Fiber-Extended Copper Line Architecture With End-to-End Data Transmission and Link Monitoring

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ABSTRACT We demonstrate a prototype hybrid, full duplex fiber-extended copper line with frequency-reusability and simultaneous fiber and copper line monitoring. The link architecture is composed of three main units: a central office; a remote-node copper to fiber converter (CuFiC); and a radio head. A fiber optical link connects the central office to the remote node, while the remote node is connected to the radio head by a copper line. Even though the prototype is built with two full duplex channels, more channels can be supported by the architecture, and an optical feedforward linearization scheme for the transmitter is demonstrated for that purpose. In-service simultaneous multi-copper and fiber monitoring is possible with the right choice of frequency bands, a result backed by the Error Vector Magnitude measurement of data channels in simultaneous coexistence with monitoring channels. A frequency multiplication unit, built into both the transmitter and the remote node, allows for a single seed tone to generate all the sub-carrier multiplexed channels for up and downstream in both the fiber and in the copper links without the need of local oscillators. This not only simplifies the architecture, but also allows for optimal homodyne up-/down-conversion. The demonstrated prototype figures as a potential candidate for interfacing fiber to the home and fiber to the building (FTTH/FTTB) links with legacy copper infrastructure currently allowing: up to eight 20MHz LTE 64QAM channels to be subcarrier-multiplexed onto a single optical carrier and seamlessly demultiplexed into individual copper channels, backed by a ≤8% EVM measured at the radio head; concurrent 7dB dynamic range 10 meter spatial resolution intermediate-haul fiber monitoring (up to 15 km) as well as copper line monitoring both available at the central office. The next steps beyond the presented proof of concept include simultaneous bi-directional transmission among multiple receivers, automated feed-forward linearization, and the study of factors that may limit the achievable dynamic range.

INDEX TERMS WDM/SCM-PON, backscattering techniques, OTDR, signal processing.

I. INTRODUCTION Extending the reach of legacy copper networks by means of optical fibers is an efficient and cost-effective way of preserving the legacy installations and reducing deployment costs. A recent work has explored legacy 4G infrastructure in a heterogeneous 4G/5G system extended by optical fibers to provide solid integration/transition to novel 5G technologies [1]. There is, however, an intrinsic cost associated to this extension when digital modulation is used, namely the introduction of digital modulation interpreters in the remote node, which can be expensive. The escalation of this cost for next-generation concepts such as Fiber to the Building, where a centralized transmitter feeds multiple remote nodes,
has tipped the scale in favour of analog modulation formats, such as analog radio over fiber (a-RoF) [2]. For these, the copper extension requires a low complexity remote node which performs the optical-to-electrical conversion and, eventually, down converts the center frequency of the signal so that it can be transmitted through the copper line. Unfortunately, analog modulation formats do not support error correction strategies as their digital counterparts [3]. Thus, usage of analog RoF demands a greater level of robustness of the communication link to data transmission, which could be assured by a reduction of the non-linear effects and excess losses introduced by the link [4]. For the latter, link supervision can be extremely successful in case it does not impact on data transmission while delivering continuous and accurate status of the physical layer so that the link operator can be forewarned whenever repairing is necessary [5], [6]. The former is a lingering issue in telecommunications, but both pre-distortion [7] and feed-forward [8] solutions have been proposed that successfully deal with the problem [9].

Recently, link monitoring of fiber-extended copper lines has been demonstrated and shown to be compatible with a-RoF architectures [6]. The remote node structure performs the simple tasks of electro-optical and opto-electric conversions and up/down conversions of the transmitted signals, and has been dubbed Copper-to-Fiber Converter (CuFiC). Ultimately, the CuFiC operates as a spatial demultiplexer of the subcarrier multiplexed a-RoF channels that travel together through the optical fiber link. Its architecture is compatible with next-generation concepts such as Fiber to the Building (FTTB) or Fiber to the House (FTTH), where a single optical fiber can feed a CuFiC, which, in turn, feeds multiple users at different floors by connecting, through the legacy copper lines, to multiple radio heads dispersed in the building or house [10]. The motivation behind the CuFiC architecture is to make use of the legacy copper cable infrastructure currently installed and reach it using a fiber connection that, due to its greater carrying capacity, is able to feed multiple copper channels and, therefore, multiple users.

