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Sharing of Copper Pairs for Improving DSL Performance in FTTx Access Networks

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ABSTRACT In this paper, we analyze two techniques allowing to significantly improve the bit rate per user in the current and future FTTx access networks. They are based on the possibility of sharing copper pairs at data link level among subscribers served by the same distributor. Sharing can be achieved by inserting low-cost devices in the current FTTx access networks. In particular, as shown in this paper, sharing of copper pairs is obtained according to two different approaches. The first approach considers the possibility of increasing bit rate by a radio-shared channel that can be accessed locally by all authorized customer premises equipments (CPEs) inside the building(s). The system providing radio access is connected to the DSLAM by means of extra and temporarily unused copper pairs in the main cable connecting the DSLAM to the distributor. The second approach considers the possibility of inserting an active transceiver device in the current passive distributor(s) bridging the DSLAM to the CPEs. Depending on the activity of CPEs connected at the same distributor, results show that both the solutions allow to achieve very high downstream bit rates per user (about 800 Mb/s at 100 m with 50% CPE activity). Devices to be inserted in the FTTx network can be realized using electronic components currently available on the market.

INDEX TERMS Subscriber loop, VDSL2, wireless access.

I. INTRODUCTION

The Fiber-To-The-Cabinet (FTTC) access network architecture is the current widely adopted solution for Very high-speed Digital Subscriber Line type 2 (VDSL2) deployment based on 17a and 35b profiles [1]. The transition from 17a to the new 35b asks for changes and/or upgrades of DSLAMs (DSL Access Multiplexer) in the Cabinets and substitution of the customer premises equipment (CPE) at the user premises. Evolution of FTTC to FTTDp (Fiber-To-The-Distribution point) seems to be the next step, and Fast access to subscriber terminals technology (G.fast, ITU G.7201) [2] is the main candidate to replace VDSL2. The ultimate goal is the Fiber-To-The-Home (FTTH) network, in spite of the very large cost to bring the optical fiber to the customer's premises. Performance of FTTC, expressed in terms of the achievable bit rate per user, can be significantly improved by introducing "vectoring" (ITU G.993.5) [3], which allows to fully exploiting the transmission capacity of copper pairs. Other methods to increase the bit rate per user are to assign individually to the single CPE more than one copper pair. In the current practice, pair bonding techniques can be used to increase the achievable bit rate per user by assigning to the single CPE two pairs at least. This approach can be effective when the cable from the Cabinet carries unassigned pairs. Furthermore, when two pairs are bonded together the so called "phantom" technology [4], [5] allows to create a third virtual channel in addition to physical channels. By so doing, the user bit rate can be almost tripled, while the used physical resource is doubled. One possible use of the bonding/phantom approach is in cellular backhaul systems to feed 4G and, possibly, forthcoming 5G base stations [6]. However, once one unused copper pair (indicated in the following as "extra pair") is assigned to one CPE it cannot be re-used in any way to serve other CPEs even when the beneficiary CPE is not active. Furthermore, the number of available extra pairs in the cable is limited and so is the number of CPEs that can be served with more than one pair. In addition, the practical deployment of bonding (with or without phantom) could be expensive due to the need of installing more copper pairs over an existing communication facility at the customer premises, which has been originally designed to host only one copper pair.

The capacity of current FTTx (x: C or Dp) VDSL2-based networks is still not fully exploited by present technologies and deployments for the following reasons at least.

1) The capacity offered by the single copper pair (or more copper pairs in the case of bonding/phantom) is not shared among CPEs in any way (e.g. one user is assigned one (or more) dedicated pair(s)). Then, current FTTx access network infrastructures should evolve in order to allow the implementation of statistical multiplexing techniques over the available copper pairs in the cable.
2) When in the group of CPEs some of them are not ultra-broadband type, or the pair connected to the user is only for voice service, the available capacity for transmitting data is wasted.
3) When one CPE is temporarily switched off (or similar conditions, e.g. bursty packets) the capacity is wasted.
4) No intelligence or, more simply, no resource management strategies are inserted at the DSLAMs, i.e. the main function of the current DSLAM is to relay information units (IUs) from the central office to the CPEs and vice versa on the copper lines dedicated to the connected CPEs. In particular, present DSLAMs are not able to control and manage groups of copper pairs, which is a vital function for implementing statistical multiplexing over copper pairs.

In this study, we investigate on two effective techniques to significantly improving the transmission capacity of existing FTTx networks. This is achieved by introducing statistical multiplexing over groups of shared copper lines. The main focus of this paper is on the FTTC architecture even though concepts can be easily extended to the FTTDp case. It is shown that the considered techniques can be valid and very low cost alternatives to the extensive deployment of optical fiber for Fiber-To-The-Building (FTTB) and FTTH access. This could push forward the time when copper switch-off will be necessary, thus increasing the profitability of the (existing) copper network. Furthermore in several Countries customers are constantly moving from fixed to wireless access thus, freeing up more copper pairs that can be used to increase the bit rate of the (remaining) fixed customers.

As shown in this paper, multiplexing over shared copper pairs can be obtained by deploying new device(s) to be installed at the distributors on the existing FTTC plants and by updating existing DSLAMs with extra management functionalities. The distributors are flexibility points commonly used to ease maintenance and copper pair replacement in the case of fault, which are present in every FTTx network. Groups of copper pairs are extracted out of the main cable coming from the Cabinet and are connected to the distributor instead of being directly sent to network terminations (NTs). Then, the NTs are connected using copper pairs departing from the distributor. For backup purposes, the number of pairs accessing the distributor is usually larger than the number of served NTs. This allows having extra pairs to be used for maintenance as well as for other purposes as shown in the following of this paper. Usually, distributors are passive devices consisting of one or more patch panels bridging copper pairs extracted from the main cable with pairs connecting the NTs. In a typical FTTC deployment, distributors are close to the buildings (e.g. in Italy distances typically do not exceed 70 m), or they can be installed at the basements of the buildings.

In the following of the paper, we consider two separate techniques for introducing statistical multiplexing in current FTTC networks by:

a. inserting a local radio system (RS) connected to the passive distributor and providing a radio access channel, which is shared among CPEs inside the building;
b. inserting an active device at the distributor implementing (different) transmission technologies, e.g. VDSL2 and G.fast, the former for connecting the DSLAM with the distributor, and the latter for connecting the distributor with the CPEs. This active device acts to relay the bit streams from the DSLAM to the connected CPEs, and vice versa.

Functionalities of the present DSLAM in the Cabinet have to be updated in order for the DSLAM to manage groups of copper pairs at the distributors and to interact/manage the devices in above points *a* or *b*. As shown in the following, the possibility of implementing statistical multiplexing on group(s) of copper pairs connecting the DSLAM to each distributor allows to significantly improve transmission capacity. The two types of devices indicated in points *a* and *b* lead to two different architectures for the FTTC access network.

In the first architecture case, referred in the following as Hybrid Wireless-Wired FTTC solution (HWW), we consider a RS providing a local high capacity radio access channel, which is shared among the CPEs in the building(s). The RS can be inside or outside the building(s), and may include one or more radio access points properly positioned so to cope with radio propagation issues. It is out of the scope of this paper to investigate on solutions for the practical deployment of the RS. The RS and the CPEs can be equipped with the same (standard) radio technology such as LTE, Wi-Fi or, in future, 5G new radio (NR) [7]. In order to drastically reduce the costs of the RS infrastructure and to speed up the RS deployment, we assume the radio access point(s) of the RS is (are) directly connected to a subset of copper pairs at the distributors to receive/transmit data from/to the DSLAM. The main costs of the proposed HWW solution are due to the RS development and deployment. They can be reduced with the adoption of standard radio technologies such as Wi-Fi and/or LTE possibly with Licensed Assisted Access (LAA). The proposed solution is different from the mixed wireless/wired approaches already proposed in the current literature to improve DSL access by means of LTE, [8]–[10]. In these cases, the radio access network is separated from the fixed access network and traffic from fixed and wireless infrastructures are recombined in the core network. In our solution all the traffic from users (both fixed and wireless) is routed by the network through the same DSLAM. This solution has some advantages. First, it greatly simplifies the deployment and the management of the access network, which has no need to merge data coming from two or more different and separated access networks. Due to local transmission characteristics of the RS, very low cost access technologies such as Wi-Fi could be adopted instead of LTE. In addition, while LTE coverage for DSL applications is mainly provided through macro (or maybe small) cells, in our case RSs realize a dense wireless network offering better coverage adaptation to serve indoor CPEs and providing a higher capacity with respect to LTE networks.

