

# Radio over Telephone Lines in Femtocell Systems

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**Abstract**—Wireless over Cable (WoC) paradigm is a new technique to enable distributed antennas systems. WoC is based on the relay of radio frequency wireless signals over a cable infrastructure through a bidirectional (analog) amplify and forward device that translates the bandwidth of wireless signals to comply with the specifications of the wired links. Following the WoC concept, here xDSL connection in femtocell architecture is replaced with a plain connection of the antenna with telephone lines after up/down-frequency conversion to enable Radio over Telephone Lines. Baseband processing and radio resource management is carried out simultaneously for multiple femtocells thus centralizing scheduling and mitigation of radio frequency interference among neighboring femtocells. We propose the envisioned Radio over Telephone Lines architecture for femtocells and get insights into the hindrances of propagation over twisted pair copper lines via numerical analysis by employing OFDMA signals over the air interface (WiMAX/LTE) that coexist (and interfere) with xDSL services.

**Index Terms**—IEEEtran, journal, L<sup>A</sup>T<sub>E</sub>X, paper, template.

## I. INTRODUCTION

Data rates envisioned for the 4G wireless systems in reasonably large areas do not appear to be feasible with the conventional cellular architecture due to the spectrum usage above the 2GHz band, where in-building radio penetration is heavily penalized. This has been driving the cell-size reduction trend that has been experienced in the last years. Cell reduction down to the range 10-50m, possibly indoor, is the paradigm of femtocells based on low-power, low-cost user-deployed base stations. Figure 1-(a) shows a conventional femtocell system. The basic idea of femtocells lies in deploying in-house base stations (or femtocell access points - FAPs) capable of providing wireless voice and broadband services (such as UMTS, WiMAX and HSPA/LTE) to customers in home or office environments connected with the operator's core network through a broadband connection (such as xDSL). Compared to other techniques for increasing system capacity, the key advantages of femtocells are the reduced deployment cost for the service provider, and the increased indoor/outdoor coverage (namely for spectrum allocation beyond 2GHz).

However, the femtocell paradigm unavoidably has to face with several (still) open issues such as synchronization (especially if using Orthogonal Frequency Division Multiple Access - OFDMA - as access method), security, interference and mobility management (see, e.g., [1]). All these issues could be more efficiently handled by a centralized approach rather than by employing dislocated and likely uncoordinated FAPs.

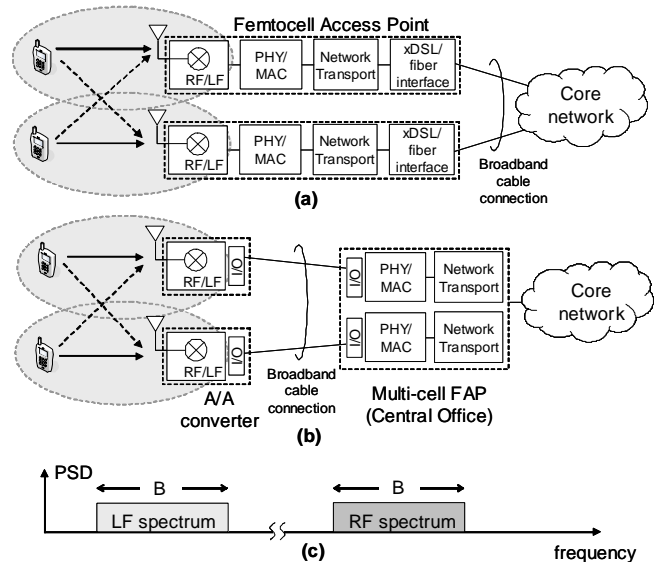


Fig. 1. Comparison of (a) conventional Femtocell architecture with FAPs over xDSL connections and (b) proposed FemtoWoC architecture over the same telephone lines. In FemtoWoC architecture (b), the analog-to-analog (A/A) converters are remotely deployed in every cell to replace conventional FAPs, while processing is centralized in Multi-cell FAP (e.g., placed at Central Office). A/A devices convert the RF wireless signal (RF spectrum) into a low frequency signal (LF spectrum) and vice versa (c).

Focusing on the PHY/MAC level, the operators experience dichotomy between mitigating radio frequency (RF) interference and allocating spectrum to femtocell and macrocell users. The scarce availability of radio resources, together with flexibility in the deployment, would preferably lead to the usage of the same spectrum bandwidth, with the unpleasant effect of the arising of RF interference, both *co-tier* (among neighboring femtocells) and *cross-tier* (femtocell-to-macrocell and macrocell-to-femtocell). In this context, due to the heavy dislocation of the end-users that deploy customized FAPs, centralized frequency/power planning is prohibitive, so that FAPs are required to include some algorithms for the minimization of the radio interference (both cross- and co-tier) [2], e.g., based on the periodical optimization of power level and neighbors' parameters. However, these self-configuring policies are not suited to the highly varying nature of the femtocell environment, where fast fading effects of the radio channel superpose with unpredictable femtocell activation and deactivation. Moreover, the low cost target for the FAPs pre-

vents to perform sophisticated algorithms, so that decentralized interference mitigation is an active area of research.