By employing a high-frequency swept tone monitoring technique [11] and tailoring the monitoring signal such that it occupies the same bandwidth of a subcarrier channel, the optical fiber layer could be monitored in [6] whenever a void data channel was available. In such cases, upon arrival at the CuFiC, the monitoring channel would be directed to the copper line and supervision of this physical layer could also be accomplished. Even though the presence of the monitoring channel was shown not to disturb adjacent channels, simultaneous supervision and data transmission on the same copper line was not demonstrated due to the fact that the monitoring signal must replace the data signal.

The main contribution of this article is to demonstrate and detail the operating condition and achievable figures of merit (with respect to data transmission and link supervision) of a functioning prototype fiber-extended copper line link based on a CuFiC structure. In order to perform this demonstration, the following three main units are assembled:

- the Central Office, whose roles are: 1) generate data and monitoring signals as well as a seed tone reference; 2) transmit these through an optical fiber using a-RoF; 3) receive and process the upstream signal and the monitoring signals from both fiber and copper.
- the Remote Node, represented by the CuFiC, whose roles are: 1) transparently demultiplex the subcarrier signals coming from the central office and direct them to their respective copper lines; 2) transparently multiplex the upstream signals coming from the radio head through the copper line into a single optical carrier and send it through the full duplex optical link to the central office; 3) group and deliver the copper monitoring signals back to the central office.
- and the Radio Head, whose roles are: 1) receive downstream signals transmitted by the CuFiC through the copper line; 2) send upstream signals to the CuFiC through the copper line.

The presented prototype CuFiC allows for continuous supervision of the optical fiber as well as of the copper lines simultaneously with full duplex data transmission. Furthermore, frequency multipliers replace local oscillators in both the CuFiC and the central office in such a way that a single seed tone, generated by the central office, is enough to generate all the frequency multiplexed channels for up and downstream in both the fiber and in the copper links [12], which alleviates the complexity of the CuFiC. We propose and demonstrate an antenna unit concept, validating its performance with simultaneous up and down transmission along with copper monitoring. Finally, we also show that the copper monitoring solution is not limited to localizing abrupt cable defects, but is also capable of localizing slight impedance mismatches and non-incapacitating power losses along the copper link. These advancements bring the deployment of Sub-Carrier Multiplexing (SCM)-based fiber-extended copper lines to a near future.

II. ARCHITECTURE DETAILING

The architectural concept of the prototype fiber-extended copper line revolves around the transmission of several analog channels frequency-multiplexed into a single optical carrier. Upon arriving at the remote node, the signals are demultiplexed and directed to specific radio heads through copper lines. Each radio head, in turn, sends upstream signals to the remote node, which is responsible for performing the inverse operation, i.e., frequency multiplexing the spatially separated upstream signals so that an upstream optical carrier delivers them to the central office. The fact that up and downstream signals are transmitted simultaneously demands that both the fiber and copper links support full duplex transmission. The overview of the architectural concept of the prototype is presented in Fig. 1.

The full duplex optical link is implemented by wavelength division multiplexing, so that the downstream signal occupies one DWDM channel (channel 34 of the DWDM grid) whereas the upstream signal occupies another
FIGURE 1. Overview of the prototype architecture, depicting its three main structures, central office, remote node (CuFiC) and radio heads, and the physical links that connect each of them. Up and downstream communication is supported in both optical and copper links.

FIGURE 2. Full duplex optical link as implemented in the prototype fiber-extended copper line link. The monitoring signal is directed towards the optical circulator by the WDM. CO: central office; OC: optical circulator.

