Efficient HetNet Implementation Using Broadband Wireless Access with Fiber-Connected Massively Distributed Antennas Architecture

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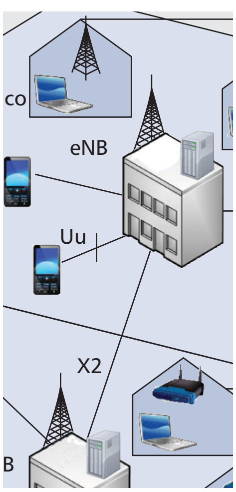

The authors introduce a novel HetNet architecture employing fiber-connected distributed antenna systems, named broadband wireless access with fiber-connected massively distributed antennas (BWA-FMDA).

Abstract

We introduce a novel HetNet architecture employing fiber-connected distributed antenna systems, named broadband wireless access with fiber-connected massively distributed antennas (BWA-FMDA), which facilitates coordination of resource allocation and interference management. Among various opportunities realized by the proposed approach, our focus in this article is on CoMP for UMTS LTE femto- and picocells, to which we refer as femto-CoMP. Through extensive simulation results we demonstrate the superior performance gain of a femto-CoMP HetNet over independent femto- and picocell operation in traditional HetNet scenarios. We analyze both link- and system-level feasible throughput as well as scheduling delay for round-robin and proportional fair schedulers.

Introduction and Motivations

The explosive growth of wireless traffic, fueled by an ever increasing availability of mobile wireless devices and the demands of end users to be always connected, provides a challenge for cellular and broadband wireless access technologies. Shrinking cell sizes through installation of further macro-access nodes is no longer a sustainable solution to handle the traffic load, especially as the demand for indoor wireless connectivity increases.

An emerging solution to address the increased network capacity demand is to improve utilization of spectral resources in a localized manner. More specifically, deploying smaller-scale access points that can form femto- or picocells facilitates a higher level of reuse of available spectrum, thereby shifting the cell planning model in future wireless networks toward a universal frequency reuse (UFR) pattern.

In essence, creation of femto- and picocells within a macrocell shortens the communication links, especially for indoor users, which in turn reduces the co-channel interference (CCI) level in the network. As the capacity of most packet-based wireless communication technologies is interference-limited, such a reduction in network interference level directly translates into capacity enhancement of the system. On the other hand, new forms of interference, mainly mutual interference between femto- or picocell access nodes with macrocell users, arise in this new network architecture paradigm, which mandates more intelligent resource allocation strategies.

The research community in academia and industry has started to more carefully address such coexistence problems recently under the umbrella term *heterogeneous networks* (HetNets). Whereas heterogeneous networking was previously meant to refer to cooperation of different wireless technologies, say complementary operation of a wireless local area network (WLAN) in conjunction with a cellular network, HetNet is focused on a single wireless standard. In this article we limit our discussions to Third Generation Partnership Project's (3GPP) Long Term Evolution (LTE) and LTE-Advanced standards for the universal mobile telecommunications system (UMTS). However, the essence of our solution is directly applicable to other technologies such as IEEE 802.16j too.

Why HetNet is Needed?

The research community has produced a substantial body of knowledge on various cellular communication techniques, ranging from wide area to picocells, in the past. However, no strategy to leverage the capabilities of such solutions within a unified framework has been developed so far. By forming a hierarchical cellular network, HetNet aims to improve the network per-

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formance by coordinating the resource allocation and service delivery using nodes with different transmission capabilities within a given cell.

In June 2009, 3GPP decided to include HetNet as a study item for UMTS LTE-Advanced in its TSG RAN Plenary#44 meeting [1]. A HetNet in the LTE-Advanced context comprises a macrocell associated with an enhanced NodeB (eNB), and a random distribution of lower-power access nodes, such as femto and pico home eNBs (HeNB), which form their own closed subscriber groups (CSGs) and relay nodes [1]. Thus, HetNet represents a network of a specific radio access technology where access nodes might have different radio frequency (RF) capabilities, ranging from macro- to femto- and picocell scales.