**Contribution.** We propose a centralized approach based on Wireless over Cable architecture for femtocells illustrated in Fig.1-(b). This novel architecture, referred to as FemtoWoC architecture, aims at mitigating the interference arising from a group of neighboring femtocells sharing the same spectral resource. The new paradigm is based on the concept of leaving to the in-home device the analog RF processing, while deferring the PHY/MAC functionalities for multiple devices to a remote destination that employs the multiple femtocell access points (Multi-cell FAP). Namely, on the one hand, the in-home device acts as a bidirectional wireless-to-cable adapter that guarantees that the femtocell RF signals are transferred to/from antennas from/to the remote Multi-cell FAP node using the analog connectivity (telephone wire or coax or power lines or optical fiber) in place of digital link (as for xDSL). On the other hand, the remote Multi-cell FAP guarantees strict cell coordination/synchronization to efficiently exploit the concept of centralized multi-cell processing for reducing co/cross-tier interference. In this paper, deployment of the FemtoWoC architecture over twisted pair telephone lines is considered, thus enabling the Radio over Telephone Lines paradigm. The aim is to evaluate feasibility of the envisioned Radio over Telephone Lines architecture for femtocells despite the hindrances arising from propagation over twisted pair copper lines (with emphasis to coexistence with xDSL-like services), together with the benefits of multi-cell processing.

In Sec. II, the reference paradigm of the proposed FemtoWoC architecture is presented. Baseband system model for the Radio over Telephone Lines architecture employing OFDMA signals over the air interface is detailed in Sec. III. Coexistence issues with xDSL and E1/T1 services deployed in neighboring copper pairs for the case of IEEE 802.16e air standard [3] are investigated in Sec. IV through numerical analysis. Conclusions follow in Sec. V.

## II. FEMTOWOC ARCHITECTURE

The new Femtocell through Wireless over Cable (FemtoWoC) architecture in fig. 1-(b) resembles the conventional architecture of femtocell systems (fig. 1-(a)) except for the in-house device. The underlying principle of the FemtoWoC architecture is to ensure an amplify and forward transferring of the wireless signals from/to femtocell users belonging to a group of neighboring femtocells towards/from a remote Multi-cell FAP, so as to enable a paradigm of centralized interference handling via multi-user MIMO processing. With respect to the conventional femtocell deployment, FemtoWoC architecture is accomplished by the following devices:

(i) *Analog-to-analog converter.* Every in-house FAP is replaced by a bidirectional amplify and forward device, namely analog to analog (A/A) converter, capable of handling a bidirectional analog flow to interface the radio environment with the available cable infrastructure. Specifically, the A/A converter is in charge of performing a frequency conversion of the RF wireless signal incoming from a femtocell user to a lower frequency appropriate for transmission over the

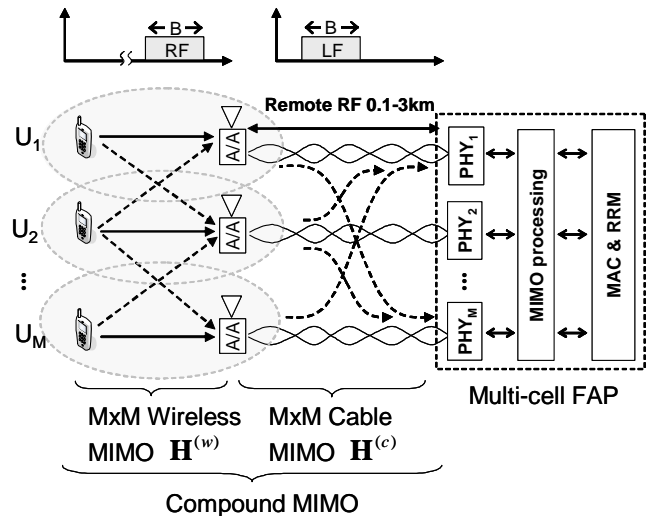


Fig. 2. Multi-cell FAP exploits compound MIMO channel as the cascade of wireless MIMO and cable MIMO channel.

available cable infrastructure for the uplink, and vice-versa for the downlink (see fig. 1-(c)). Moreover, the A/A device adapts the spectral mask of the signal both at the antenna and cable interface, so as to accomplish the standard-specific power requirements. Of course, the technological solution of the A/A converter as home-device depends specifically on the existing home-to-Multi-cell FAP connections, namely copper-based (telephone line or coax or power line), or optical fiber.