FIGURE 3. Full duplex copper link connecting the CuFiC to one of the radio heads through a copper cable. The frequency panel of the transmitted signals at each part of the architecture is depicted for clarity.

Establishing a higher fixed frequency band for the copper monitoring signal makes it possible for the central office to inspect all copper channels at the same time. In addition, the monitoring frequency band can be adjusted within the CuFiC architecture to be the same for both copper and fiber, so a simple opto-electrical conversion and filtering is enough to direct the monitoring signal on its downstream direction. An important part of the full duplex copper structure presented in Fig. 3 is the locally referenced copper frequency domain reflectometry (FDR), which is responsible for the copper link supervision [6].

In order to implement the subcarrier multiplexing of multiple data channels feeding the CuFiC by a single optical carrier, each channel must be assigned to a specific subcarrier. Ultimately, a set of local oscillators would generate these carriers so that the baseband data signals can be upconverted, frequency multiplexed in the optical carrier sideband, and sent through the optical fiber. Upon arriving at the CuFiC, the same set of local oscillators would have to be present in order to downconvert each data channel so that they can each occupy the 30 to 70 MHz bandwidth of each copper line. Homodyne beating at the remote node, however, causes the relative phase between local oscillators (the one in the transmitter and the one in the remote node) to play a major role in the resulting signal’s signal-to-noise ratio: the cosine of the relative phase appears multiplying the filtered signal’s amplitude [13]. Although phase retrieval methods are well documented in the literature, their application would be contrary to the purpose of reducing the complexity and, thus, cost, of the CuFiC structure.

To overcome this limitation, a frequency-reusable architecture is employed, where a single seed tone, transmitted from the central office to the CuFiC, is used to generate all the radio frequency subcarriers necessary for the transmission protocol in all stages of the link. As depicted in Fig. 4, a seed tone of 50 MHz is generated in the central office and sent through a set of frequency multipliers that generate the subcarriers for each of the data channels. This structure is here called the Frequency Multiplication Unit (FMU), and it is present at the central office as well as at the CuFiC.
node. Each tone generated in the FMU passes through a phase shifter so that the phases can be individually tuned for optimal homodyne beating at the remote node.

Each data channel is addressed to a specific tone generated at the FMU after going through the radio frequency mixers. The 50 MHz frequency elected to be the seed tone is such that no overlap between the up-converted channels with 40 MHz bandwidth of double-sided spectrum will ever take place no matter which multiplication factor is chosen; when the channels are combined in a radio frequency power combiner, as depicted in Fig. 5, they can be, ideally, de-multiplexed after transmission through the fiber. Also in Fig. 5, the fact that both the seed tone and the monitoring signal are combined into the downstream signal can be observed. Since the bandwidth selected for the monitoring channel ranges from 130 to 150 MHz, the first subcarrier channel available is the one corresponding to the \( x \times 4 \) multiplier of the seed, i.e., 200 MHz.

At the CuFiC, the downstream detected signal is split so that the seed tone can be recovered in the remote node. After its recovery, the seed tone is directed to an FMU equivalent to the one in the central office. The generated radio frequency tones have the same exact frequency of the tones used for upconversion in the central office, so they are used to downconvert each data channel to the baseband using homodyne beating. In order to guarantee minimum leakage from one channel to the other during frequency de-multiplexing low-pass filtering is performed on the signal after downconversion. Therefore, optimal recovery of the data channels in the remote node depends on the relative phases of the seed’s harmonics. Since the same seed was responsible for the generation of all tones, all the phase differences, however random, are fixed. In Fig. 6, the downstream CuFiC architecture is presented. In order to adjust the phases, the central office uses the information arriving from the upstream signals, which are multiplexed onto the optical carrier using the tones generated at the FMU inside the CuFiC. Using this information, all the relative phases of each local oscillator are adjusted remotely from the central office, so the CuFiC needs only to implement a seed recovery and multiplication. Since the monitoring signal’s frequency range is the same both in the fiber and in the copper, a bandpass filter is enough to direct it to the copper lines.