There are four interference scenarios that should be noted in any HetNet analysis [2]. In the downlink (DL), a given macrocell user may be interfered with by nearby CSG communications. Furthermore, a neighboring HeNB may interfere with CSG users associated with a specific HeNB. In the uplink (UL), on the other hand, macrocell users might create significant interference to neighboring HeNBs. Also, UL performance of users within the macrocell can be improved using a path-loss-based association scheme at the expense of increasing interference to CSG users, especially those near the cell edges. While several studies in the literature have addressed various aspects of two-tier networking architectures [3, 4], a comprehensive solution that covers the challenging tasks of network operation, user association, resource allocation, and interference management in HetNets within a unified framework is yet to be proposed.

Our Proposed HetNet Solution

In this article we introduce a novel architecture named broadband wireless access with fiber-connected massively distributed antennas (BWA-FMDA), which facilitates coordinated resource allocation as well as ubiquitous network coverage in a HetNet setting. This unique networking paradigm harnesses the advantages of distributed networking architecture as well as the benefits of having a centralized decision making capability. Our numerical analysis verifies the considerable performance enhancement achieved in HetNets utilizing the proposed architecture.

What differentiates our proposed BWA-FMDA from other HetNet solutions is the possibility of coordinating femto- and picocells in delivering packets to various users. Given that the current 3GPP standardization efforts do not provision an X2 interface for femto base stations, coordinating these reduced-scale access nodes is not feasible in the same manner that eNBs can be coordinated [1]. Therefore, the proposed BWA-FMDA solution will facilitate novel scheduling and interference management solutions in the LTE-Advanced context, as detailed in this article.

BWA-FMDA bridges the innovations in distributed antenna system (DAS) with radio-over-fiber (RoF) transmission techniques. The capabilities of DAS, for instance, in supporting virtual multiple-input multiple-output (MIMO) communications, have produced promising network capacity improvement results which are reported in a growing number of studies in the literature. Similarly, RoF provides a high-bandwidth reliable communication platform, which has stimulated considerable research interest in academic as well as industrial institutions. The proposed BWA-FMDA exploits both these innovative advancements to deliver high-throughput ubiquitous wireless access to end users.

The rest of the article is organized as follows. The main components of BWA-FMDA architecture are elaborated on. HetNet implementation based on the proposed solution is introduced. Interference management through multiuser beamforming in the BWA-FMDA and numerical results verifying its superior performance over independent HetNet implementation are discussed. Finally, we conclude the article and point out some of our future research goals.

System Architecture

The proposed BWA-FMDA comprisea three main components: simplified access nodes, a fiber connection medium, and a central processing entity. In the following subsections we elaborate on the aforementioned system components.

Massively Distributed Antenna System

Reduced-scale wireless access nodes provide a convenient means of delivering blanket coverage for a targeted locale, while avoiding the time consuming and costly cell planning phases. In BWA-FMDA, the processing functionalities of access nodes are transferred to the central processing entity; thus, the access nodes are merely a distributed set of antenna elements. Given the fast and reliable fiber connection medium to/from the central processing entity, the aforementioned DAS has the potential to scale from a few antenna elements, covering tens of square meters of space, to tens of antenna elements covering a few square kilometers of the targeted area.

Similar to traditional two-tier networks, the location arrangement of individual antenna elements in this massive DAS is quite arbitrary, providing ease of deployment. Due to the coordination capability of BWA-FMDA, however, a much more efficient interference management strategy than traditional femtocell networks can be achieved in the proposed system. For instance, UMTS LTE standard supports a cooperative mode of operation between macrocells, named coordinated multipoint (CoMP) transmission. However, due to the independent operation of femto- and picocells, and lack of interaction infrastructure in the second tier of the network, coordination of transmissions to/from HeNBs is not possible. On the other hand, BWA-FMDA facilitates coordinated transmission/reception schemes not only at the macro level but also in the femto- and picocell tier. We provide some numerical analysis to demonstrate the benefits of such coordination strategies.