(ii) *Multi-cell FAP.* The baseband processing functionalities typically implemented at the traditional FAPs (see fig. 1-(a)) are deferred to the remote Multi-cell FAP. Multi-cell FAP can be located at the Telephone Company Central Office, and provides PHY/MAC termination to different A/A devices, so as to enable centralized control and resource management.

FemtoWoC architecture centralizes the processing (PHY/MAC) tasks for a group of neighboring femtocells and it is envisioned to merge advantages deriving from conventional femtocell implementations and distributed antenna systems [4], namely high indoor coverage and MIMO processing/diversity exploitation. Time and frequency synchronization is mandatory to handle all these signals simultaneously and to make the MIMO processing at the Multi-cell FAP be maximally efficient in interference mitigation (or spatial-diversity exploitation).

The drawback of FemtoWoC architecture is the additional source of interference that might arise from home-to-Multi-cell FAP cable connection. In other words, even if radio signals of two femtocells are operating over different spectrum (and thus not-interfering), once signals are down-converted by the A/A devices to fit onto the cable spectrum allocation, they could be interfering over the cable as for the case of twisted pair telephone lines (Sec. III).

Even if fiber to the home (FTTH) paradigm would be in the long term vision the ideal cabling situation [5], the so called *copper last mile bottleneck* is still the realistic situation in up-to-day access network infrastructures. For this reason, in short term the exploitation of existing phone lines will be

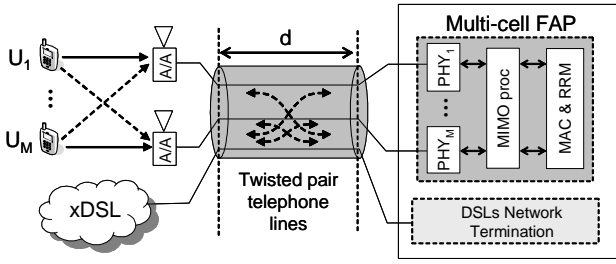


Fig. 3. FemtoWoC architecture composed of  $M$  femtocells (one user per femtocell) connected to the remote Multi-cell FAP through  $d$ -long twisted pair telephone lines. xDSL services coexist in the same cable binder, creating FEXT/NEXT interference to the FemtoWoC signals.

the necessary enabling element for spreading the FemtoWoC architecture, thus resorting to Radio over Telephone Lines principle. In this case, multi-cell processing is adapted to the cascade of wireless (fading) MIMO arising from co-channel users and cable MIMO from the users employing interfering copper twisted pairs in the same binder, as depicted in fig. 2. Moreover, besides attenuation, propagation over the cable is hampered by crosstalk (both near- and far-end, see Sec. III) due to possible coexistence of xDSL services employed in other twisted pairs in the same cable binder. In Sec. III, the system model for the scenario in fig. 2 is defined. Coexistence issues with xDSL services are investigated in Sec. IV.

### III. FEMTOWOC OVER TELEPHONE LINES

Let us consider the system in fig. 3, where  $M$  femtocells are connected to a common Multi-cell FAP via twisted pair telephone lines deployed in the same binder and having the same length  $d$ . To simplify, each femtocell serves a single user (denoted as  $U_m$ , with  $m=1, 2, \dots, M$ ) thus creating a compound  $M \times M$  MIMO system composed of the cascade of  $M \times M$  wireless MIMO and  $M \times M$  cable MIMO channels (fig. 2). Femtocells are assumed to share the same spectrum, so that mutual interference arises on the radio environment. Crosstalk also occurs within the cable propagation, due to the electromagnetic coupling among adjacent pairs. The latter type of interference is generally classified as near-end crosstalk (NEXT) when caused by signals propagating in opposite directions, and far-end crosstalk (FEXT) when caused by signals propagating in the same direction. More specifically, signal transmitted by the  $m$ th A/A converter is affected either by crosstalk by the other  $k \neq m$  wirelines connecting the  $k$ th A/A to the Multi-cell FAP (referred to as self-crosstalk, both self-FEXT and self-NEXT), and by crosstalk from services deployed over other twisted pairs in the same cable binder (xDSL, E1/T1). NEXT is much larger than FEXT as interfering transmitters are placed close to the receiver. Even if in principle self-NEXT can be avoided by selection of the duplex (TDD or FDD), self-FEXT cannot be avoided, and it is regarded as a performance-constraining factor, especially as the coupling distance becomes shorter [6]. In the following, due to space limitations, we discuss the system model for the uplink. Downlink model is dual with respect to the uplink, and can be easily derived.