After retrieving the downstream data channels in the baseband, the CuFiC must up-convert them to the 30 to 70 MHz bandwidth of the downstream copper line channel. For this, the seed tone can be used, since it is designed to be at 50 MHz; a sample of the seed is taken from the FMU for this purpose. The upstream signal that arrives from the copper lines, on the other hand, has been designed to be centered at 100 MHz, between 80 and 120 MHz, and the CuFiC must down-convert them to the baseband before up-converting it to the upstream fiber channels.
FIGURE 8. Network architecture diagram with the main steps from data transmission at the central office, to channel data recovery and monitoring data recovery from both the optical fiber and the copper cables.

architecture for ease of visualization. A summary of the main steps involved in the full data transmission, data recovery and fiber/copper cable monitoring is shown in the block diagram in Fig. 8.

III. ELECTRO-OPTICAL LINEARIZED CONVERSION AND DATA TRANSMISSION RESULTS

A sensible issue in a-RoF transmission is the suppression of intermodulation, which may render the link inoperable. In order to minimize the contribution from high order intermodulation products and guarantee maximum signal-to-noise ratio, we employed the optical feedforward linearization scheme similar to the one presented in [14] that was already demonstrated for complex modulation signal linearization such as the LTE-A CA [15], [16]. Apart from fiber transmission in the presence of multiple optical sub-carriers, feeding multiple antennas using a-RoF, even though simpler than in the case of d-RoF, where a radio digitalization is necessary in the remote node, is not straightforward.

The optical transmitter including the linearization scheme is shown in Fig. 9. The linearization is accomplished by tuning the phases $\phi_{ij}$ through the variation of the bias current at each branch of the polarization-multiplexing dual parallel Mach-Zehnder modulator (PM-DPMZM), such that distortions in the combined optical modulated signal are minimized. The PM-DPMZM was emulated by using two differential quadrature phase-shift keying Mach-Zehnder modulator (DQPSK-MZM) integrated devices in parallel arrangement. The output of each DQPSK-MZM are combined by using a polarization beam splitter (PBS). The monitoring of the linearized spectrum is locally performed by using an Electrical Spectrum Analyzer (ESA).

The prototype fiber-extended copper line link contains a single full duplex CuFiC channel, which is transmitted through the fiber centered at 200 MHz ($\times 4$ multiplier from the MFU). The signal is generated in the baseband in the central office by a Vector Signal Generator (VSG) and analyzed, in the far end of the link, by a Vector Signal Analyzer (VSA). The VSA replaces the radio head and deems the transmission successful based on the Error Vector Magnitude (EVM): the EVM upper limit for 20 MHz 64 Long Term Evolution Advanced (LTE-A) channels is 8%.

Two data channels centered at 200 and 250 MHz respectively, combined with the monitoring signal and the seed tone at the input of the CuFiC downstream receiver are presented in Fig. 10, where the usage of the feed-forward electro-optical linearized conversion scheme has been compared with a conventional electro-optical converter. In this case, to each signal is assigned a maximum amplitude corresponding to one tenth of the full modulation depth of the converter such that seven data channels – in a total of eight – could be added in the present configuration (one tenth for each channel corresponds to eight data channels, one monitoring channel, and one seed channel). This amplitude value of one tenth of the modulation depth was achieved after performing tests for several different amplitudes, and, when using amplitudes lower than the one tenth of the modulation depth, an SNR of less than 20 dB was obtained. Thus, despite the capability of the FMU to implement, in theory, as many subcarriers as necessary, our FMU is limited to $N = 11$ (seed $\times 4$ through seed $\times 11$ been assigned for 8 data channels).