In the second architecture, referred to as Enhanced Wired FTTC (EW) [11], we substitute the passive patch panel at the distributor with an active device. This device incorporates functionalities to switch IUs received from the DSLAM to the copper line connecting the distributor to the intended CPE. The IU is forwarded by the DSLAM to the distributor using anyone of copper lines in the group to the distributor. This means that there is no one-to-one fixed association between the copper line from the Cabinet/DSLAM and the final NT. The active device at the distributor decouples the copper line from the Cabinet and the target NT. As explained in the following, to allow full exploitation of shared capacity provided by the group of copper lines at the distributor, the transmission technology used on the DSLAM-to-distributor link can be different from the DSL technology on the distributor-to-NTs link. The concept of copper pairs sharing in the main cable from the Cabinet has been originally presented in [5] and simply re-adapted in [12] to a group of copper pairs in the same cable to feed a G.fast modem in place of the fiber. In [13] a design strategy for optimally deploying groups of shared copper pairs to feed G.fast modem has been presented. In both papers no theoretical nor practical solution for the realization of the sub-system allowing sharing among copper pairs has been proposed or discussed. Furthermore, implications of the adoption of this device on the existing FTTC architecture have not been discussed. In this paper we analyze, discuss and provide one solution for existing FTTC (or FTTDp) networks to incorporate sharing feature. As previously indicated, this is achieved by integrating into the existing FTTC access network: *i.* one active device at the distributor acting as transceiver (including switching/routing functionalities), which divides the DSLAM-to-CPE link into two separate and independent segments; *ii.* required modifications in the present DSLAM to correctly operate the proposed device within the evolved FTTC architecture. The active device operates at data link protocol layer (L2), thus allowing to aggregate capacity of copper pairs even using different DSL technologies (and not G.fast only) for transmission on the two segments. In Table 1 we summarize the main contributions concerning bonding and sharing in the literature and market products for mixed wireless/wired access.

As shown in this paper, the considered HWW and EW solutions allow to significantly improve the bit rate at the CPE. Both can be used with or without vectoring. The inclusion of system-level vectoring feature further improves the performance for all CPEs. Devices that implement system-level vectoring of up to 200 copper pairs are already available on the market for the VDSL2 35b profile. They can be inserted in the DSLAM to improve capacity for each group of pairs at their respective distributors. Due to the short distance between the distributor and the connected CPEs, in the case of EW vectoring could be avoided, so allowing to simplify the arrangement and to reduce the implementation costs of the active device at the distributor. It is worth to note that performance of EW can be further improved using recent MIMO-DSL techniques presented in [14], where each group of lines at the distributor can be seen as a MIMO sub-group. Finally, the phantom technology with (improved) system-level vectoring could also be used to virtually increase the number of copper lines per group at the single distributor.

TABLE 1. Selected contributions to bonding and sharing in the literature for FTTC and market products for mixed wireless/wired access.

References	Main Contributions
[4]	Introduces bonding technique for CPEs, which assigns more than one copper pair to one CPE only in an exclusive way. Proposes phantom technology allowing to create virtual channel(s) in addition to physical channels obtained with bonding
[5]	Introduces the concept of copper pairs sharing in the cable from the Cabinet
[12]	Re-adapts the concept in [5] to a sub-group of copper pairs in the main cable so to feed a G.fast modem; the group of copper pair replaces fiber for G.fast
[13]	Defines an (optimal) design strategy for deploying groups of shared copper pairs to feed G.fast modem for current and new FTTC access networks
[14]	Introduces the concept of MIMO for DSL technologies
[8], [10]	Available products for mixed wireless/wired access by means of LTE to improve DSL performance

This paper is organized as follows. In Section II, we detail the HWW FTTC access network architecture. In Section III, we describe the EW FTTC solution and we detail the architecture of the active device at the distributor. In Section IV, we define the procedure used to assess performance for both architectures. Results are then presented and commented in Section V. Finally, conclusions are drawn in Section VI.

II. HYBRID WIRELESS-WIRED FTTC

The principle scheme of the considered HWW FTTC solution is depicted in Figure 1. The DSLAM is installed at the Cabinet. In a typical arrangement, on one side of the Cabinet it is connected with fibers to the Central Office (CO) and, on the other side, to one (or more) cable carrying up to 200 copper pairs typically grouped into 4 binders. Intermediate distributors close or inside the buildings typically host from 20 to 40 pairs extracted from the main cable. Distributors are positioned at increasing distances from the Cabinet.

In Figure 1, we observe that CPEs can access the shared radio channel through one (or more) wireless interfaces provided by the RSs. In general, the single RS should be designed to ensure the best radio coverage for the CPEs in the building. As an example, one or more directive antennas illuminating the building could be adopted to mitigate propagation effects, as well as interference with other existing wireless systems in the area.

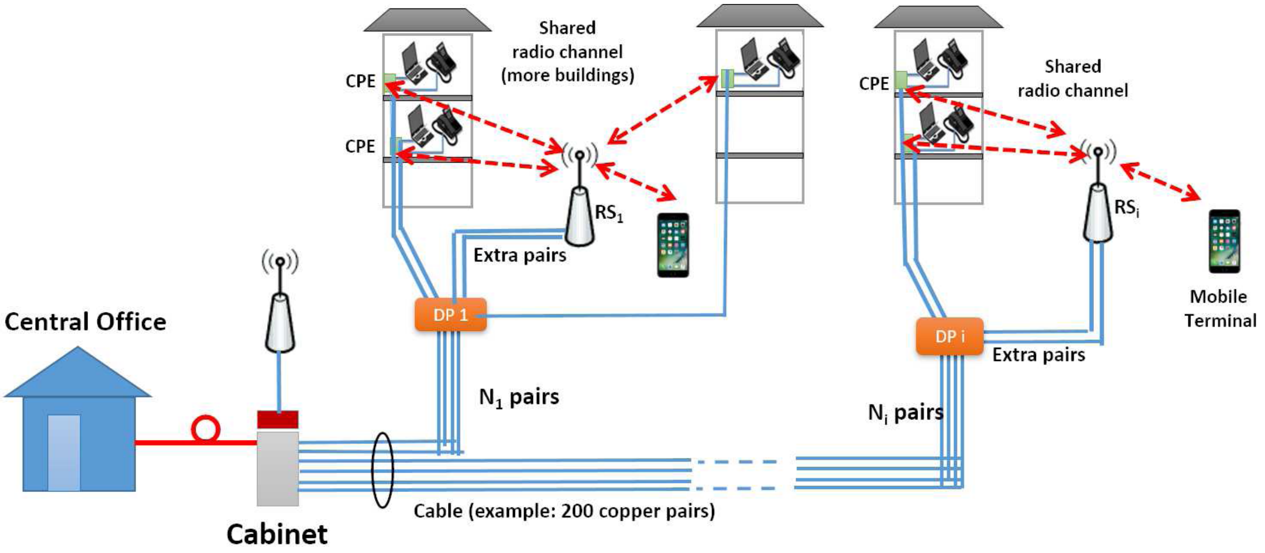

FIGURE 1. HWW FTTC access network architecture including RSs.

The HWW solution requires minimum modifications of the DSLAM currently available on the market. This allows minimizing the infrastructure costs. In principle, one (or more) radio access technology could be added to the present CPEs. This can be obtained by connecting the wireless devices used for accessing the shared channel, to the universal serial bus (USB) or to (one of) Ethernet ports in the CPE and updating the CPE firmware and software. In more advanced settings, CPEs could organize in a mesh network so to relay data to out-of-coverage CPEs. Finally, RSs could be also used to serve outdoor users moving in the proximity of the building.

