Hybrid Fiber Radio Link for Feeding DOCSIS Wireline and Wireless Heterogeneous Access Nodes

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***Abstract*—We demonstrate the successful transmission of Data Over Cable Service Interface Specification (DOCSIS) signals in the 600 MHz and 5.5 GHz frequency bands. Both signals are generated simultaneously using an optical harmonic up-conversion of the DOCSIS signal provided by a cable modem termination system (CMTS). The optical signal is transmitted over 10 km SSMF. After photo-detection, the wireline (600 MHz) signal is sent through standard CATV cable, while the wireless (5.5 GHz) signal is radiated over a 15 m indoor link. Both, wireline and wireless signals were received successfully at the cable modem (CM) side.**

***Index Terms*—Hybrid fiber-wireless access networks, microwave photonics, frequency conversion, radio-on-fiber, broadband access networks**

I. Introduction

Broadband wireless access seems to be the future technology for last mile access networks. Besides the existing cable or fiber infrastructure, broadband wireless offers the opportunity of extending networks easily with relatively low deployment costs, faster revenue and increased flexibility from both operator and user sides, as providing/accessing a service will not depend on a cabled connection.

One of today's most extended technology to provide data services is the Data Over Cable Service Interface Specification (DOCSIS) which is, jointly with xDSL, the most important wireline access standard. DOCSIS offers the capability of serving a huge amount of users with broadband access and has QoS and security capabilities. Intended for operation over existing analogue CATV networks it offers a robust transmission system with equalization and forward error correction (FEC).

In this paper we present an optical modulation technique, based on a single dual-drive Mach-Zehnder modulator (DD-MZM) which allows the simultaneous transmission of DOCSIS signals in their original band and up-converted to an RF band in order to implement a fixed wireless access. The technique has LO remote delivery capabilities which results in a simplified base station (BS) design [1-5]. Wireline and wireless users can be served simultaneously by a single cable modem termination system (CMTS) over both transmission media. This feature can be used to implement, for instance, disaster recovery strategies or back-up connections (figure 1).

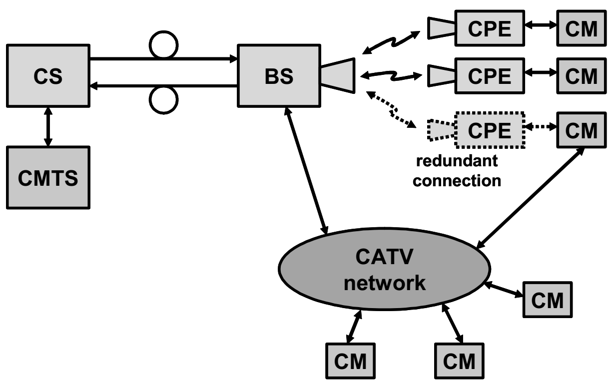

Fig. 1. Network topology of the reported scheme. A CMTS is connected to the control station (CS) where the harmonic up-conversion takes place. Afterwards signals are transmitted over fiber and recovered in the BS. Then they are distributed either to wireline or wireless terminals. Costumer premise equipments (CPEs) for wireless users are introduced in order to down-convert/up-convert incoming and outgoing signals. The subscriber is connected through standard DOCSIS cable modems (CMs).

First, general information about the modulation technique and transmission system will be given with reference to simulation results we obtained. Then, we present measurement results for the CS/BS feeder obtained in our lab. Finally, we demonstrate the successful operation of a wireline/wireless DOCSIS [6] network using the scheme reported in this paper.

This work has been carried out in the frame of the FP6 European project IST-1-507781 GANDALF (Gbit/s Access Network using remote Delivery opticAL Feeder for heterogeneous broadband wireless and wireline nodes) [7].