#### A. Uplink Baseband Model

Each femtocell user  $U_m$  in fig. 3 employs OFDM modulation over  $N$  subcarriers with carrier spacing  $\Delta f$  and transmits  $N$  symbols within time slot  $t$ . Time division duplex (TDD) is assumed, so that no self-NEXT occurs over the cable. In this section, system model is based on the following assumptions: (i) perfect frequency synchronization among the  $M$  femtocells, so that no inter-carrier interference occurs; (ii) bandwidth of each carrier is less than the end-to-end (cascade of wireless and cable) channel coherence bandwidth; (iii) all femtocell users employ a cyclic prefix with length greater than the maximum compound channel memory; (iv) block transmission to/from the Multi-cell FAP is block synchronized. Accordingly, the compound MIMO-OFDM channel reduces to a collection of  $M \times M$  flat fading MIMO channels, one for each of the  $N$  subcarriers. Each MIMO channel is further composed of the cascade of  $M \times M$  wireless flat fading MIMO channel and  $M \times M$  cable flat fading MIMO channel. Per-carrier uplink frequency domain baseband model is detailed in the following.

1) *Wireless MIMO*: Let  $\mathbf{s}(t; k) = [s_1(t; k), s_2(t; k), \dots, s_M(t; k)]^T$  denote the set of frequency domain symbols transmitted by the  $M$  femtocell users at time slot  $t$  over the  $k$ th OFDM subcarrier. In the following, indices  $k$  and  $t$  are neglected for simplicity in notation. Symbols are assumed to have normalized energy, such that  $E[|s_m|^2] = 1$  (for each  $m$ ), and transmitted power is the same and equal to  $P^{(w)}$ . Frequency selective Rayleigh fading and path loss affect propagation between each of the  $M$  femtocell users and the  $M$  A/A converters. Radio channels are assumed to be fixed during a time-slot, and to vary independently over time slots. Let  $\mathbf{g}_{ij} = [g_{ij}(0), g_{ij}(1), \dots, g_{ij}(D-1)]$  be the baseband equivalent channel between the  $i$ th femtocell user and the antenna of the  $j$ th A/A device in time slot  $t$ , being  $D$  the maximum channel order of all the  $M^2$  radio channels. We assume that, for each  $(i, j)$ th link, equivalent channel  $\mathbf{g}_{ij} \sim \mathcal{CN}(\mathbf{0}, \alpha_{ij}\mathbf{\Gamma})$ , where  $\alpha_{ij}$  is the the propagation attenuation occurring over the  $(i, j)$ th link, and matrix  $\mathbf{\Gamma} = \text{diag}\{\gamma(0), \gamma(1), \dots, \gamma(D-1)\}$  depends on the normalized power delay profile  $\{\gamma(\ell)\}_{\ell=0}^{D-1}$  such that  $\text{trace}(\mathbf{\Gamma}) = 1$ . Recasting on the canonical vector-matrix baseband formulation for MIMO systems, received signal by the ensemble of  $M$  A/A converters is, in compact form:

$$\mathbf{x}_{A/A} = \sqrt{P^{(w)}} \mathbf{H}^{(w)} \mathbf{s} + \mathbf{n}^{(w)}, \quad (1)$$

where  $\mathbf{H}^{(w)}$  is the  $M \times M$  MIMO channel matrix over wireless medium, such that the entry  $[\mathbf{H}^{(w)}]_{ij}$  is the  $k$ th bin of the Fourier transform of channel  $\mathbf{g}_{ij}$ , and  $\mathbf{n}^{(w)} \sim \mathcal{CN}(\mathbf{0}, N_0^{(w)} \Delta f \mathbf{I}_M)$  is a  $M \times 1$  vector of i.i.d. Gaussian noise samples with the same variance  $N_0^{(w)} \Delta f$  for noise power spectral density  $N_0^{(w)}$ .

2) *Cable MIMO*: The A/A converter acts as a bidirectional amplify and forward device, besides translating analog signals (by up or down conversion) according to the specific radio protocol and cable connection. Power levels over subcarriers can be also adapted and optimized to maximize the system performance (not covered in this paper). Here the received power from the  $m$ th femtocell user can be adapted to a

predefined spectral mask  $P_m^{(c)}$ , and thus the gain for the  $m$ th A/A converter becomes

$$\beta_m = P_m^{(c)} / E[|\mathbf{x}_{A/A}|_m^2]. \quad (2)$$

The  $M \times 1$  baseband signal received by the Multi-cell FAP over the  $k$ th subcarrier turns out to be

$$\mathbf{y} = \mathbf{H}^{(c)} \mathbf{B} \mathbf{x}_{A/A} + \mathbf{n}^{(c)}, \quad (3)$$