In this approach, the extra capacity provided by the shared radio channel is the minimum between the aggregated capacity of the extra pairs assigned to the RS and the capacity of the selected wireless radio interface. When the limitation is due to the radio interface, it can be overcome by increasing the wireless bandwidth or adopting more than one radio technologies (e.g. LTE and Wi-Fi). The Wi-Fi is the most popular and stable technology currently available on the market. However, it can be often congested since in many cases the CPE incorporates a Wi-Fi modem that serves all in-house devices, e.g. laptops and tablets. Thus, the Wi-Fi signal of the RS to the CPE could interfere with these in-house Wi-Fi networks. This could result in increased interference in the Wi-Fi bands and, therefore, in decreased RS-CPE connection performance and home Wi-Fi network performance. Improvements can be provided by the upcoming Wi-Fi standard version (i.e. IEEE 802.11ax), which is designed to operate in dense environments providing high capacity up to 10 Gbit/s. Other present and future radio technologies can be adopted, as the HWW approach is radio-interface agnostic.

In general, several transmission strategies can be adopted to tailor the wireless link to the specific characteristics of the local environment (e.g. obstacles layout, interference and achievable radio coverage). Design of the local radio system can leverage on the proper selection of the local radio access technology, on the adoption of MIMO transmission even considering high gain/directive antennas, on the proper selection of transmission frequency and bands, on the adoption of spectrum management, spectrum agility techniques, and so on.

One alternative solution to the previous radio access scheme would consist in RS directly transmitting to the end-user device (e.g. laptop and/or tablet) and by recombining flows in the end-user terminal instead of CPE. Even though this approach would be more effective, it could be difficult to implement in practice for the following two main reasons:

- all user terminals should be equipped with two wireless radio network interface cards (NICs) at least; in the Wi-Fi case, this avoids each terminal in the house with one NIC to act as client over two distinct access points;
- multi-link transmission between the remote server and the user device should be managed by one multi-link protocol, such as multi-path TCP (MPTCP), which is in charge of coordination among the different/available links. This implies the protocol stack inside any user device should be (always) based on multilink protocol so to exploit all the available capacity from the different links.

In principle, another option could consist of terminating all copper pairs at the RS, and using the radio access link from that point onward. This alternative involves designing the radio link and scheduling algorithms to allow all users to receive the same transmission rate regardless of their location being indoors or outdoors. However, in this case the fixed link is not used and this prevents from providing each user with a connection permanently available at the guaranteed minimum bit rate. Anyway, even considering the ''best'' design of the radio system, the maximum achievable shared capacity could be limited by the aggregate capacity provided by the L extra pairs assigned by default to the RS. To avoid this limitation and thus further increase the downstream (DS) transmission capacity compared to that obtained only with the extra pairs, we consider the possibility that the RS receives data from the DSLAM using the pairs assigned to the CPEs at the same distributor, provided that they are temporarily inactive. This can be obtained using the arrangement in Figure 2. The pair assigned to each CPE is split (by means of a tap) at the distributor and one end is also connected to the RS. Using this strategy, we can connect up to N copper pairs to each RS with $N - L$ pairs already assigned to the CPEs for DS transmission only, and the L extra pairs for RS transmissions both in the upstream (US) direction and in the DS direction. The distance between the RS and the distributor could depend on the RS physical location, which is selected to optimize the wireless performance and coverage. The RS installation requires the deployment of up to N additional copper cables from the distributor to the RS. We can expect the length of these copper cables to be relatively short, from a few meters to tens of meters.

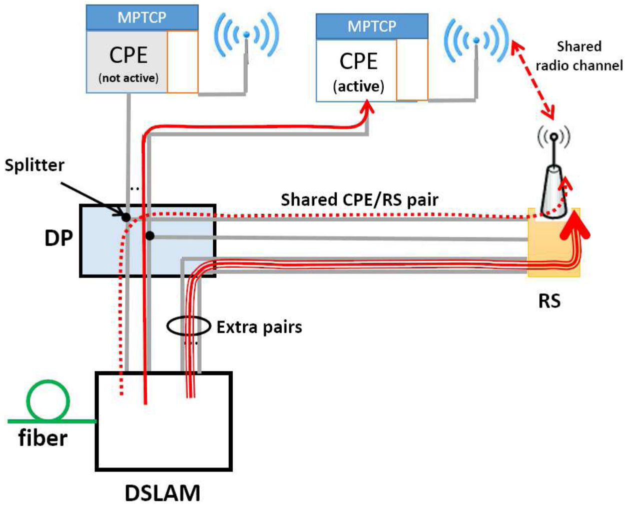

FIGURE 2. **Schematic of the arrangement at the distributor for copper pairs sharing.**

The setting in Figure 2 allows the DSLAM to send IUs (e.g. Ethernet frames) to the CPE or to the RS, each with its own MAC address or any other identifier (ID). The considered arrangement only requires minor modifications in current DSLAM operations. The DSLAM should send frames to the RS by also using the pair already assigned to the CPE (i.e. shared pair) only when no frames have to be forwarded to the CPE itself. The frame directed to the RS is also received by the CPE that discards it due to the mismatch of the destination MAC address. In the case of transmission errors, the frame directed to the RS is also discarded by the CPE.

Instead, as shown in Figure 2, each active CPE can receive data from the DSLAM, either from the assigned copper pair or from the shared radio channel provided by the RS. Data carried over the fixed and wireless channels could be recombined at higher protocol layer in the CPE, for example by means of the MPTCP protocol. It is out of the scope of this paper to further investigate on this aspect.

The HWW FTTC solution presented in this paper can be implemented by proper software modifications of the current DSLAM equipment. However, FEXT can significantly reduce performance. The application of vectoring in the non-shared pairs case is straightforward, and no modifications are required to the current DSLAM already equipped with the vectoring processor. The application of vectoring in the setting shown in Figure 2 is more complex. The vectoring control entity in the DSLAM should measure the FEXT transfer function between any two copper pairs in the network. The measurement between two copper pairs including one shared pair needs to be repeated twice since the single shared pair can be ‘‘terminated’’, alternatively, on the CPE or on the RS. The FEXT measurements are then stored, updated periodically, and used to generate the matrices used to precode symbols being transmitted on each sub-carrier. These matrices are generated by the DSLAM in accordance with the number and positions of active CPEs in the network, the extra pairs and the shared pairs assigned to the RSs. A technique to calculate the pre-coding matrix is provided in [15]. It is based on the knowledge of the $M \times M$ channel matrix $\mathbf{H}$, and M is the number of active copper pairs belonging to the cable running from the Cabinet.

When considering M copper lines including K shared lines with RSs, the DSLAM should be able to compute one unique channel matrix of dimensions $(M + K) \times (M + K)$. The single non-diagonal entry of this matrix contain the FEXT channel transfer function corresponding to interference of the generic i-th line (serving RS or one CPE) on the j-th line (serving RS or one CPE). Considering the simplest procedure to evaluate the non-diagonal matrix entry, the DSLAM can send pilot data to the i-th and to the j-th CPE/RS, which can measure reciprocal FEXT contributions and then return data to the DSLAM. Obviously, in the case of FEXT measurement on the generic shared line the pilot data should contain the logical address of the intended recipient i.e. the CPE or the RS.

During normal transmission, it is assumed the DSLAM always knows all the IDs of the intended M recipients. Some of these recipients could be the RSs that can receive data using one (or more) shared copper line(s). In this case, in order to build the correct pre-coding matrix the DSLAM extracts the $M \times M$ pre-coding matrix from the $(M + K) \times (M + K)$ estimated channel matrix by properly selecting the rows and columns corresponding to the intended receivers. A simplified example of this procedure (with $M = 3$, $K = 1$ i.e. only the copper line 1 is shared, $L = 1$ i.e. one extra pair assigned to the RS) is shown in Figure 3 and Figure 4. The considered simplified topology has been shown in Figure 3.