II. Transmission Technique

A. General description

The optical modulation technique allows the transmission of a data signal in its original frequency band and at the same time up-converted to a frequency which is determined by the

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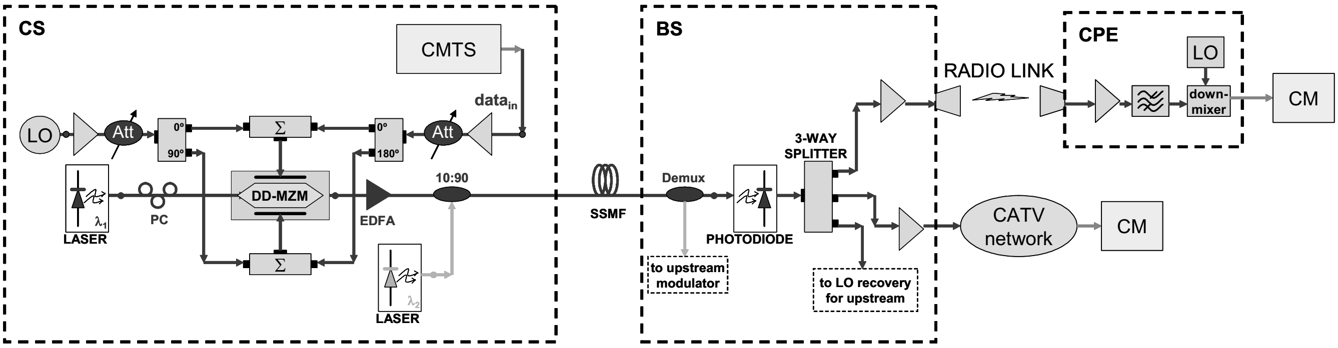

Fig. 2. Schematic of the proposed system (downstream). It cosists on a CS, containing a DD-MZM as optical modulator, a LO source, a CMTS and two laser sources for downstream and upstream carriers, a fiber link, and a BS where LO, IF and RF data signals are separated and amplified. In the wireless access case, the RF signal is down-converted in order to apply the data to the CM, whilst in the wireline access case, the network architecture does no change.

frequency of the local oscillator tone which is provided in the central station (CS)

$$f_{RF} = 2 \cdot f_{LO} + f_{IF} \tag{1}$$

where f_{RF} is the frequency of the up-converted data signal, f_{LO} is the LO's frequency which also can be recovered at the BS side and f_{IF} the frequency of the original data signal.

The recovered current for IF and RF signals depends on the LO's power according to

$$I_{IF} \propto J_0^2(\alpha) \tag{2}$$

$$I_{RF} \propto J_1^2(\alpha) \tag{3}$$

with

$$\alpha = \frac{\pi V_{LO}}{V_\pi} \tag{4}$$

where I_{IF} and I_{RF} are the recovered electrical currents of the corresponding data signal, J_0 and J_1 are the Bessel-Functions of 1st kind, 0th and 1st order, respectively. V_{LO} is the LO peak-peak voltage and V_π is the DD-MZM's half wave voltage ($V_\pi = 2.8V$ for the DD-MZM available at the laboratory). The modulator is biased at the quadrature point. From (2) and (3) it can be seen that the power distribution between the two data signals can be controlled by the LO; by increasing the LO level the power of the IF signal will decrease, while the RF signal's power will rise, and vice versa. Data signals at f_{IF} and f_{RF} are not affected by fiber chromatic dispersion and therefore, there is no carrier suppression effect induced. The LO tone at f_{LO} can also be recovered, due to dispersion tolerant remoting at the BS side [8-10]; it is used for down-conversion of the RF upstream signal.

Figure 2 shows a detailed schematic of the DOCSIS downstream path. In the CS relatively high LO powers (*+11 dBm*) are required so the LO tone is amplified and, for accurate operating point adjustment, led through a variable attenuator. Afterwards, the tone is split in two 90º phase different paths in order to achieve an optical single side band (SSB) modulation. The downstream data signal generated by the DOCSIS CMTS is also led through a power adjusting stage to achieve different modulation depths. Afterwards the data signal is split into two phase-opposite parts and combined with the corresponding 0º and 90º LO tone. These two resulting signals are applied to the RF ports of the DD-MZM where the CW laser is modulated and afterwards amplified by an erbium-doped fiber amplifier (EDFA). The optical downstream signal is combined with a CW laser which is later used in the BS as optical carrier for the upstream direction. After transmission over a fiber link the downstream optical carrier is separated from the upstream carrier, and photo-detected using a wide-band photo diode. A frequency selective 3-way splitter separates the electrical signal in LO tone, IF and RF data signals. The LO tone will be used for down-conversion purposes in the upstream electronics. The IF DOCSIS signal is amplified in order to satisfy the power specifications for a CATV network. The RF signal is amplified and radiated. After reception in the costumer premise equipment (CPE), it is amplified, band-pass filtered and down-converted. Both wireline and wireless signals are received by standard DOCSIS cable modems (CMs).