Central Processing Entity

As discussed in the previous subsection, the DAS employed in BWA-FMDA lacks any processing power. All the processing functionalities are concentrated in the central processing entity,

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which provides an opportunity to enhance the system performance from several perspectives. First, the resource allocation decision making in each femto- and picocell associated with any given antenna element will be made in harmony with neighboring cells. In general, the interference among femtocells or between macro- and femtocells can be prohibitively high in two-tier HetNets. Availability of the central processing entity in BWA-FMDA allows joint processing of network-wide resource utilization and a lower interference level, which yields better system performance as verified by our numerical results.

Furthermore, by centralizing the resource allocation, BWA-FDMA significantly reduces the signaling overhead associated with coordination transmission and reception of data, such as through employing CoMP in the LTE context. In effect, BWA-FMDA realizes a distributed architecture with centralized decision making capabilities.

Fiber Connection Medium

The backbone of BWA-FMDA is a network of fiber optic cables connecting the central processing entity to each antenna element. The key in widespread deployment of BWA-FMDA is an efficient but inexpensive optical fiber backhaul, which itself is composed of two parts.

First, a mechanism for electrical-to-optical conversion and vice versa is in charge of transforming the communicated signal over various sections of the BWA-FMDA according to their medium requirements. This scheme is known as RoF in the literature [5]. Unlike wireline network counterparts, such as the Ethernet, the conveyed signal will remain analog, as opposed to digital, over the fiber connection medium. Several proof-of-concept demonstrations, mainly focusing on WLAN over fiber communications, have been reported in the literature [6].

Second, the optical links will form a network that can utilize passive or active optical networking protocols. A passive optical network (PON) is a more cost-efficient implementation, which employs one pair of optical fibers for duplex transmissions between an antenna element and the central processing entity. In the simplest case, each antenna element employs different transmit and receive antennas connected via power and low-noise amplifiers to the respective fibers. The transmission/reception of signals from/to each antenna element is then controlled based on a time-division multiplexing (TDM) scheme. If multiple transmit/receive antennas at an antenna element or multiple antenna elements are fed via a shared pair of optical fibers, wavelength-division multiplexing (WDM) techniques can further be exploited [7].

HetNet Implementation

The adoption of BWA-FMDA in a UMTS LTE HetNet setting provides a viable and cost-effective solution for delivering broadband wireless connectivity. In Fig. 1 a comparison between major architectural elements of a traditional HetNet and a BWA-FMDA HetNet is presented. The network and user interfaces, based on 3GPP specifications, are also highlighted in this figure. More specifically, the macrocell to user equipment (UE) link follows the Uu interface protocol, whereas direct interaction of different macrocells (e.g., to operate in CoMP mode) is achieved via an X2 interface. Both macrocell and HeNBs can be connected to the operator's backhaul network, known as the evolved packet core, utilizing S1 interface. On the other hand, a group of HeNBs can be connected to a single home NodeB gateway (HNB-GW), which serves as a concentration point toward the backhaul network. Finally, an IuCS/IuPS interface coordinates HNB-GW communications to/from the mobility management entity (MME)/system architecture evolution (SAE) gateway within the evolved packet core [8, 9].

Replacement of HeNBs with the DAS of BWA-FMDA and inclusion of the central processing entity in the HetNet architecture is readily implementable within the UMTS LTE specification framework. The Iuh interface in BWA-FMDA is active between the central processing entity and the safety GW, which is a logical architecture entity and might physically be implemented as parts of HNB-GW [8]. The Iuh interface directly connects the HeNBs and the safety GW in a traditional HetNet setting. Furthermore, in very dense urban areas, with a high concentration of residential and business users, several BWA-FMDAs, each with their dedicated central processing units, can serve different enterprises or residential premises. Then, the HNB-GW will serve as a concentration point toward the MME/SAE GW, very similar to traditional HetNet scenarios.