As shown in Figure 4 when the RS is not using the shared copper line and/or the DSLAM needs to transmit to the CPE (which should always have the highest priority over its assigned copper line), the channel matrix to be used for precoding is extracted from the $(M + K) \times (M + K)$ matrix by

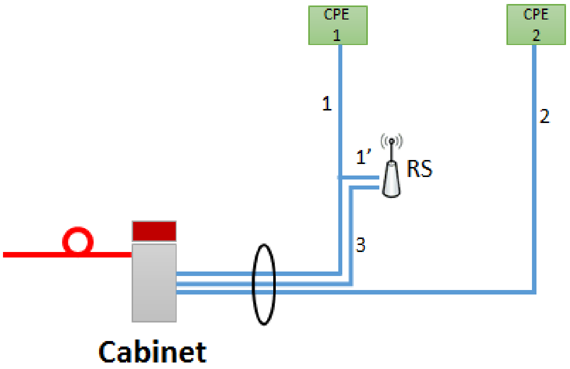

FIGURE 3. Calculation example of the channel matrix for pre-coding on DS transmission: considered topology.

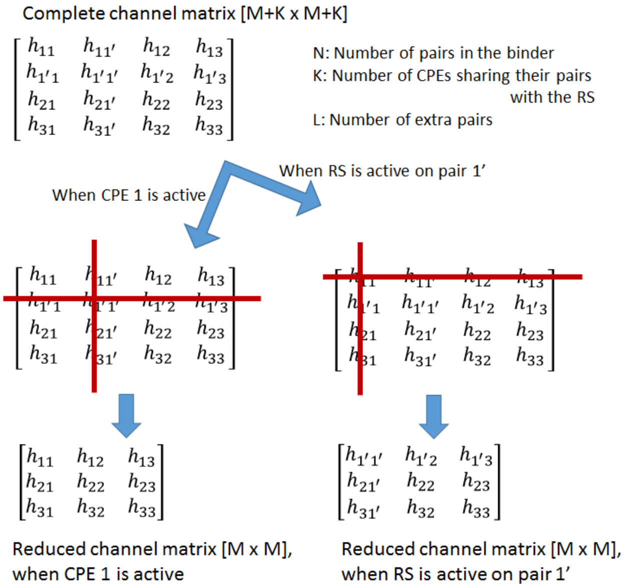

FIGURE 4. Calculation example of the channel matrix for pre-coding on DS transmission: procedure for channel matrix calculation.

deleting the rows and columns indicated in the left side of Figure 4. Instead, when the DSLAM transmits data to the RS over the shared copper pair, the corresponding channel matrix is obtained as indicated on the right side of Figure 4.

It seems difficult to apply the same principle for sharing copper lines on the US direction due to lack of coordination of transmissions among the RS and the CPE connected to the same shared copper line. The pre-coding matrices should be updated every time the topology changes. Events leading to a topology change are: *i.* one active CPE goes inactive and vice versa; *ii.* the single CPE is subject to reset or powered on/off. The single CPE may return active when the DSLAM receives one frame from the network to be directed to the inactive CPE. In this case, the RS ceases to use the shared line (if any). To facilitate the management of the single shared pair, it is envisaged that the DSLAM should use/allocate two separate buffers, i.e. one buffer stores the frame directed to RS and another one the frames to the CPE.

Even though the adoption of (non-mandatory) vectoring in the shared pairs case could be more involved (see before), it should be remarked that the management/control logic can be entirely implemented in the DSLAM, thus simplifying the practical implementation. As shown in the results section below the performance improvement due to vectoring is significant and can enable RS to support traffic even for some classes of forthcoming 5G services.

III. ENHANCED WIRED FTTC

The main characteristics of the EW FTTC solution for DS transmissions are detailed in this section. The following considerations can be easily extended to the upstream direction. In the EW solution the passive patch panel at the distributor is replaced by an active device operating as a transceiver including switching functionalities. Let N_i be the number of copper pairs from the main cable connected to the i-th distributor. We assume the single copper pair can transport IUs or data frames (typically Ethernet frames) directed to any one of the CPEs connected at the i-th distributor. In Figure 5 we detail the principle scheme of the active device at the distributor for the DS direction only. The distributor communicates with the DSLAM using N_i pairs of copper extracted from the main cable coming from the Cabinet. Considering DS transmission, the N_i shared pairs at the i-th distributor can be logically seen as a single data group managed by the DSLAM. Downlink data coming from the central office can be structured as Ethernet frames. They are directed to any one of the $P_i \leq N_i$ NTs connected to the i-th distributor. The DSLAM transmits these structured data on *any one* of the N_i pairs belonging to the same data group. Taking into account of the user activity, the combination of multiple resources (i.e., the "group of N_i copper lines" connected to the i-th distributor) allows to increase the transmission capacity experienced by the single user, so achieving a significant multiple access advantage.

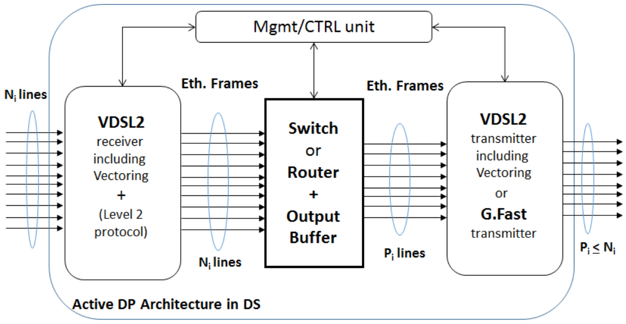

FIGURE 5. Principle architecture of the active transceiver including switching to be inserted at the distributor. DS transmission only.

The N_i pairs at the distributor are connected to N_i VDSL2 receivers possibly implementing vectoring or MIMO-DSL functionalities. The data frames recovered at the output of each VDSL2 receiver are sent to a switch, or to a router.[1] Data frames at the single switch output are then buffered for subsequent transmission on the corresponding

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[1] This allows to increase flexibility at the distributor at the expense of higher costs of the active device and increased processing time.

copper line, which is directly connected to the intended CPE. Buffers in Figure 5 are necessary to separate the receiving side by the transmitting section in the active device and possibly to absorb timing differences between the two stages.

The additional transmission delay due to presence of the active device at the distributor compared with the passive distributors can be estimated by considering the time sequence diagram in Figure 6. From Figure 6, the overall initial delay for frame transmission T_Δ is:

$$T_\Delta = T_{t1} + T_F + T_{p1} + T_{f1} + T_{sw} + T_{f2} + T_{p3} + T_{f3} + T_{t2} \tag{1}$$

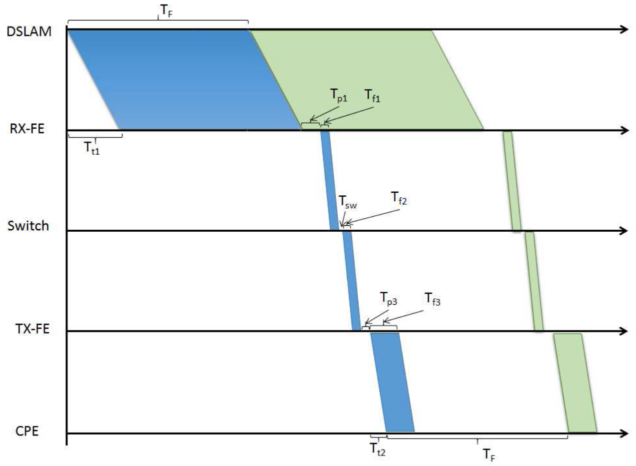

FIGURE 6. Frame transmission time diagram including the active device at the distributor. DS transmission only.

where $T_F = L/R_b$ is the duration of the frame on the link connecting the DSLAM to the front end receiver (RX-FE) in the device at the distributor. L is the frame length (bit) and R_b is the bit rate over the copper line. T_{t1} and T_{t2} are the delays due to propagation from DSLAM-to-RX-FE and from the transmitter front end (TX-FE) inside the distributor to the CPE, respectively. T_{p1} is the processing time inside the RX-FE and T_{f1}, T_{f2}, T_{f3} are the times required for transmitting the frame from the RX-FE to the internal switch, from the switch to TX-FE and from TX-FE to the CPE, respectively. We assume the time delay for switching T_{sw} is negligible with respect to the other contributions. Finally, T_{p3} is the processing delay in the TX-FE (for example due to vectoring pre-coding operations). Transmission times T_{fi} $i = 1, 2$ of the frames inside the active devices are (significantly) shorter than T_F i.e. we assume that the bit rate of connections among internal sub-systems are higher than the copper pair transmission bit rates. For T_{f3} we have assumed the bit rate of the DSL technology used for transferring frames to the CPE is higher than R_b. Finally, as shown in Figure 6 the maximum achievable frame rate per single copper-line is limited by the achievable frame rate DSLAM-to-RX-FE link, $1/T_F$. It should be observed that, in the presence of passive distributor the overall initial delay is the propagation time from the DSLAM to the CPE but the achievable frame rate can be lower than $1/T_F$. This is due to the fact that the bit rate on the copper line from the DSLAM to the CPE can be lower than R_b.