where  $\mathbf{H}^{(c)}$  is the  $M \times M$  MIMO channel matrix over cable, and diagonal matrix  $\mathbf{B} = \text{diag}\{\sqrt{\beta_1}, \sqrt{\beta_2}, \dots, \sqrt{\beta_M}\}$  accounts for the amplitude gains of the A/A converters. Diagonal entries  $[\mathbf{H}^{(c)}]_{ii}$  of cable MIMO channel represent the transfer function of a twisted pair cable of length  $d$  [7]

$$[\mathbf{H}^{(c)}]_{ii} = e^{-\Gamma(f) \times d}, \quad (4)$$

where the propagation constant  $\Gamma(f) = \sqrt{(R + j2\pi fL)(G + j2\pi fC)}$  depends on cable characteristic parameters (i.e.,  $R$ ,  $C$ ,  $G$  and  $L$  are the resistance, capacitance, conductance and inductance per unit length, respectively), and frequency  $f$  corresponds to the spectral position of the  $k$ th OFDM subcarrier over the cable. Off-diagonal terms of cable MIMO channel matrix  $\mathbf{H}^{(c)}$  account for the cable far-end crosstalk transfer function between the  $i$ th and  $j$ th twisted pair ( $i \neq j$ ), these are modeled as [8]:

$$[\mathbf{H}^{(c)}]_{ij} = j2\pi f e^{-2\Gamma(f) \times d} \int_0^d c_{ij}(x) dx \quad (i \neq j), \quad (5)$$

where the coupling capacitance  $c_{ij}(x)$  between pairs  $i$  and  $j$  is assumed as constant, for simplicity. Moreover,  $\mathbf{n}^{(c)}$  is the vector of  $M$  i.i.d. complex, zero mean Gaussian noise samples with variances  $N_{0,m}^{(c)} \Delta f$  depending on the noise single-sided power spectral density  $N_{0,m}^{(c)}$  at the  $m$ th cable termination ( $m = 1, 2, \dots, M$ ). Specifically, power spectral densities  $N_{0,m}^{(c)}$  account for the following effects (in order of importance): (i) cumulative FEXT and NEXT produced by the xDSL/E1/T1 services coexisting in the same cable bundle; (ii) cable thermal noise.

### B. Uplink Multi-cell FAP Processing

The Multi-cell FAP receiver performs linear MIMO processing. Decoding of symbols  $\mathbf{s}_k$  of  $k$ th subcarrier is based on  $M \times M$  weight matrix  $\mathbf{W}_k$  as  $\hat{\mathbf{s}}_k = \mathbf{W}_k \mathbf{y}_k$ . The post-processing signal-to-interference-plus-noise ratio experienced on the  $k$ th subcarrier of the  $m$ th stream follows from (3) and it is:

$$\text{SINR}_{k,m} = \frac{P^{(w)} |[\mathbf{W}_k \mathbf{H}_k^{(c)} \mathbf{B}_k \mathbf{H}_k^{(w)}]_{mm}|^2}{(P^{(w)} \sum_{n \neq m} |[\mathbf{W}_k \mathbf{H}_k^{(c)} \mathbf{B}_k \mathbf{H}_k^{(w)}]_{mn}|^2 + N_0^{(w)} \Delta f \sum_n |[\mathbf{W}_k \mathbf{H}_k^{(c)} \mathbf{B}_k]_{mn}|^2 + \sum_n N_{0,n,k}^{(c)} \Delta f |[\mathbf{W}_k]_{mn}|^2)} \quad (6)$$

Due to space constraints, we only consider the zero forcing (ZF) receiver  $\mathbf{W}_k = \left( \sqrt{P^{(w)}} \mathbf{H}_k^{(c)} \mathbf{B}_k \mathbf{H}_k^{(w)} \right)^\dagger$ .

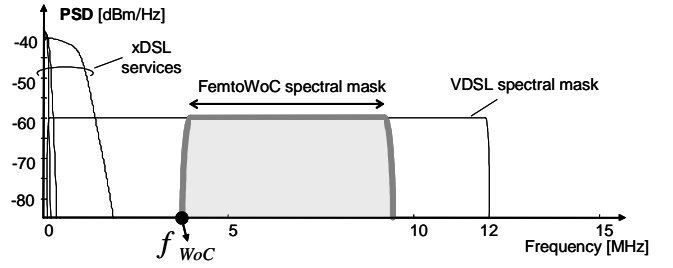


Fig. 4. Spectral map of xDSL services over telephone-lines and coexistence with FemtoWoC signal.