In the upstream direction (see figure 3) the CM connected through the wireless connection send its upstream signal to the CPE where it is up-converted and radiated. Then the radio signal is band-pass filtered, amplified and down-converted in the BS. The $2 \cdot f_{LO}$ tone required for down-conversion is recovered from the f_{LO} downstream signal of the CS. For the CM connected through the wireline connection the upstream signal is sent through the CATV network and amplified after

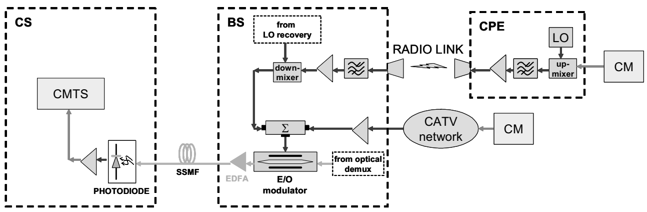

Fig. 3. Schematic of the upstream system. The signal of the wireless CM is up-converted and radiated. In the BS both signals for wireline and down-converted wireless CM are combined. Afterwards, modulated onto the optical carrier and sent to the CS where the DOCSIS signal is photo-detected, amplified and applied to the CMTS.

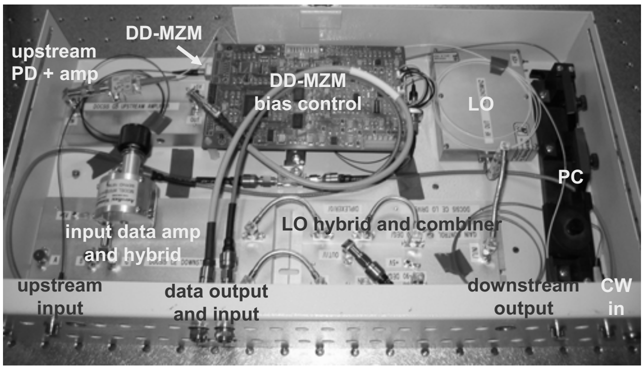

Fig. 4. Integrated control station. Consisting of the local oscillator source (LO), the LO hybrid coupler, and data hybrid coupler and the combiner for these signals. The DD-MZM, fed by an external CW laser source; the polarization controller (PC) is located in the CS. The modulator is automatically biased at the quadrature point. For the optical upstream path a photo diode and an amplifier are located in the CS.

reception in the BS. Here, both upstream signals are combined and modulated onto the optical upstream carrier. The optical signal is amplified and arrives to the CS after transmission over the fiber link. Here it is photo-detected, amplified and injected to the input port of the CMTS.

B. *Simulation results*

In order to specify the characteristics of all electrical and optical components we carried out simulations of the whole system. Also, link budgets were calculated to obtain gain and noise figure requirements of all components. We focused on 64-QAM downstream and 16-QAM upstream signals, which are values often used by CATV operators.

As a first operation requirement we analyzed the electrical signal powers that have to be applied to the DD-MZM. The power of the LO tone has been chosen so that IF and RF data signals can be recovered with equal powers at the BS side. Calculations and simulations show that this point is reached with P_{LO} = *+11.23 dBm* (*α=1.3*) at the DD-MZM ports. The optimum data power applied to the optical modulator is chosen by considering two conflicting effects: employing higher power signals allows to obtain higher modulation depths but increases the distortion induced by the modulator non-linearity. If a single DOCSIS channel is launched, the optimum value was found to be -10 dBm, but increasing the number of channels will reduce this optimum value.