Before presenting the interference management solutions for the proposed BWA-FMDA, it is worth mentioning that this architecture might be more suitable for scenarios with dense indoor users such as offices, hotels, high-rise buildings, and airports due to the need for installation of optical fibers. This is a differentiating point with other all-wireless HetNet solutions such as those based on mesh networks. In terms of the signaling overhead, BWA-FMDA is not as sensitive to signaling load as all-wireless HetNet solutions due to the availability of very high bandwidth fiber links in the network.

Inteference Management and Numerical Results

The two-tier architecture of HetNet along with the possibility of independent or cooperative communications in this setting provides numerous degrees of freedom in devising resource allocation strategies. Striking the right balance among various involved trade-offs in developing an efficient HetNet scheduling paradigm is a challenging task. For instance, exploiting static frequency planning alleviates the need for interference management, whereas dynamic channel assignment in a UFR scheme mandates signaling overhead so as to coordinate the resource allocation in an interference-limited regime. The available bandwidth per cell within a specific frequency reuse pattern will be a fraction of total

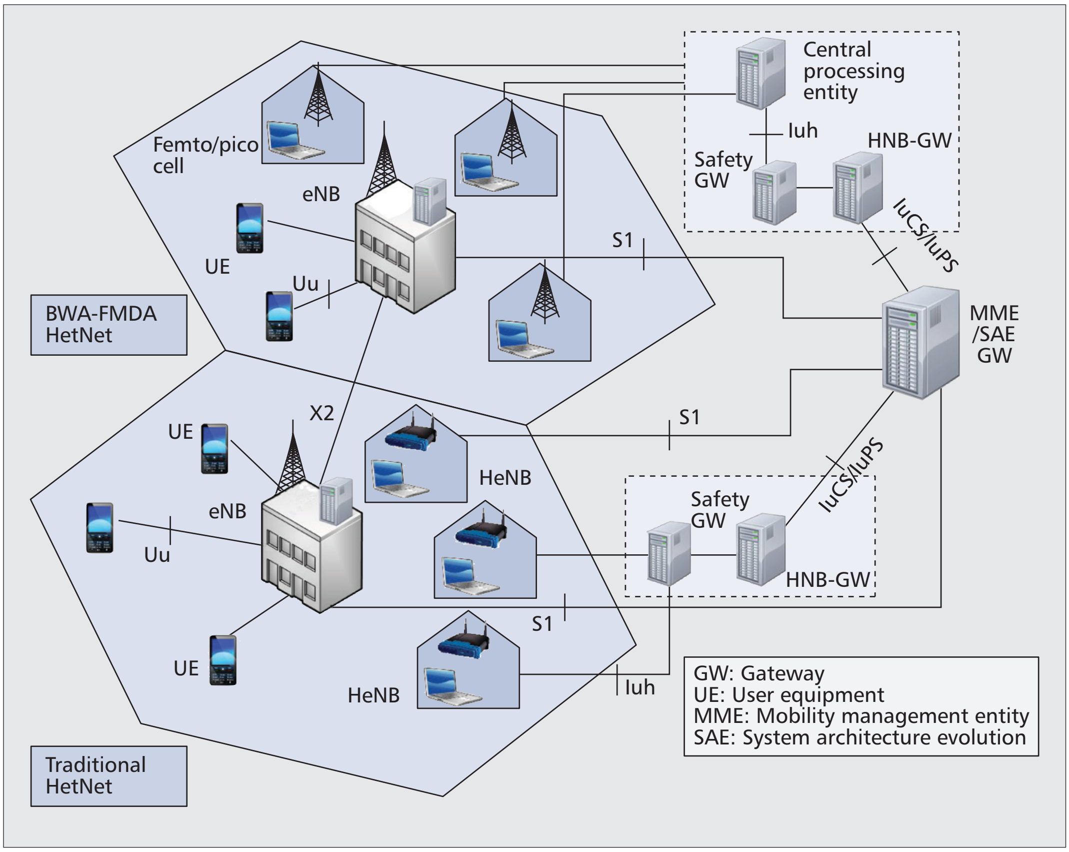

Figure 1. *Comparison of traditional and BWA-FMDA HetNet architectures.*

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bandwidth. On the other hand, the CCI level in the UFR regime will affect the feasible throughput in each cell.