Thus, to fully exploit the available shared capacity, the transmission technology from the distributor to the CPEs could be different from that used on the DSLAM-to-distributor link. In fact, in principle one CPE should be enabled to use all the aggregated capacity of the N_i lines when it is the only active CPE at the distributor. Then, taking into account the short distance between the CPE and the distributor, the second transmission technology should be characterized by relatively large transmission bands even larger than the 35 MHz band of VDSL2. It is out of the scope of this paper to provide indications on the full set of features that this second transmission technology should possess. To fix ideas on one possible practical implementation of the active device in the distributor, we can consider VDSL2 for connecting DSLAM to the distributor (as in today's FTTC plants) and G.fast as the repeating technology. In fact, the simple adoption of VDSL2 technology on the distributor-to-CPE link does not permit the single user to better exploit all the available shared link capacity when other CPEs at the same distributor are not active. It is worth to note that the maximum theoretical bit rate limit for the VDSL2 profile 35b is about 392 Mbit/s (when all DS sub-carriers are loaded with 15 bits per symbol), which can be much lower than the capacity provided by the aggregated N_i pairs especially when the distributor is close to the Cabinet. The adoption of the G.fast technology on the distributor-to-CPE link allows better exploitation of shared DSLAM-to-distributor capacity for each subscriber. Furthermore, due to separation between VDSL2 and G.fast transmissions at the distributor, there is no need for G.fast to start transmissions from frequencies higher than those of VDSL2. This allows to full exploit the G.fast transmission capacity up to 1 Gbit/s over the single copper line for the profile 106b (106.1 MHz) or up to 2 Gbit/s for profile 212a (212.2 MHz). It is worth to mention that US flow control over the distributor-to-CPE links is necessary so to ensure proper operation of the devices as well as to regulate access to the shared DSLAM-to-distributor link.

The proposed active device operates at data link protocol layer (L2), and the active device located at the distributor switches the frames to/from the CPE. By using this approach we have abstracted the PHY layer. Then, the proposed transceiver device can be inserted in any position along the copper cable so switch and relay frames independently of the considered input and output DSL technologies. In other words, we can re-use our conceptual solution considering for example: VDSL on the DSLAM-to-distributor link and VDSL from the distributor-to-CPE links; G.fast from the DSLAM-to-distributor and G.fast or VDSL on the distributor-to-CPE links, etc. As shown in the following, the considered EW architecture allows to significantly improving the transmission capacity as seen by each user due to the beneficial effects of statistical multiplexing of the shared capacity offered by the N_i copper pairs at the distributor. The capacity of the single copper line decreases with the distance from the Cabinet. Therefore, the aggregate transmission capacity at the distributor decreases accordingly. The considered solution works for both short and long copper lines, since sharing of copper lines allows to increase the capacity which an end user experiences. When possible, unused copper pairs in the cable could be attached to the farthest distributor so to try to "equalize" the aggregate capacity at each distributor. More effective copper pairs planning strategy has been presented in [13]. The considered architecture naturally evolves towards the FTTDp if we assume that the G.fast modems located at the distributors are equipped with a plug for the optical fiber.

A. ON THE SHARING OF EW FTTC INFRASTRUCTURE IN THE MULTI-OPERATOR CASE

It is simple to apply the EW FTTC solution to the single operator case. In the multi-operators scenario the EW FTTC infrastructure should be shared among operators in accordance with specific national regulations. In principle, the single Cabinet in the EW FTTC network, including a modified DSLAM and one or more active distributors along the cable, could be shared among operators in accordance with bitstream approach including the virtual unbundling of the local access (VULA). In this case the IUs reaching the DSLAM are routed to the intended CPE at the distributor independently of the operators they belong to, i.e. only the CPE ID (e.g. the MAC address in the Ethernet frame) in the data frame is used to route it to the destination CPE. On the contrary, when operators need to directly access and manage their transmission resources, the sub-band vectoring (SBV) technique in [16] allows solving the infrastructure sharing problem. In this case, the DSLAM can transmit IUs of each operator using all the available copper pairs at the distributor but the signals transmitted on the single copper pair occupies the assigned VDLS2 band as specified by the SBV technique. In general, when considering the application of SBV to the EW FTTC we can distinguish, at least, the following two options:

- the SBV technique is applied on the DSLAM-to-distributor link only, i.e. no SBV on the distributor-to-CPE link is provided; this strategy allows the single operator to control/manage the assigned physical resource up to the distributor;
- the SBV technique is applied on the two-hops link up to the CPE; in this case the operator owns full control of *physical* resource up to the CPE.

The single Cabinet of the EW FTTC could also be shared on a time division basis even though this option may require the entire revision of the currently adopted technologies for DSL-based access networks.

The problem of the sharing of the EW FTTC infrastructure is slightly more complicated when the single operator is allowed to control/manage its assigned copper pairs. The main difficulty may arise when one operator would not share its copper pairs with other operators. In this case, the single group of copper lines at the distributor could be partitioned into more sub-groups. Each sub-groups is assigned to one operator and the corresponding copper lines could be connected to one active device at the distributor, which is managed and controlled by the operator itself. This single active device uses a reduced number of copper lines, that are shared by the users of the operator. Furthermore, for what concern the DSLAM we need to distinguish between the following two possibilities. In the first option the DSLAM is shared among operators while in the second each operator installs and manages its own DSLAM at the (same) Cabinet. In the former case, the single DSLAM should be able to forward the IUs to the CPE on the basis of the CPE ID and on the ID of the operator since IUs should be forwarded only using the subset of copper lines assigned to the operator. In the latter case the problem is automatically solved using more separated DSLAMs each one serving its sub-group of copper lines. When operators share the DSLAM, Vectoring+Phantom and/or MIMO techniques can be easily applied on the whole set of copper lines in the main cable. This allows to significantly improve the performance for all operators. In the case of more separated DSLAMs at the Cabinet (one per operator), to apply vectoring and/or MIMO to the entire cable, an additional unit is necessary to coordinate DSLAMs. As an alternative, SBV techniques using disjoint sub-bands could be adopted to avoid the installation of this coordination unit.

B. A SHORT DISCUSSION ON THE PRACTICAL IMPLEMENTATION OF THE EW FTTC SOLUTION

For a practical implementation of the EW FTTC solution, the functionalities of the current DSLAM should be properly updated. In principle, main modifications required in current DSLAMs can be realized in software. As discussed in the previous section, the modified DSLAM should be able to forward the data frames to one CPE in the i-th group using any one of the N_i copper lines connected to the i-th distributor. To this purpose, multi-link protocols like IEEE 802.3ad can be helpful. At the same time the DSLAM should ensure the fair allocation of shared capacity among users in the same data group, i.e. the DSLAM should implement (optimal) scheduling strategies to manage data traffic on the N_i shared pairs at the i-th distributor. In order for the EW FTTC system to properly operate, the updated DSLAM should be able to automatically identify the copper lines assigned to each distributor and then to achieve the IDs (e.g. the MAC addresses) of the CPEs connected to it. To this aim, the active device at the distributor should send a kind of test-tone signal over any one of the N_i lines so to allow the DSLAM to identify them in the main cable. After this association has been carried out, the identification of the single CPE connected to the copper line should proceed in accordance with the usual VDSL2 procedures and the active device at the distributor should be transparent. As an alternative, the active device at the distributor could perform the identification of its connected CPEs and then transmit this information to the DSLAM.