The optical system is mainly defined by noise level considerations. The considered noise terms are laser relative intensity noise (RIN), EDFA amplified spontaneous emission (ASE) noise and the shot noise of the photo detector. Simulations have shown that the most limiting factor in the optical system is the RIN of the laser, with *RIN = -155 dB/Hz* a sufficient SNR is achieved at the BS side. Optical powers were set to achieve *+6 dBm* at the photo diode input.

Using these parameters, signals at the photo detector output of the BS have the following levels: IF data -45 dBm, RF data -45 dBm, LO tone -19 dBm.

Furthermore, we obtained a maximum noise figure of 14 dB for the whole downstream path from the photo detector output

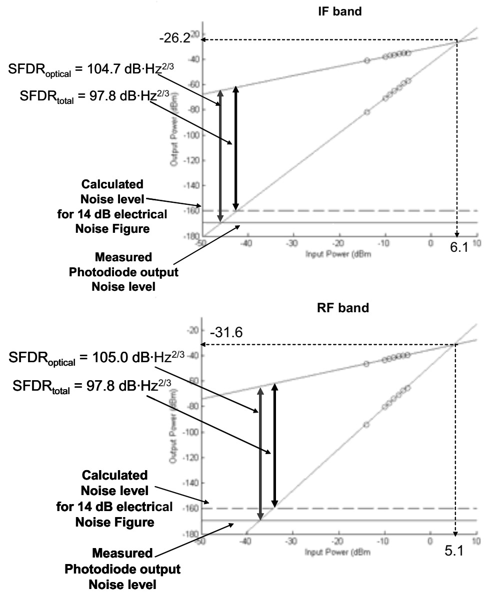

Fig. 5. Spurious free dynamic ranges (SFDR) for signals in the IF and RF bands. The SFDR is 105 dB·Hz$^{2/3}$ at the PD output and 98 dB·Hz$^{2/3}$at the CM input.

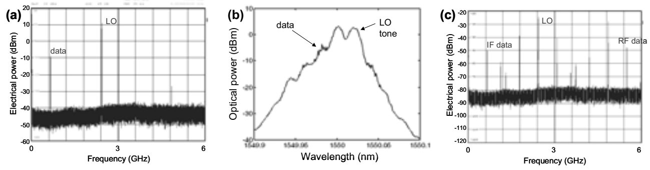

Fig. 6. (a) Spectrum of the signal applied to the DD-MZM, data and LO component can be observed. (b) Optical spectrum of signal arriving at the BS photo diode with data and LO components. (c) Spectrum of the photo detected electrical signal showing IF and RF data components and the LO tone.

to the CM input (wireless and wireline). This value is sufficient to receive the signals successfully.

III. Measurements

A. *Measurement setup*

In our measurements we examined the downstream transmission behavior of the CS/BS configuration. An image of the integrated CS is shown in figure 4. The CMTS is connected by external connectors. The LO emits a tone at 2.425 GHz. The LO power was set to +10.79 dBm, the point were recovered IF and RF data signal have the same power. Data power was adjusted separately for each case we considered. The DD-MZM is fed by an external CW laser and automatically biased at the quadrature point (QB). The outgoing optical signal is led to an EDFA and launched into a 10 km fiber link. At the BS side, the signal is photo detected and directly measured at the PD output with a vector analyzer.

In the upstream path a photo diode and an electrical amplifier are introduced in the CS.

B. *Spurious free dynamic range*

To assess the linearity of the system, the spurious free dynamic range (SFDR) has been evaluated. To measure this parameter, we applied two unmodulated carriers at the data ports of the CS in order to obtain harmonic generation. As a DD-MZM biased at the quadrature point does not emit second order harmonics we only measured the third order products. We measured the SFDR at the PD output, furthermore we assumed a noise figure of 14 dB for the electrical system from PD output to CM input and calculated so the SFDR at the user side. Results are shown in figure 5. The SFDR at the PD output is, for both IF and RF, about 105 dB·$Hz^{2/3}$. At the user CM, considering a noise figure of 14 dB, the SFDR will be 98 dB·$Hz^{2/3}$.