In our numerical analysis we focus on interference management in the second tier of HetNet (i.e., femto- and picocell access nodes). More specifically, we compare the performance of saturated DL transmission in fully independent femto- and picocells, to which we refer as independent HetNet, and the proposed fiber-connected DAS architecture implemented in the UMTS LTE setting, which we refer to as BWA-FMDA HetNet. We consider several frequency reuse patterns throughout the network and investigate the effect of two widely utilized scheduling techniques, round-robin and proportional fair, on the link and system performance.

Furthermore, as the femto- and picocells in our proposed DAS architecture are capable of jointly serving a given UE, reminiscent of CoMP capability in a macrocell LTE system, we exploit this femto-CoMP capability as the main interference management tool in our study. In this approach a set of distributed antenna elements, which are controlled by one central processing entity via the fiber connection medium while each forms its own CSG, collaborate to form a beamforming cluster. We adopt the Monte Carlo simulation approach for analyzing this scenario, assuming perfect channel knowledge is available at a given HeNB between the HeNB and its associated UE in the independent HetNet case, and at the central processing entity between any UE and any antenna element in the femto-CoMP scenario.

Simulation Model

We consider 24 LTE femtocells densely deployed in a four-floor office building, each floor having six rooms that are divided into two rows by a 2-m-wide corridor. Each room covers 12 × 6 × 3 m^3 volume and contains one HeNB and two UE units with fixed locations.

Every device attaches to only one channel with 1.4 MHz bandwidth in the 2.5 GHz band. When considering frequency reuse patterns other than UFR, multiple 1.4-MHz channels are used. In such circumstances simulated throughput is divided by the number of channels for fair comparison among different frequency reuse modes. The channel of each link, composed of static path loss, spatially independent static shadowing, and time-varying fading, follows the indoor propagation model in International Telecommunication Union — Radiocommunication Standardization Sector (ITU-R) M.1225. The penetration loss follows the COST231 model: 18.3 dB per floor and 6.9 dB per wall. Any link within one room is assumed as a Ricean channel with κ factor equal to 10 for the first tap and 0 for other taps. The total transmission power constraint is 20 mW/MHz in independent HetNet and 20 × N_{HeNB} mW/MHz in femto-CoMP, where N_{HeNB} is the number of HeNBs (antenna elements) within one femto-CoMP cluster. The noise factor at each UE receiver is assumed to be 10 dB.

Our performance criteria include system throughput, time-averaged UE throughput, and scheduling delay. Throughputs are calculated from the instantaneous throughput of a given UE at a given time slot, which is a sum of Shannon capacities of all subcarriers used by this UE. The scheduling delay is defined as the number of time slots between two consecutive transmissions. Note that all packets are transmitted in a slotted manner: each slot lasts 1 ms, and each simulation scenario lasts 5 s.

