 50 Ω. This produces impedance matching of the signal source to the laser in a considerable bandwidth (100MHz – 2.4GHz). With conventional methods based on lossless L-C circuits, a good impedance match would be obtained only for a very narrow bandwidth (Fano theoretical limit). However, the use of an attenuator reduces the level of the signal applied to the laser. As a consequence, in most applications an amplifier is introduced before the attenuator. In our application, the introduction of an amplifier will depend on the values of the average optical power and optical modulation index.

Results obtained in test measurements of the laser driver are shown in Figure 5. The picture in the left-hand side of Figure 5 is the transmission characteristic. As can be seen, the transmission value is -24 dB (electric to optical domain conversion) and has a variation in the range of 1 dB, in the measurement bandwidth. This curve represents the transfer characteristic of the laser driver, defined by the following expression:

\[ T_{db} = 20 \cdot \log \left( \frac{T(W/V)}{1(W/V)} \right) \]

Figure 5 – Characteristics of the optical transmitter.

In the right side of Figure 5 we see the reflection coefficient at the laser driver input. This parameter varies from -17 dB at 1.9 GHz to -24 dB at 2.01 GHz. The corresponding VSWR is always less than 1.3:1. Therefore, we may conclude that the laser is well matched. Concerning the laser driver, we may say that it has a good performance in all bandwidth of the signal.

From the measures we have concluded that an amplifier before the impedance matching circuit is not needed to achieve all the project specifications. Because of this, the circuit shown in Figure 4 is the complete optical transmitter.

B. Optical receiver

A functional diagram of the tuned optical receiver is shown in figure 6.

Figure 6 - Front-end block diagram.

In order to obtain the response of the front-end, it is necessary to characterise each functional block. Therefore, we have considered firstly the models of the photodiode and of the amplifier, and we have designed the tuning circuit [3] [4] afterwards.

The schematic for the overall receiver is obtained by cascading the individual schematics [5] of the various functional blocks, as shown in Figure 7.

Figure 7 – Optical receiver schematic.

The photodiode chosen was the model FID3Z1LXF of Fujitsu. This photodiode has a modulation bandwidth of 3 GHz. For the optical receiver front-end was chosen the MESFET ATF-10136 of Agilent Technologies. This transistor has 13 dB of gain at 4 GHz, a noise figure (NF) of 0.5 dB at 4...
GHz, and a 1 dB output compression point (\(P_{\text{dual}}\)) of 20 dBm at 4GHz. For the last section of the receiver we used two RAM-6 amplifiers of Mini-circuits. This MMIC amplifier has 10 dB of gain at 2 GHz, a noise figure of 2.8 dB, a 1 dB output compression point of 2 dBm, and a third order intercept point (IP3) of 14.5 dBm.

Using the models extracted for the various functional blocks, we have simulated the above circuit. In Figure 8 we present both simulated and measured scattering parameters, for comparison.

![Figure 8 – Optical receiver S parameters.](image)

The transfer characteristic of the optical receiver is shown in the left-hand side of Figure 8, and is represented by:

\[
T_{\text{dB}} = 20 \cdot \log \left( \frac{T(V/W)}{(W/W)} \right)
\]

As may be seen, the simulated and measured results are very similar. In the signal bandwidth, the gain varies about 1.5 dB. In the right-hand side of Figure 8 we see the reflection coefficient of the output port. As before, the simulated and measured results are very close. In the bandwidth of interest we have a reflection coefficient of less than -17 dB. Therefore, we may conclude that the receiver has a good performance.

III. PERFORMANCE MEASURES

In this section we present practical performance measures of the SCM system. In order to draw conclusions about its performance with the transmitter and receiver described in the previous sections, we had to perform linear and non-linear measurements. The linear measurements are based on the scattering parameters and on the system output noise and CNR. The non-linear measurements are based on the third order intermodulation products (IMP), because the signal bandwidth is much less than an octave.

A. Scattering parameters

The test setup to measure the scattering parameters S11, S22 and S21 is shown in Figure 9. Note that we did not need to measure S12, because this parameter is zero.

![Figure 9 – Downlink scattering parameters.](image)

We present in Figure 10 the measured magnitudes of the reflection coefficient parameters at the input and output ports.

![Figure 10 – Input and output reflection coefficients.](image)

As may be seen in Figure 10, the input reflection coefficient is less than -17 dB and the output reflection coefficient is less than -19 dB, in the signal bandwidth. Therefore, we may say that the input and output impedances have the nominal value of 50 Ω, because the input and output ports are well matched. The maximum value of the corresponding VSWR is 1.3:1.