C. Single channel system

We implemented a downstream link with a single DOCSIS channel. The spectrum of the signal which is applied to the DD-MZM ports is shown in figure 6a; the data carrier at 651 MHz (-9.89 dBm in 6 MHz) can be seen as well as the LO tone. Besides, a tone at 4.85 GHz ($2{\cdot}f_{LO}$) can be observed. This tone is generated due to non-linearity in the amplifier but is very weak, about 40 dB below LO, and thus will not affect the system performance.

The modulated optical signal arriving at the PD is illustrated in figure 6b. The optical carrier can be seen at 1550 nm and the SSB-modulated LO tone at the right sideband. On the left sideband the data signal is observed. The powers in the optical subsystem were adjusted in a way that the optical power at the PD input was +6 dBm.

The spectrum of the PD photo current is shown in figure 6c. IF and RF data terms and the LO tone can be clearly seen. The spectra and eye diagrams (in and quadrature-phase) presented in figure 7 are shown for IF and RF data signals. Both signals have the same power, as intended. The modulation error ratio (MER) was measured to be 29.8 dB for IF and 29 dB for RF.

D. Four channel system

As our CMTS system is able to emit up to four DOCSIS channels we were able to measure the influence of the harmonic up-conversion scheme on a multiple channel system.

First we transmitted four adjacent channels at 651, 657, 663 and 669 MHz. Powers applied to the DD-MZM were about -9 dBm per channel. At the BS side the IF channels were detected with a power of about -43 dBm and MER around 26 dB. RF channels were recovered with -47 dBm power and 25.5 dB MER. The mean MER penalty from CS input to BS output is about 4 dB. Exact values for each channel are shown in table I. The lower powers of the RF data result from a slightly lower LO power (+10.5 dBm) applied in the CS, due to instabilities of our modulator bias controlling hardware when higher powers were applied. Increasing the channel spacing will not result in different recovered signal powers, but the mean CS input to BS output MER penalty is slightly reduced to 2.5 dB.

IV. DOCSIS NETWORK DEMONSTRATION

After performing the measurements for the CS/BS system, we implemented a whole full-duplex CMTS to CM system using the system implementation shown in figure 8. The CS is configured as described in section III.A, while the BS now is extended by a wide-band power splitter, and a band-pass filter and an amplifier (+30 dB) for the radio path (5.5 GHz). The wireline connection consists of a 15 m coax-cable connecting one port of the BS splitter with a CM. For radio transmission

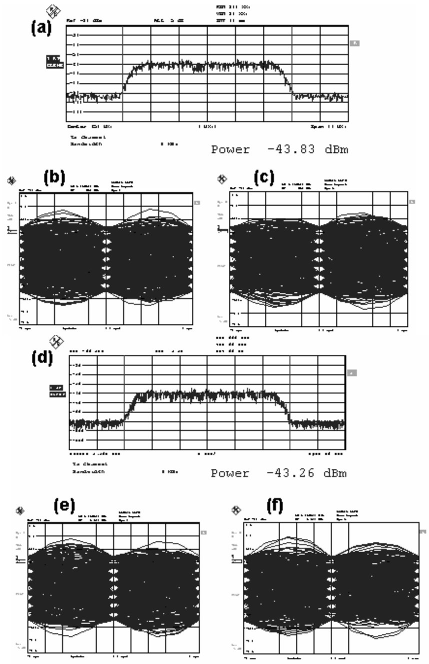

Fig. 7. DOCSIS channels recovered at IF and RF bands. (a) Spectrum of IF channel. (b) In-phase eye diagram of IF channel. (c) Quadrature-phase eye diagram of IF channel. (d) Spectrum of RF channel. (e) In-phase eye diagram of RF channel. (f) Quadrature-phase eye diagram of RF channel.