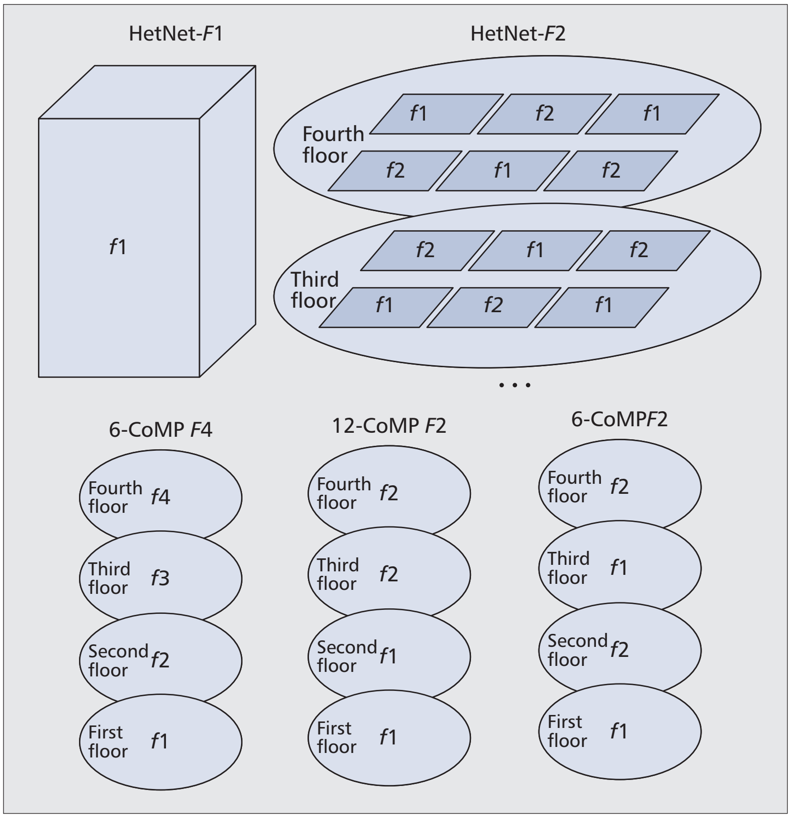

Figure 2. *Frequency reuse modes.*

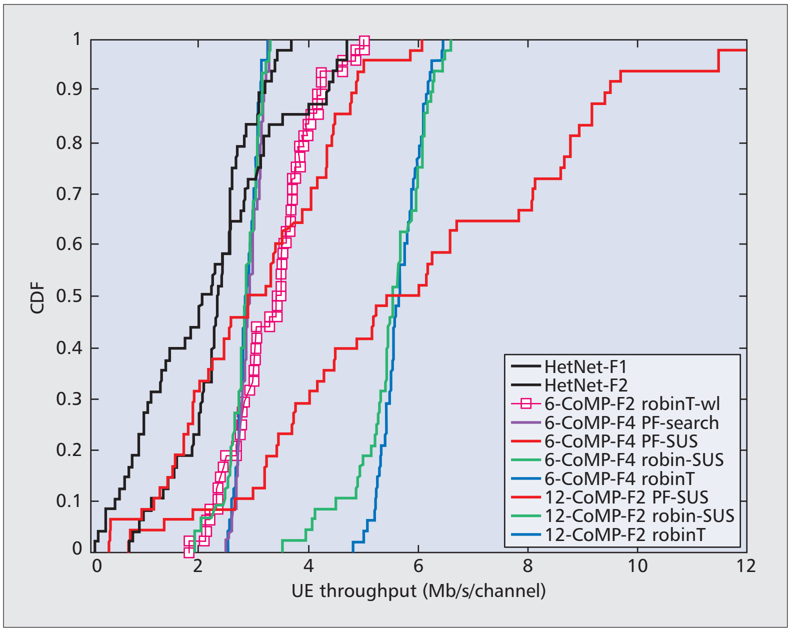

Figure 3. *CDF of UE throughput assuming two UEs per room.*

Frequency Reuse

We consider the following modes to reuse frequencies in the building, as shown in Fig. 2:

HetNet-F1: UFR under the independent HetNet regime.

HetNet-F2: Devices in adjacent rooms (on the same floor and on adjacent floors) use different frequencies, operating over independent-HetNet system.

6-CoMP F2: Six HeNBs on each floor form a femto-CoMP whereby femto-CoMPs on adjacent floors use different frequencies.

6-CoMP F4: Six HeNBs on each floor form a femto-CoMP, while the available frequency range on each floor differs from all other floors.

12-CoMP F2: Twelve HeNBs on every two floors form a femto-CoMP; however, adjacent femto-CoMPs use different frequencies.

We use HetNet-F1 mode as the performance benchmark to demonstrate the advantages of the proposed BWA-FMDA architecture for HetNet implementations.