## IV. ANALYSIS OF FEMTOWoC OVER TELEPHONE LINES

Purpose here is to evaluate the benefits of FemtoWoC architecture over telephone lines and the degree of coexistence with xDSL services subject to spectral mask constraints on both air and cable interfaces. Towards this goal, we consider an IEEE 802.16e OFDM signal at the air interface, and we regard throughput  $T_m$  experienced by the  $m$ th user as the metric function:

$$T_m = \Delta f / (1 + g) \sum_{k=1}^N \mathcal{S}_{AMC}(\text{SINR}_{k,m}), \quad (7)$$

where  $g$  is the cyclic prefix ratio and  $\mathcal{S}_{AMC}(\cdot)$  is the Adaptive Code Modulation (AMC) function that maps the signal-to-interference-plus-noise ratio  $\text{SINR}_{k,m}$  (given by (6) for the uplink) experienced by the  $m$ th user over the  $k$ th subcarrier onto a specific code and modulation format. More specifically, SINR thresholds for AMC switching have been chosen based on [3]. Notice that WiMAX scheduler is assumed to adopt carrier-by-carrier AMC for all the  $N$  carriers (i.e., throughput loss due to guard and pilot carriers is neglected). Performances are in terms of the average wireless throughput estimated from (7) using independent realizations of the wireless channel vectors.

### A. IEEE802.16e FemtoWoC Compatibility ( $M=1$ )

Let us consider an IEEE 802.16e OFDM signal with sub-carrier spacing  $\Delta f = 10.94$  kHz,  $N = 1024$  subcarriers, sampling factor equal to 28/25, cyclic prefix ratio  $g = 1/8$  (effective bandwidth is  $B = 11.2$  MHz) [3]. Each user is constrained to transmit with power  $(P^{(w)} / \Delta f) B = 20$  dBm over bandwidth  $B$ , while  $N_0^{(w)} = -166$  dBm/Hz. Path loss attenuation over the direct link of each  $m$ th femtocell user is  $\alpha_{mm} = -78$  dB (corresponding to a distance of approx 10 m at a 2GHz carrier frequency for indoor), while frequency selective radio channels have the same exponential power delay profile such that  $\mathbf{\Gamma} = \text{diag}\{1, e^{-1/2}, \dots, e^{-5/2}\}$  ( $D = 6$  taps). Typical characteristic parameters for twisted pair line are employed as in [7]. With the aim of minimizing the impact of FemtoWoC signals onto the existing xDSL and E1/T1 services over the cable, we allocate the spectral mask of the FemtoWoC signal so as  $P_m^{(c)} / \Delta f = -60$  dBm/Hz similar to VDSL [9], and starting frequency  $f_{WoC} = 100$  kHz (see fig. 4).

DL and UL communication over the cable is impaired by three different noise scenarios: (i) AWGN with power spectral density equal to -140 dBm/Hz (case A); (ii) case A noise +

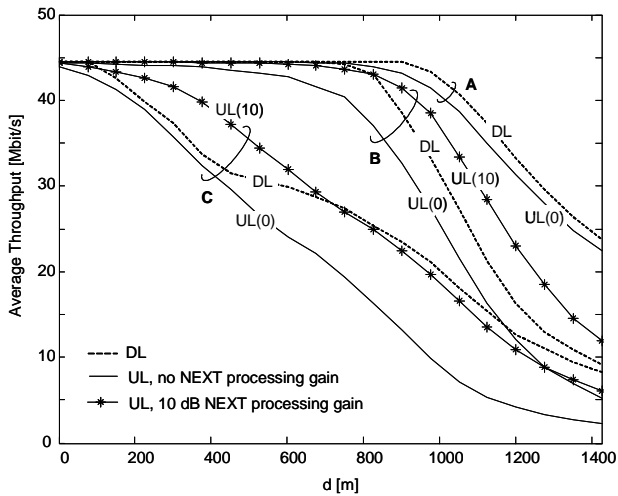


Fig. 5. Coexistence of FemtoWoC signal with other services. Downlink and uplink communication over the cable is impaired by three different noise scenarios: (i) -140dBm/Hz AWGN (*case A*); (ii) case A noise + 10 ISDN, 10 ADSL, 4 HDSL, 2 T1 services (*case B*); (iii) case B noise + 20 VDSL disturbers (*case C*). Dashed lines refer to DL, solid lines to UL with no NEXT mitigation, solid lines with stars to UL with 10 dB NEXT reduction.

10 ISDN, 10 ADSL, 4 HDSL, 2 T1 services (*case B*); (iii) case B noise + 20 VDSL disturbers (*case C*). Crosstalkers are assumed to exist at both the far- and near-end of the cable for each link direction. Power spectral densities of ISDN, ADSL, HDSL and T1 signals, as well as NEXT and FEXT crosstalk coupling functions, are generated according to [10], and FSAN method has been used for crosstalk summation [11]. In all our simulations, we adopted the FDD Band Plan 998 for VDSL [9] (the optional 30-138kHz band is not used). Central office hosts both physical termination of the xDSL/T1 services and the Multi-cell FAP. NEXT interference of xDSL towards FemtoWoC signal can be mitigated by making xDSL modem and Multi-cell FAP to cooperate in exchanging signaling (soft information) on interference. This results in a reduction of NEXT for the FemtoWoC service (only UL) and it is accounted for by the NEXT processing gain (or equivalently NEXT attenuation) that here is 0dB (no NEXT mitigation) and 10dB (typical NEXT reduction capability with respect to signal, as a worst case in [12]).