TABLE I
RESULTS FOR MULTI-CHANNEL SYSTEM

P_{LO} = 10.5 dBm		INPUT				OUTPUT							
						CH1		CH2		CH3		CH4	
		CH1	CH2	CH3	CH4	IF	RF	IF	RF	IF	RF	IF	RF
SINGLE CHANNEL SPACING	Power (dBm)	-9,31	-9,07	-8,98	-8,21	-43,18	-47,79	-44	-47,74	-43,85	-47,42	-42,74	-46,41
	MER (dB)	31,55	30,12	32,21	27,67	27,03	27,41	25,8	25,52	27,67	26,8	25,27	25,32
	MER penalty (dB)					**4,52**	**4,14**	**4,32**	**4,6**	**4,54**	**5,41**	**2,4**	**2,35**
DOUBLE CHANNEL SPACING	Power (dBm)	-9,31	-9,07	-8,98	-8,21	-43,02	-47,08	-42,88	-47,16	-42,66	-47,05	-43,84	-46,65
	MER (dB)	22,65	29,95	32,48	28,4	22,2	17,2	26,5	26,59	28,07	27,8	26,68	25,75
	MER penalty (dB)					**0,45**	**5,45**	**3,45**	**3,36**	**4,41**	**4,68**	**1,72**	**2,65**

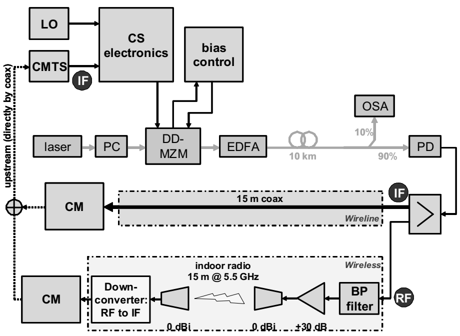

Fig. 8. Block diagram of the implemented demonstration system. The downstream path is implemented in order to serve a wireline and wireless CM simultaneously. Wireless transmission takes place at 5.5 GHz in an indoor environment. The optical upstream path was not implemented, but directly connected via a coax-cable.

TABLE II
RESULTS FOR MULTI-CHANNEL DEMONSTRATION

channel #	*frecuency (MHz)*				*SNR (dB)*	
	651	*657*	*663*	*669*	*Wireless*	*Wireline*
1		used			25,9	25,9
2		used	X-talk		25,9	26
3		used	X-talk	X-talk	25,1	25,9
4	X-talk	used	X-talk	X-talk	23,5	23,2

and reception we used isotropic antennas (0 dBi), for a 15 m radio link. In the CPE a simple down-converter from RF to IF frequency was implemented. The upstream path from the CMs back to the CMTS was directly fed back by a coax-cable connection due to the lack of a second mixer.

The CMs have an internal signal quality measurement software utility, so parameters such as SNR can be measured during system operation. Both the wireline and the wireless CMs have used the same DOCSIS frequency channel multiplexed in TDM. We measured the SNR at the CM input using its software application. The optimum CM and CMTS powers are automatically controlled by the DOCSIS MAC layer.

First, we launched only the used channel at 657 MHz, both cable modems established connection with the CMTS. The obtained SNR was 25.9 dB for the wireline as well as for wireless connection. Now we added the adjacent channel at 663 MHz to evaluate the influence of the adjacent channel crosstalk. The SNR measured by the CM did not change. Adding a second channel at 669 MHz decreased the wireless quality slightly by 0.8 dB while the wireline SNR was stable. After switching on the fourth channel at 651 MHz, intermodulation was noticeable in a SNR reduction of about 2.5 dB for both modems. The exact SNR values for each case are listed in table II.

We successfully transmitted a streaming video from one PC connected to the wireline CM to another PC connected to the wireless modem in an indoor environment.

V. CONCLUSION

We presented a dispersion-tolerant optical feeder scheme which allows full-duplex transmission of DOCSIS signals simultaneously in two frequency bands over a hybrid fiber-radio link. Some fundamental theoretic and simulation results were presented. Detailed measurements confirm that the CS/BS feeder is able to generate the signals in both bands with high quality. The functionality of the whole wireline/wireless DOCSIS system was demonstrated by transmission of a video stream in an indoor environment.

The proposed approach may result in a significant advantage for the implementation of fiber-fed heterogeneous and multi-service broadband wireline and wireless access networks.

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