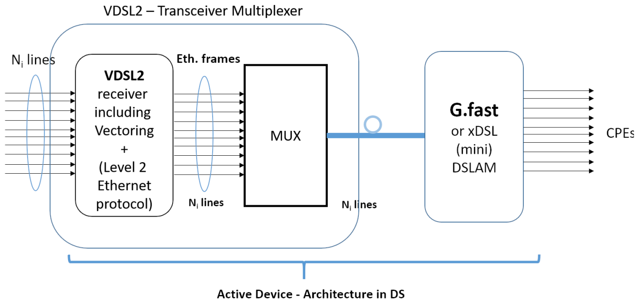

FIGURE 7. Principle scheme of implementation of the active device at the distributor.

One practical implementation of the active device at the distributor is shown in the scheme in Figure 7 for the case of combined use of VDSL2 and G.fast standards. The active devices in Figure 5 has been functionally decomposed into two cascaded devices. The main purpose of the first device indicated in Figure 7 as VDSL2 transceiver multiplexer is to receive the Ethernet frames on the VDSL2 copper lines at its input and to multiplex them on the optical (Ethernet) link at its output. The optical link is in input to the (standard) G.fast DSLAM using 24 up to 48 ports, which is already available on the market.[2] Then, as shown in Figure 7 the only new device to be designed and developed is the VDSL2 transceiver multiplexer. All the complexity required to routing frames to the CPEs is then relegated to the G.fast DSLAM. It is worth to note that the copper link between the DSLAM and the VDSL2 transceiver multiplexer at the distributor could be imagined as a copper (‘‘red’’) fiber connecting the DSLAM in the Cabinet to the remote G.fast DSLAM i.e. the considered EW FTTC practically realizes the FTTDp or the FTTB access solutions using a bunch of copper pairs instead of the optical fiber. Thus, the considered sharing technique can boost G.fast deployment in existing copper cable plants allowing immediate no-fiber G.fast deployment and so pushing gradual increase of customers asking for very fast ultra-broadband speed. This can be achieved without risky investments for the operator.

IV. SYSTEM MODELING

In this section we introduce the main parameters used to assess the transmission performance of the proposed HWW/EW FTTC access schemes and the corresponding mathematical models used in our computer calculations.

A. BIT RATE CALCULATION PER SINGLE COPPER PAIR

The main parameter assessing DSL performance is the achievable bit rate for the (generic) i-th subscriber at distance d_i from the Cabinet:

$$R_b(d_i) = R_s \sum_{k \in I_c} B[\rho_k(d_i)] \tag{2}$$

where I_c is the set of sub-carriers indices assigned to DS transmission, R_s is the symbol rate. $B[\cdot]$ in (2) is the number of bits to be allocated on the k-th sub-carrier in accordance with the following criterion:

$$B[x] = \begin{cases} b_{max} & \text{if } x \geq b_{max} \\ x & \text{if } b_{min} \leq x < b_{max} \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

where b_{min} and b_{max} are the minimum and maximum number of bits, respectively, that can be allocated per sub-carrier. The $\rho_k(d_i)$ in (2) is:

$$\rho_k(d_i) = \log_2\left(1 + \frac{SINR_k(d_i)}{\Gamma}\right) \tag{4}$$

and Γ is the performance Gap [3]. Let $SINR_k(d_i)$ be the Signal-to-Interference plus Noise Ratio (SINR) on the k-th sub-carrier at frequency f_k for the i-th reference user at distance d_i from the Cabinet. It can be approximated as:

$$SINR_k(d_i) = \frac{|H_{D,k}(d_i)|^2 P_{i,k}}{\eta_k + \nu_k I_{F,k}(d_i)}, \tag{5}$$

where η_k is the power of the Background Noise at frequency f_k; $P_{i,k}$ is the power transmitted by the i-th (reference) user at distance d_i from the Cabinet on the k-th sub-carrier. The $I_{F,k}(d_i)$ is the FEXT power and ν_k is the coefficient accounting for FEXT reduction due to vectoring pre-coding. We have $\nu_k = 1$ in the non-vectoring case and $\nu_k \ll 1$ otherwise. In general ν_k depends on the sub-carrier frequency. The average FEXT power $I_{F,k}(d_i)$ experienced by the i-th CPE at distance d_i from the Cabinet is:

$$I_{F,k}(d_i) = \sum_j |H_F(d_i, l_{ij})|^2 P_{j,k} \cdot (1 - \delta_{ij}), \tag{6}$$

where δ_{ij} being the Kronecker delta and the summation extends over the index j indicating the active copper pairs. The $H_F(d_i, l_{ij})$ in (6) is the FEXT transfer function, whose expression is [17]:

$$H_{F,k}(d_i, l_{ij}) = \sqrt{\chi_F l_{ij}} f_k 10^{X_{ij}/20 - \Delta_{ij}/20} 10^{\iota \phi_{ij}} H_{D,k}(d_i) \tag{7}$$

where $\{\phi_{ij}\}$ are random phase terms independent of k and uniformly distributed in $[0, 2\pi)$; l_{ij} is the coupling length between the i-th and j-th active users that can be obtained from the access network geometry. The χ_F is the FEXT coupling coefficient and the random variables $\{X_{ij}\}$ (in dB) model FEXT fluctuation with respect to the 1% FEXT condition, [17]. The single X_{ij} are assumed to be Beta distributed, whose statistics are invariant with the distance from the Cabinet and with the sub-carrier frequency. Furthermore, the $\{X_{ij}\}$ are assumed to be i.i.d. [17]. The Δ_{ij} (in dB) are constant terms accounting for coupling among copper pairs lying in the same or in different binders. Their values have been obtained experimentally and are reported in [17]. They depend on the relative positions of the binders in the main cable. Obviously, we have $\Delta_{ij} = 0$ when the i-th and the j-th copper lines lie in the same binder. Finally, $H_{D,k}(d_i)$ in (5) and in (7) is the direct propagation transfer function evaluated at sub-carrier frequency f_k.

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[2] The typical number of copper pairs at each distributor is of some tens. In Italy, this number varies from 10 up to 40.

B. PERFORMANCE PARAMETER FOR HWW FTTC

We start analysis from the single distributor situation depicted in Figure 2. Let $R_{b,F}(d)$ and $R_{b,W}(d_{RS}, d_{CPE-RS})$ be the achievable (gross) bit rates at the active CPE from the assigned pair (F) and from the shared radio channel (W). Then, the total bit rate at the CPE can be approximated as:

$$R_{b,CPE}(d) \cong R_{b,F}(d) + R_{b,W}(d_{RS}, d_{CPE-RS}). \tag{8}$$

In (8) we have evidenced the dependence of the achievable bit rate at the CPE on the distances d of the CPE from the Cabinet and on the distance d_{RS} of the RS from the DSLAM. The d_{CPE-RS} is the radio distance of the CPE from the RS. In the following derivation we assume $R_{b,W}(d_{RS}, d_{CPE-RS})$ is (approximately) equal to the total aggregate transmission capacity provided by the extra and shared pairs assigned to the RS i.e. $R_{b,W}(d_{RS}, d_{CPE-RS}) \cong R_{b,W}(d_{RS})$.[3] Thus, we do not consider any particular radio access technology, and we assume the radio interface allows the single CPE to access the full radio capacity when it is alone. Let N be the numbers of pairs at the generic distributor and L the number of extra pairs assigned to RS. For simplicity, we consider only one RS at each distributor. Let Q the number of active CPEs connected to the (generic) distributor and $0 \leq Q \leq N - L$. Indicating with $R_{b,RS}$ the total bit rate capacity provided by the extra and (non-active) shared pairs at RS and assuming (ideal) fair access of $Q \geq 1$ active CPEs to the radio channel, we have[4]:

$$R_{b,W}(d_{RS}) \cong \frac{R_{b,RS}(d_{RS}) - R_W}{Q} \tag{9}$$

where R_W is the bit rate assigned to serve outdoor users moving in the proximity of RS and $R_{b,RS}(d_{RS})$ is:

$$R_{b,RS}(d_{RS}) = \sum_{l \in S_L} R_{b,E}(d_{RS})_l + \sum_{l \in S_{N-L-Q}} R_{b,S}(d_{RS})_l \tag{10}$$

where S_L is the set of indices indicating the copper pairs corresponding to the extra pairs (E) and S_{N-L-Q} is the set of indices corresponding to the shared pairs (S) of non-active CPEs. The $R_{b,E}(d_{RS})_l$ and $R_{b,S}(d_{RS})_l$ are the bit rates provided by the l-th extra pair assigned to the RS and the bit rate on the l-th unused shared pair.