Fig. 5 shows the average throughput of the  $M = 1$  femtocell user versus cable distance  $d$  for both uplink and downlink for the different noise scenarios (for the uplink, 0 and 10 dB NEXT processing gain at the Multi-cell FAP has been considered). Even in this simple case of one user, uplink and downlink behavior is asymmetric because of the different xDSL interference experienced on the cable-link. Namely, case A is used as reference of the throughput vs cable attenuation as there is no interference. Therein, UL curve is lower than DL curve due to the asymmetry in the noise floor at the receivers. Compared to the full WiMAX throughput (44.8Mbit/s for this scenario), the loss arises for distance  $d > 1000\text{m}$  due to the low-pass characteristic of the cable medium. When case B cable interference impairs the FemtoWoC signal over the low part of the spectrum, or VDSL services are superimposed (case C), the throughput is reduced and asymmetric for UL

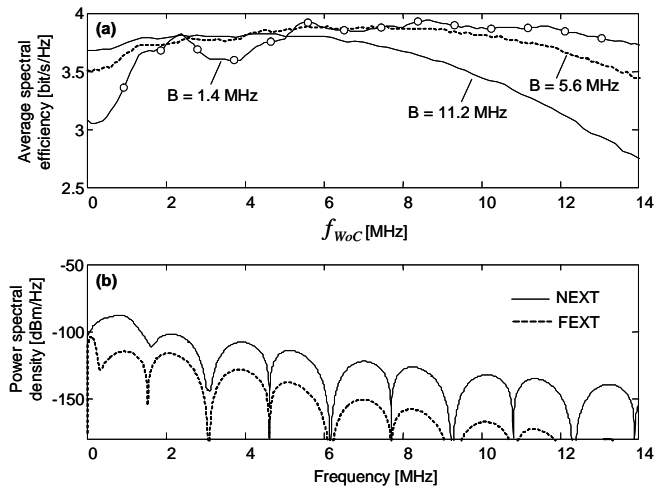


Fig. 6. Analysis of coexistence in moderately interfered scenario ( $d = 700\text{m}$  without VDSL users): (a) uplink average spectral efficiency of  $M = 1$  femtocell user employing an IEEE 802.16e signal with effective bandwidth equal to 1.4MHz (line with circles), 5.6MHz (dashed line) and 11.2MHz (solid line) versus different frequency allocations over the cable (in terms of  $f_{WoC}$ , see fig. 4); (b) FEXT and NEXT power spectral density versus frequency (case B in fig. 5).

(solid line) and DL (dashed line). The NEXT interference from VDSL over the high portion of the spectrum severely limits the UL throughput below 5Mbit/s for  $d > 1000\text{m}$  (case C). However, 10dB of NEXT processing gain (line with stars) can restore the benefits for the UL (there is no benefit for DL as NEXT onto the downlink FemtoWoC service cannot be reduced in any way).

### B. Spectral Allocation Over The Cable ( $M=1$ )

Scheduling of FemtoWoC signals needs to account for interference both over the radio and cable environment, as down-converted wireless spectrum from the A/A device would be allocated over the cable on the same spectrum of existing xDSL services. To highlight this concept, figure 6-(a) and 7-(a) show the uplink average spectral efficiency of the  $M = 1$  femtocell user employing an IEEE 802.16e signal with effective bandwidth  $B = 1.4\text{MHz}$  (line with circles), 5.6MHz (dashed line) and 11.2MHz (solid line) versus different frequency allocations over the cable (in terms of  $f_{WoC}$ ) for case B and C noise (see Sec. IV-A), respectively (without any NEXT mitigation). System parameters are selected as in fig. 5, except for  $d = 700\text{m}$ . Best spectral allocation results in a trade off between crosstalk interference (whose frequency power spectral density in terms of FEXT and NEXT is shown in fig. 6-(b) and 7-(b) for case B and C, respectively) and low-pass response of the cable (notice that for this scenario the maximum achievable spectral efficiency is 4bit/s/Hz for all the bandwidths). Specifically, for low spectrum usage, scenario is NEXT dominated, while in the high spectral region it is mostly cable-attenuation dominated.