Three important results shall be highlighted from the frequency panel of Fig. 10. First, each data channel, with
a 40 MHz band, is nearly 3 dB below the monitoring channel, which occupies half of the data signals band. Thus, since the same power is assigned to the seed, which has all its power centered in one frequency, then each transmitted signal is assigned with the same amount of power, and the modulation depth limit is respected. Second, all the transmitted signals could be recovered with an SNR greater than 35 dB. And third, even though the non-linear response of the converter causes multiple intermodulation products to drastically lower the signal-to-noise ratio, the feed-forward linearizer is capable of removing these detrimental contributions to the SNR.

Presently, the linearization scheme deals only with the non-linear contributions from the electro-optical conversion, while the detectors are assumed to operate linearly. Although non-linear effects of the optical fiber, such as chromatic dispersion, may also contribute to interference between data channels they were not considered here because the length of the optical links for FTTH and FTTB mostly fall into the short to mid haul (up to 20 km) [11], [17], where chromatic dispersion is not extremely detrimental. Since the CuFiC is designed such that no control mechanism is built into its structure, the compensation for such fiber effects would have to be a responsibility of the central office, which is a challenge when compared to equalization solutions or the usage of fixed chirped fiber Bragg gratings at the receiver. A mechanism for remotely assessing the chromatic dispersion by measuring the width of an ultra-narrow backreflected pulse has been presented in [18], and the inclusion of this asset into the present linearization scheme is a study in progress.

Once a reasonable signal-to-noise ratio is achieved at the CuFiC’s downstream receiver, it is important to make sure that the FMU is recovering the seed and properly generating the desired frequency tones. In Fig. 11, the output frequency spectrum of the FMU at the central office is compared to the one at the CuFiC. The fact that the tones generated at the central office have a much cleaner spectrum is expected since they have not undergone conversion, transmission, detection, and recovery. Also, a small power difference can be observed between correspondent transmitted tone and recovered tones, which is due to the use of different amplifiers for each case; a smaller difference could be achieved having the same amplifiers available. The result, however, clearly shows that the tones have been successfully generated in the CuFiC and can be used for the transmission purposes as described in the previous section. As depicted in Fig. 7, after recovery in the CuFiC, the 50 MHz tone (seed) will be responsible for setting the copper line downstream center frequency, the 100 MHz tone (seed \( \times 2 \)) will be responsible for recovering the copper upstream signal in the baseband, and the 200 MHz tone (seed \( \times 4 \)) will be responsible for setting the fiber subcarrier upstream and downstream center frequencies.

The final stretch of the full duplex link is the copper cable, where up and downstream and monitoring signals coexist. The results shown in Fig. 12 correspond to the experimentally acquired frequency panel, which has been depicted ideally in Fig. 3; the figure labels of each signal channel have been kept consistent so that the results can be compared to the architectural concept. The high signal-to-noise ratio depicted in this frequency panel attests that the frequency-reusable architecture in the CuFiC introduces a comparatively low amount of interference and noise to the recovered signal. This conclusion, which will be elaborated momentarily in Section IV with the results from the EVM of both up and downstream, confirm two of the three roles attributed to the CuFiC in Section I, i.e., that both up and downstream signals are transparently converted between the two media connected to the CuFiC: fiber and copper.

The path of the down-link data signal in the proposed architecture, as introduced so far, involves several steps: radio-frequency up-conversion using the tones from the FMU, feed-forward linearized optical up-conversion using the setup of Fig. 9, transmission through the optical fiber, optical down-conversion at the CuFiC, followed by radio-frequency
FIGURE 12. Up and downstream data channels and monitoring signal inside the copper line. Since the signals travel in opposite directions, two traces measured at each terminal of the copper line compose the full frequency panel.

down- and up-conversion for transmission in the copper line with the seed-based recovered tones at the FMU, and a final down-conversion step at the antenna head. The same, but in reverse order, is true for the up-link data signal. Ideally, the system should be completely transparent from the point of view of the user, which can be quantified by making use of the Error Vector Magnitude (EVM) of the constellation received at either side (from the central node to the antenna head and vice-versa). We use these results as baseline to, then, introduce the monitoring signal and observe how the transmission quality is undermined by an increasing monitoring power. The determination of the EVM for the downlink signal is performed by creating a data channel using a Vector Signal Generator (VSG) and connecting a Vector Signal Analyzer (VSA) at the output of the antenna head; for the up-link signal, the VSG and VSA are swapped.