In general, the indices and the dimension of S_{N-L-Q} vary with time in accordance with the activity of the CPEs connected to the shared pairs at the RS. The bit rates in (8) and (9) can be calculated using (2) once distances d, d_{RS} and the (present) interference scenario (i.e. the overall number of active users and their positions) have been determined.

C. PERFORMANCE PARAMETER FOR EW FTTC

In the case of EW FTTC let $R_{b,D}(d_D)$ be the gross aggregate bit rate available at the generic distributor at distance d_D from the Cabinet:

$$R_{b,D}(d_D) = \sum_{l \in S_D} R_{b,D}(d_D)_l \tag{11}$$

where $R_{b,D}(d_D)_l$ is the achievable bit rate on the l-th copper pair (including the extra pairs) at the considered distributor. It is given in (2) once distances d_D and the (present) interference scenario on the copper cable from the Cabinet have been specified. Assuming the effect of the additional distance from the distributor to the CPEs is negligible and assuming access fairness to the shared capacity, let $Q \geq 1$ the (present) number of active CPEs in the building, the bit rate per single CPE is:

$$R_{b,CPE}(d) \cong \frac{R_{b,D}(d_D)}{Q}. \tag{12}$$

We assume that the RS is designed to minimize the degradation due to radio propagation. It is worth to note that when $R_W = 0$ in (9), all the non-active pairs (including the extra pairs) are assigned to the RS and $d_{RS} \cong d_D \cong d$ (i.e. we neglect propagation due to the additional distance of the CPE from the distributor) the bit rates in (8) and (11) are identical for the same number of active CPEs, Q.

For simplicity in previous formulas we have assumed that the achievable (shared) capacity at the distributor is equally partitioned among the CPEs. As previously outlined, it is out of the scope of this paper to further investigate on the (several) strategies for the optimal and fair sharing of fixed aggregate link or radio link capacity among CPEs. For what concerns the HWW solution, the optimal design of the radio link covering the intended CPEs should account for the propagation characteristics of the local environment. Instead, when considering the application of EW on an existing FTTC network, some of main parameters to be considered for optimal management of the shared capacity are the selection of the distributor-to-CPE transmission technology (e.g. G.fast or G.mgfast) and the adoption of adaptive/intelligent allocation strategies of the shared capacity on the basis of the type of traffic generated by each CPE connected to the distributor.

V. PERFORMANCE ANALYSIS

In this section we evaluate the performance of the considered solutions for the data link sharing of copper pair capacity among CPEs. FTTC performance is expressed in terms of the bit rate per user at the distributor in (8) for HWW and in (12) for EW and have been obtained by computer calculation. Assumptions used to derive bit rate results are first explained. Then, results concerning both solutions and their variants are presented and discussed.

A. CALCULATION ASSUMPTIONS

The VDSL2 profile 35b technology has been considered for transmission between the DSLAM at the Cabinet and the

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[3] As previously noted, the RS should be properly designed so to avoid degradation due to radio propagation. This could be obtained for example by adding more radio access points providing radio coverage of the single building at different heights, etc.

[4] When $Q = 0$ we assume $R_{b,CPE}(d) = 0$, i.e. there is no active user at the considered distributor. In the calculation of statistics for the achievable bit rate per user at each distributor, the events $R_{b,CPE}(d) = 0$ have been discarded.

distributors located along the copper cable. To fix ideas, we consider a copper cable from the Cabinet with 200 pairs uniformly grouped into four separate binders. A number of groups of ten copper pairs each are extracted from the single binder and then assigned to each distributor. The FEXT model in [17] has been considered and used for frequencies up to 35 MHz. In the example scenario considered in this paper we assume each distributor has a total of 20 pairs including 6 extra pairs (i.e. 30% of inactive pairs), which are assigned to the corresponding RS in the HWW scenario. Instead, all pairs are used at the distributor to transmit signals at the CPEs in the case of EW. The minimum and maximum number of bits per sub-carriers are $b_{min} = 1$ and $b_{max} = 15$, respectively; the value of the FEXT coupling coefficient χ_F is given in [17] and $\Gamma = 12$ dB. Let α be the probability the single CPE connected to the distributor is active. Thus, for each distributor we have $Q \geq 0$ active CPEs with Q ranging from 0 to $N - L$ that can share up to N copper pairs at the distributor (including the L extra pair). We assume the probability of having $Q \geq 0$ active CPE is binomial with parameters $(N - L, Q)$. Distributors are located at the following distances from the Cabinet: 50 m, 100 m, 200 m, 300 m, 400 m, 500 m, 600 m, 700 m, 800 m, and 1000 m. To simplify performance evaluation, in the following we assume v_k is independent of frequency and $v_k = -20$ dB for each k in (5), which is a practical value for current vectoring technology for the considered frequency bands and (approximated) zero forcing vectoring pre-coder. In the case of HWW solution we assume no outdoor mobile user is connected to the RS, i.e. $R_W = 0$ in (9).

B. RESULTS

Performance results presented in this section are obtained considering negligible the effects of additional distance of d_{RS} and d with respect to the distance of the distributor from the Cabinet d_D, i.e. we are considering an upper bound on the achievable performance. In this case bit rate formulas in (8) and in (12) provide the same results except when the basic HWW-FTTC configuration is considered i.e. only the extra pairs are assigned to the RS. Thus, in the following we plot only one set of curves, which are valid for both HWW and EW and we evidence the case corresponding to the basic HWW-FTTC.

In Figure 8 we plot the mean of the bit rate per user at the distributor in (8) and in (12) as a function of the distance of the distributor (d_D) from the Cabinet. Results are valid for both HWW and EW and have been obtained with and without vectoring. The activity factor has been set to $\alpha = 0.5$ and data refer to the following situations for HWW: *i.* (basic HWW-FTTC) RS capacity is provided by the assigned extra pairs; *ii.* (full HWW-FTTC) the RS is connected to all the pairs at the distributor (extra and shared). For the EW-FTTC scenario results correspond to those of the full HWW-FTTC case. For comparison we have also reported the legacy case where nor RS neither active device at the distributor have been installed (i.e. $R_{b,CPE}(d) \cong R_{b,F}(d)$). The improvement of the achievable bit rate at the distributor (and thus at the CPE) with respect to the legacy FTTC access network in the non-vectoring case is significant i.e. it is between 50% and about 65% in the basic HWW-FTTC scenario and from 95% up to 135% in the corresponding full case with $\alpha = 0.5$ and for distances up to 400 m. Adoption of vectoring allows to further improve the previous figures especially in the full HWW-FTTC and EW-FTTC scenarios where we obtain improvements up to 200% within the same distance interval.

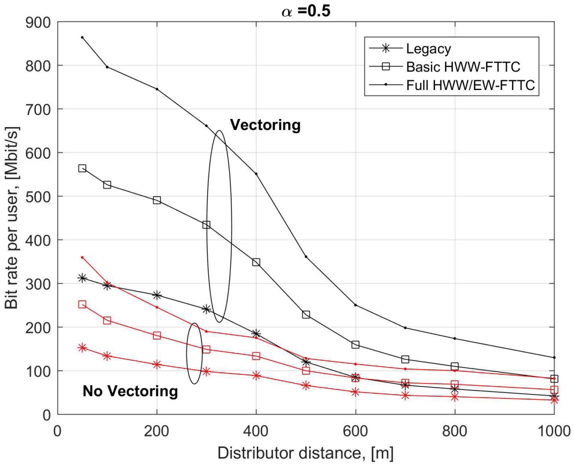

FIGURE 8. Mean bit rate per user vs distance from the Cabinet: user activity $\alpha = 50\%$, vectoring and non-vectoring cases.