### C. MIMO Processing Analysis ( $M=2$ )

Purpose here is to highlight the benefits of MIMO processing. Towards this goal, we consider  $M = 2$  femtocells,

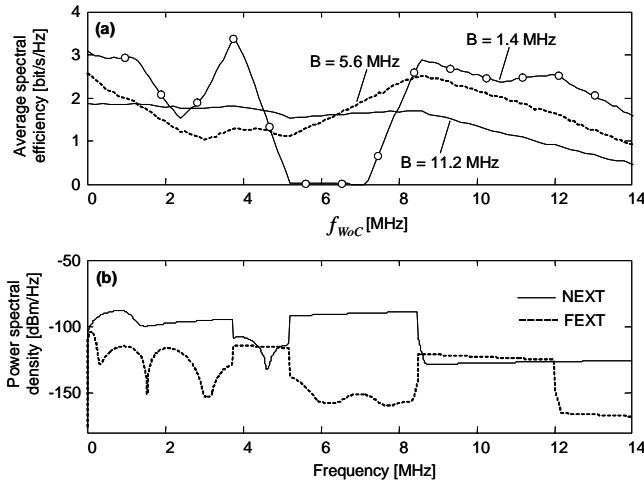


Fig. 7. Analysis of coexistence in highly interfered scenario ( $d = 700\text{m}$  with 20 VDSL users): (a) uplink average spectral efficiency of  $M = 1$  femtocell user employing an IEEE 802.16e signal with effective bandwidth equal to 1.4MHz (line with circles), 5.6MHz (dashed lines) and 11.2MHz (solid lines) versus different frequency allocations over the cable (in terms of  $f_{WoC}$ , see fig. 4); (b) FEXT and NEXT power spectral density versus frequency (case C in fig. 5).

each employing  $N = 1024$  subcarriers ( $B = 11.2\text{MHz}$ ). Broadband connections over twisted pairs are impaired over a coupling length  $d$  by case C noise (Sec. IV-A). Other system parameters are selected as in fig. 5. Fig. 8 shows the uplink average throughput of each femtocell user versus the cable distance  $d$  for different values of path-loss coefficients  $\alpha_{12} = \alpha_{21} \leq \alpha_{11} = \alpha_{22}$  (with 10 dB gain in NEXT reduction by Multi-cell FAP). As a reference, the maximum achievable throughput for this scenario is also plotted (equal to 44.8 Mbit/s from (7)). Large distance  $d$  makes crosstalk more severe with a throughput reduction. Interference mitigation by multi-cell MIMO processing makes the throughput almost insensitive to the coupling over the air of the two users ( $\alpha_{12}/\alpha_{11} = \alpha_{21}/\alpha_{11} \leq 1$ ). The benefits of MIMO processing are compared with the scenario where there is no reduction of wireless interference (i.e., weight matrix  $\mathbf{W}_k = (\mathbf{H}_k^{(c)} \mathbf{B}_k)^\dagger$  only accounts for cable MIMO channel). Notice that, in the latter case, in severe wireless ( $\alpha_{12}/\alpha_{11} = \alpha_{21}/\alpha_{11} = 1$ ) and cable condition (case C crosstalk noise) the throughput of few Mbit/s can be guaranteed over  $d = 1 - 1.5\text{km}$ .

## V. CONCLUSIONS

Wireless over Cable architecture is presented as a novel paradigm to exploit the advantages of MIMO processing in femtocell systems. In particular, study has been focused on the Radio over Telephone Lines. Despite the hindrances deriving from this hostile propagation medium, the proposed architecture has been shown to be highly beneficial in overcoming detrimental radio interference among neighboring femtocells. Scheduling of the wireless signals when transferred over the cable necessitates dynamic spectrum allocation policies that open future scenarios in this context.

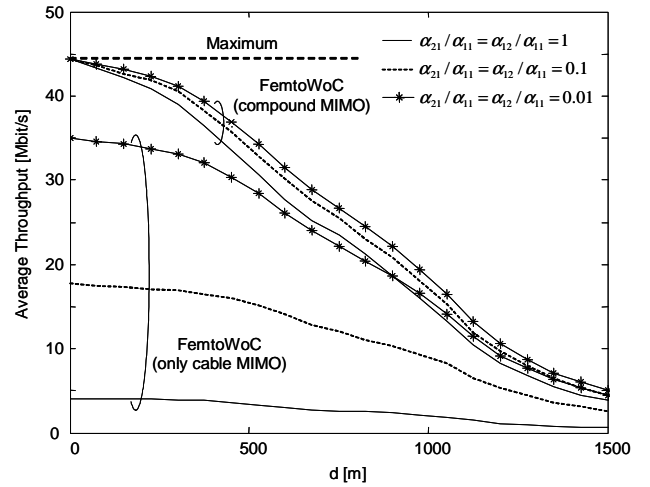


Fig. 8. Multi-cell MIMO processing throughput performances (uplink) vs. cable coupling distance  $d$  for IEEE802.16e FemtoWoC scenario and AMC scheduling (case C noise of fig. 5).

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