During all the tests, the bi-directional link is fully operational; even though the up- and down-link signals propagate at different directions, it is important to determine the impact of the fully-operational system from the perspective of the end nodes (central office and antenna head). The experimental conditions are such that the up- and down-stream optical signals carry 1 mW (0 dBm) of optical power at the output of the feed-forward linearization setup; an average 5 dB insertion loss of each DQPSK-MZM sets a requirement of the laser diode at 10 mW (10 dBm) output power. The wavelength of the down-stream is set to 1550.12 nm, whereas the up-stream wavelength is set to 1547.72 nm. Both signals counter-propagate over a 12-km single-spool optical fiber; the insertion loss of either WDM is experimentally determined to be 1.5 dB. At either photodiodes (at the central office and CuFiC), an average optical power of -5 dBm is measured.

Each channel (seed-tone included) occupies one eighth of the achievable full modulation depth, which allows recovering the data channels (after radio-frequency down-conversion) with a 30 dB-SNR. After the copper cable transmission, the measured EVM (averaged over both RF data channels) is 3.4% for the down-link channels and 3.6% for the up-link channels, which corresponds to a successful transmission, since: the back-to-back measured EVM directly between SVG and SVA is 1.8%; this result represents a comfortable operational point, far away from the 8% limit required for 20MHz LTE 64QAM channel transmission. It is important to note that, due to the spatial-mode separation between the downstream data signal and the copper monitoring signal inside the CuFiC - refer to Fig. 6 -, independent amplifiers may be employed for each signal, guaranteeing maximum linearity at the output. In possession of the baseline results of no monitoring signal, it is possible to determine the latter’s impact on the data transmission. In Fig. 14, we present the Error Vector Magnitude (EVM) variation, as a function of the monitoring signal’s amplitude.

The conclusion extracted from the results of Fig. 14 is that, at 0 dBm monitoring power, the conditions of the transmission channel are not impacted. Therefore, for the monitoring results presented in the next section, the monitoring power was set to this value. The most relevant experimental parameters used in the experiments are provided in Table 1.

TABLE 1. Experimental parameters.

| Domain | Parameter                          | Value  |
|--------|-----------------------------------|--------|
| Electrical | 50 MHz seed power                  | 0.8 mW |
|         | Monitoring data power              | 0.8 mW |
|         | Downstream Data channels power     | 0.8 mW |
|         | Copper cables length               | 60 m   |
|         | Laser output power at CuFiC        | 10 mW  |
|         | Laser output power at C.O.         | 10 mW  |
| Optical | Average power launched from C.O.   | 1 mW   |
|         | Average power launched from CuFiC  | 1 mW   |
|         | V_o DPMZM                         | 6 V    |
|         | \(\lambda_{DSS}\)                  | 1550.12 nm |
|         | \(\lambda_{DP}\)                  | 1547.72 nm |
|         | Optical fiber length               | 12 km  |

IV. FULL LINK MONITORING RESULTS

In order to supervise the copper links, an FDR measurement is employed for each copper cable. By taking a sample of the incoming monitoring signal and the reflected signal from a copper cable and sending both to a phase detector, a locally referenced FDR measurement is performed. As shown in [6], this measurement can be processed using the formula

\[
L = \left( \frac{c}{2 \pi \lambda_{DSS}} \right) \left( \frac{d \phi}{df} \right)
\]

applied from the straightforward Fourier Transform to pinpoint impedance mismatches along the cable. In the frequency-reusable architecture, the retrieval of the monitoring signal at the central office is performed as depicted in Fig. 13.