In Figure 9 and in Figure 10 we plot the complementary cumulative distribution function (C-CDF) of the achievable bit rate per user at the distributor in the basic and full HWW/EW-FTTC scenarios, for $\alpha = 0.5$, at $d = 100$ m and $d = 400$ m, without and with vectoring respectively. Results in Figure 9 for full HWW-FTTC further confirms those presented in Figure 8 showing the achievable performance overcomes that obtained in the basic HWW-FTTC scenario. In particular it can be observed that in the non-vectoring case even at relatively large distances from the Cabinet (e.g. $d = 400$ m which is the typical maximum distance for

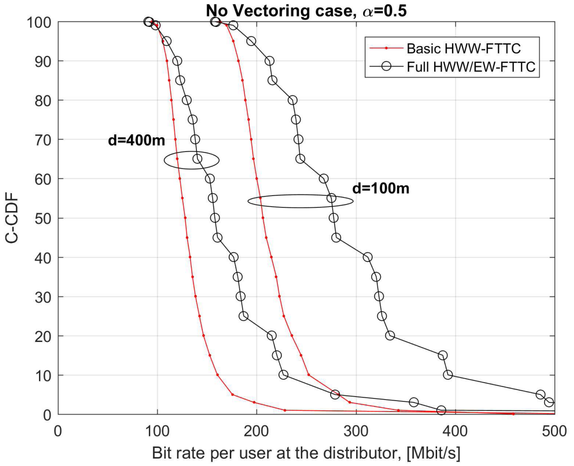

FIGURE 9. C-CDF of the bit rate per user without vectoring: $\alpha = 50\%$ and distances of the user $d = 100$ m and $d = 400$ m.

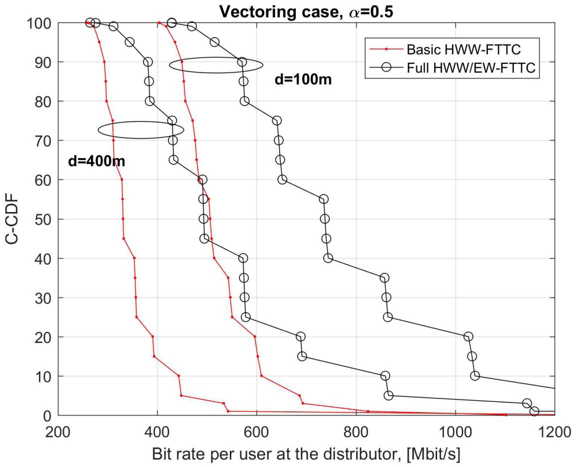

FIGURE 10. C-CDF of the bit rate per user with vectoring: $\alpha = 50\%$ and distances of the user $d = 100$ m and $d = 400$ m.

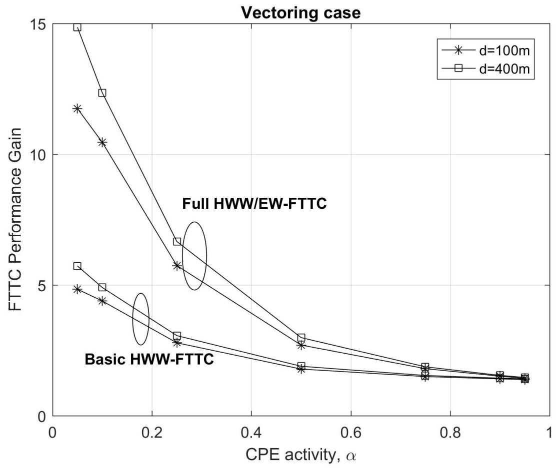

FIGURE 12. Bit rate per user as a function of the CPE activity, α, with vectoring: CPE distances $d = 100$ m and $d = 400$ m.

VDSL2 application) in the 90% of cases we obtain a bit rate higher than 120 Mbit/s. As expected, the application of vectoring allows to significantly boost performance providing bit rates higher than 380 Mbit/s in the 90% of the cases at $d = 400$ m. This is achieved at the expense of an increased complexity in the modifications to be introduced in the current DSLAM apparatus. Same considerations for full HWW-FTTC still apply for the EW-FTTC case.

The effects of user activity on the achievable bit rate per user is shown in Figure 11 and Figure 12 for non-vectoring and vectoring case, respectively. In these figures we plot the achievable performance gain of the considered HWW-FTTC and EW-FTTC solutions for variable activity factor α and for two distributors at distances from the Cabinet $d = 100$ m and $d = 400$ m. The HWW/EW-FTTC performance gain is defined as the ratio of the bit rate in (8) or in (12) with respect to the corresponding bit rate obtained in the legacy conditions with or without vectoring. From results in Figure 11 and Figure 12 it can be observed that the proposed system allow to significantly improve the achievable bit rate with respect to the legacy case. As expected, the increase of the user activity α reduces the achievable performance gain of the considered sharing solutions. However, even in the worst case (i.e. $\alpha \cong 1$) performance gain is still greater than one. This is due to the additional shared capacity provided by the extra pairs (only). From Figure 11 and Figure 12 it can be observed the availability of extra pairs to share allows to achieve at distance 100 m a (minimum) gain of about 41% with vectoring and of about 20% in the non-vectoring case and for (un-realistic) activity α close to 1. When including vectoring the HWW/EW-FTTC allows to achieve significantly higher gains with respect to legacy FTTC, specifically more than 5.7 times at distance $d = 100$ m and 6.6 times at distance $d = 400$ m assuming the lower user activity, $\alpha = 0.25$. Finally, as shown by results in previous Figures, in every case HWW/EW-FTTC allow to increase area coverage of VDSL2 well beyond the maximum distances typically envisaged for VDSL2. In particular, the adoption of EW-FTTC solution facilitates the Long-Reach VDSL deployment in sub-urban and rural areas allowing to reach bit rates greater than 100 Mbit/s for distances up to 1000 m with relatively high user activity, $\alpha = 0.5$.

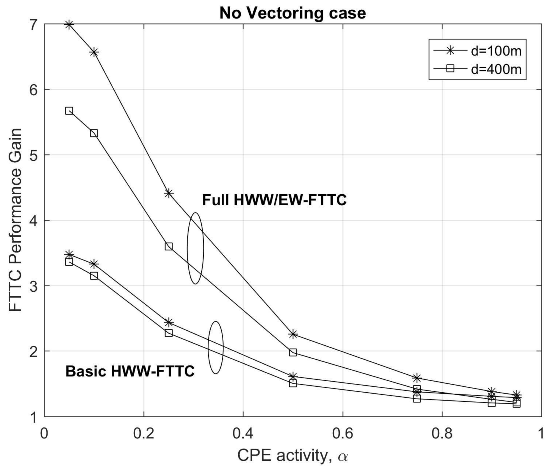

FIGURE 11. Bit rate per user as a function of the CPE activity, α, without vectoring: CPE distances $d = 100$ m and $d = 400$ m.

VI. CONCLUSIONS

Two techniques for the evolution of the present FTTC access network architecture indicated with HWW and EW have been presented in this paper. They work with and without vectoring. The HWW adopts a shared radio access channel providing extra capacity to connected CPEs inside the served building(s). In the basic HWW setting the RS creating the shared radio channel is connected to the DSLAM by means of the extra pairs available at the distributor. This facilitates and speeds up deployment. In the full HWW implementation we have evaluated the possibility for RS to receive data from DSLAM even using the copper pairs in the distributor assigned to CPEs when they are non-active. The logic of management for the shared pairs is implemented in the DSLAM. Vectoring can be easily supported in the basic HWW case.

Alternatively, we have considered the possibility of replacing the passive patch panel at the distributor with one active device allowing to share transmission capacity of the group of copper pairs connected to the distributor. This second solution, indicated as EW, allows to easily support system-level vectoring. It is important to remark that the active device at the distributor can be realized with existing electronic components available on the market.

Both HWW and EW results show that, the introduction of data link sharing permits to decisively improve performance especially in the case of moderate traffic activity of subscribers. It allows achieving bit rates of hundreds of Mbit/s even to CPEs (relatively) far from the Cabinet. The possibility of including system-level vectoring enable to further boost performance at short distances so that the considered evolved FTTC systems could be successfully used to carry data traffic even for 5G radio access points in dense 5G networks.

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