In Figure 11 we present the measured values of the transmission coefficient S21.

![Figure 11 – Transmission coefficient magnitude.](image)

The magnitude of the transmission coefficient is about 1.5 dB, and has a variation of less than 0.65 dB in the 100 MHz bandwidth (1.9 to 2 GHz) and of 0.3 dB in the 5 MHz bandwidth (channel bandwidth). The bold trace represented in the left-hand side of Figure 11 is the average of the measured values. Therefore, we may say that there is no significant amplitude distortion in the signal bandwidth.

Figure 12 shows the measured values of the transmission coefficient phase. We observe that it is approximately proportional to frequency. Therefore, the phase delay in the signal bandwidth will be approximately constant, thereby producing a response with negligible phase distortion.

![Figure 12 – Phase of the transmission coefficient.](image)
B. System output CNR

To obtain the system output CNR we used an unmodulated subcarrier and measured the output signal spectrum with a spectrum analyser. This measurement is shown in Figure 13. The input sub carrier had a frequency of 1.95 GHz and a power level of -20 dBm. As may be seen, the sub carrier at the system output has -18.18 dBm. This result confirms the system gain referred in the preceding section (= 1.5 dB).

As may be observed, the noise at the output of the system can be approximated by white noise, in the system bandwidth. So, the noise at the output system, as can be seen in figure 13, has a power spectral density of:

\[ G_n(f) = -115\text{dBm/Hz} \quad \Leftrightarrow \quad 1.9\text{GHz} < f < 2\text{GHz} \, . \]

Therefore, the total noise in the channel bandwidth (5 MHz) is:

\[ N_o = -48\text{dBm} \, , \]

and the output CNR is 29.82 dB for a signal level at the system input of -20 dBm.

C. Third order IMP

Because the overall system is inherently non linear, the multiplexing of various microwave sub carriers produces intermodulation products. Noting that all the sub carriers lie within an octave bandwidth, only the third order IMP at frequencies \( f_3 = f_2 f_1 \), will lie within the transmission bandwidth.

To measure the third order IMP we have used two sub carriers at the input port of the system with two different power levels.

The output signal spectrum is shown in Figures 14 and 15, for two input tones with -18.5 dBm and -13 dBm, respectively.

From Figure 14, we may conclude that, for input power levels of both subcarriers lower than -18.5 dBm, the intermodulation distortion is negligible. When the input power level increases to -13 dBm per sub carrier (Figure 15), we observe that the intermodulation distortion is about 50 dB lower than the carrier power:

\[ \frac{IMD}{C} = -50\text{dB} \, . \]

If required, the intermodulation distortion may be reduced further by using a MMIC amplifier (RAM-6) with a better non-linear performance. Considering that the RAM-6 IP3 is 14.5 dBm, it may be easily observed that the intermodulation distortion is 52 dB below the carrier levels, if these are -11.5 dBm.

So, for an input power of about -20 dBm per channel, we may expect that the intermodulation distortion will not be a critical factor for this system.

IV CONCLUSIONS

As seen in the last section, we may expect the overall carrier to noise+distortion to have a value equal to the CNR. For BPSK modulated signals, the CNR must have a value equal or greater to 16 dB, in order to guarantee a bit error rate (BER) lesser than \( 10^{-9} \). When the distance between the transmitter and the receiver is zero we have:

\[ \frac{C}{N + D} = 29.82\text{dB} \, , \]

so the BER is much less than \( 10^{-9} \). In the limit, and considering an average attenuation of 0.25 dB/km, we may estimate a maximum length of 55.3 km for the optical fibre link between the optical transmitter and the optical receiver.

From the above results we may conclude that we have built an almost transparent SCM optical link, which has the following main properties:
• Negligible linear distortion (in the 100 MHz bandwidth the gain changes less than 1 dB, and in the channel bandwidth (5 MHz) the gain has a maximum variation of 0.3 dB),
• Negligible non linear distortion,
• Gain of approximately 1.5dB,
• 50 Ω cascade compatible,
• Links with maximum length of 55.3km.

Besides, we have shown in this paper that, for this particular application, the implemented SCM optical communication system meets the specifications without the need of using optical isolators, which results in a significant cost reduction.

Figure 16 – Transmitter photograph.

Figure 17 – Receiver photograph.

V REFERENCES