For each data channel, the signal output from the phase detector (FDR result) is directed to a voltage controlled oscillator (VCO). Each VCO gives an output signal centered at a different low frequency tone, and, for the case of 8 data channels, these frequencies range from 1 to 8 MHz. It is important to note that a simple electronic gain adjustment is
performed in the FDR result signal before reaching the VCO input, because a frequency shift of less than 200 kHz is necessary to guarantee that two VCOs’ outputs will not overlap in the frequency domain. A power combiner is responsible for coupling all the VCOs’ outputs into one signal. This signal is mixed with the ×2 tone of the seed, which is centered at 100 MHz, and sent to another power combiner to be multiplexed with all upstream data channels.

It is important to note that the 100 MHz channel is unoccupied since there is no fiber monitoring signal sent from the CuFiC to the central office nor is there a sample of the seed tone; furthermore, the first channel occupied by upstream data is the ×4 multiplier at 200 MHz, creating no frequency overlap with the monitoring channel. Upon arrival at the central office, the signal is split and sent to an FM demodulator that can be tuned to retrieve the monitoring signal of any copper channel; after demodulation, the monitoring information is processed so that it can reveal issues with the physical layer. The FFT results, retrieved at the central office, are presented in Fig. 15. For these, the length of the copper line was set to 50m; furthermore, the cable conditions were manipulated so that induced losses at the center and edge of the cable (25m and 50m, respectively) could be made present. An extra 5 meters of cable were also included between the CuFiC output and the copper line under test, which reflects on the even location results.

The results of fiber monitoring by replacing a void data channel band with a swept frequency tone are well founded in the works of [6], [11], and [19]. The fault location procedure is based on determining the magnitude and phase of the backscattered optical signal within the monitoring bandwidth. In possession of this information an FFT uncovers positions of faults, as can be seen in Fig. 16. Since the fiber
used in the experiment is 12-km-long single-spool with no faults, the fault location results indicate a loss event at the end of the fiber channel.

V. CONCLUSION
We presented an architecture for hybrid full-duplex monitoring of both fiber and copper links with a single fixed monitoring channel in a fiber-extended copper line context. The architecture is set to allow simultaneous and continuous monitoring of both fiber and copper lines from the central office. Frequency reutilization with remotely adjustable phase control has been proven, permitting a simplification of the remote node (CuFiC) and, thus, a reduction of the implementation costs. The performance of an optical feed-forward linearization scheme was demonstrated and its compatibility with the monitoring system proved. Moreover, different than similar techniques, the simplicity of the remote node is such that it does not need a local oscillator, where, instead, a Frequency Multiplication Unit is used. Transmission tests on actual RJ45 cables were performed and even small impedance mismatches that do not completely jeopardize the communication link but can degrade its conditions have been successfully located. These results set the architecture of fiber-extended copper lines with the CuFiC node as a robust and low-cost candidate for using legacy copper links in next-generation aRoF MFH applications.

The proposed architecture relies on the pre-existing legacy copper infra-structure of buildings and homes, bridging the gap between the latter and fiber-to-the-building and fiber-to-the-home concepts of 5G. The CuFiC architecture is therefore limited to cases where this infra-structure is available or requires extra installation costs to become advantageous. Moreover, the data rates achieved with this architecture are not intended for backbone architectures, since the number of data channels is limited due to both the non-linearities of the MZM (even with the linearization methods) and the fact that aRoF requires higher power per channel since no error correction strategy is available. Nevertheless, under auspicious conditions, the versatility of the proposed architecture is a considerable advantage over other methodologies that require digital processing units at both ends of the link.

The next steps of this work can be subdivided into three categories. The first involves extending the capacity of the system by both populating all eight subcarrier channels supported by the transmitter and replicating the receiver so that simultaneous bi-directional transmission can be evaluated. The second involves automating the feed-forward linearization system such that the voltage settings as the number of channels increases can be determined without the need of an operator. The third and final future work direction is regarding the fiber monitoring, specifically identifying factors that limit the achievable dynamic range so that longer fibers as well as more drastic faults can be correctly monitored.

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