Schedulers

Two classes of schedulers are used to achieve fairness among UE: round-robin tournament and proportional fairness (PF). The time window t_c in the PF scheduler is fixed at 100 slots.

In independent HetNet, there are 24 rooms and therefore 24 HeNBs, each running a PF exhaustive search algorithm to maximize the proportional fairness in each resource block (RB), which is represented by the sum of logarithms of averaged rates. In femto-CoMP, however, a PF exhaustive search is not practical due to the huge number of combinations of UE to be beamed. We therefore reduce the search space by posing a constraint that one and only one UE must be chosen from each room. This heuristic constraint comes from a simple intuition that in a 6-CoMP setting on the same floor, with only free-space path loss (and wall penetration loss) at present, the smallest conditional number of all possible 6 × 6 submatrices out of a 12 × 6 channel matrix results from choosing only one UE per room. And in the round-robin tournament algorithm, we continued to impose this policy; we refer to the resulting scheduler as the robinT scheduler.

Besides PF based on exhaustive search, we have developed two scheduling mechanisms for femto-CoMP utilizing the semi-orthogonal user selection (SUS) algorithm [10]. The PF-SUS scheduler tries to increase proportional fairness by assuming equal transmission power for each HeNB. The robin-SUS scheduler first uses the SUS algorithm to group UEs and then beams these groups in a round-robin manner.

In 6-CoMP F2 mode, as alternating floors utilize the same frequency range, each CoMP cluster suffers from inter-CoMP interference. For simplicity, however, we conduct waterfilling during beamforming as if there is no interference from outside the CoMP cluster, to which we refer as the robinT-wI scheduler (wI for "with interference").

Among all algorithms except robinT, scheduled UE units are independent among all RBs, fully exploiting the frequency diversity. The subcarrier in the middle of each RB is used by a femto-CoMP scheduler to predict the throughput of the RB.

Throughput per Channel

We evaluate throughput per channel from two aspects: time-averaged throughput distribution among all UE, as shown in Fig. 3, and the system throughput distribution among all time slots, as shown in Fig. 4. We observe that all femto-CoMP modes except those using PF-SUS schedulers achieve higher throughput and better fairness than independent HetNet modes. For instance, the robinT scheduler in 6-CoMP-F4 mode offers 26 percent system throughput gain over HetNet-F2. The poor fairness of PF-SUS schedulers is caused by the equal transmission power assumption.

As we expected, 12-CoMP outperforms 6-CoMP at the expense of sharing more information and, for each subcarrier, inversing a 12 × 12 matrix instead of a 6 × 6 matrix. For robinT and robin-SUS schedulers, the system throughput is doubled when forming 12-CoMP clusters instead of 6-CoMP clusters due to the halved number of channels being used, which also suggests our heuristic "picking-one-UE-per-room" policy ensures small conditional numbers even in the case of 12 × 12 channel matrices.

Comparing robinT, robin-SUS and PF-search schedulers in 6-CoMP-F4 mode in Fig. 3, we found no significant difference on the system throughput and fairness. The observation suggests both robinT and robin-SUS as simple and efficient schedulers for femto-CoMP purposes.

In 6-CoMP-F2 frequency reuse pattern, where every second adjacent floor always uses the same frequency, the robinT scheduler provides 16 percent system throughout gain over 6-CoMP-F4 mode. One major reason for such throughput improvement is high SINR of UE secured by the 36.6 dB penetration loss between two floors. Lower fairness of 6-CoMP-F2 is caused by suboptimal waterfilling of zero-forcing beamforming after assuming no interference comes from outside of the CoMP cluster. In fact, the inter-CoMP interference in this case dominates over noise, and the whole system becomes interference-limited, which reveals one advantage of the robinT-wI scheduler: reducing the total power constraint while still achieving similar throughput. This advantage holds under the assumption that no interference comes from outside of this femto-CoMP system. Another advantage of the robinT-wI scheduler is its scalable frequency reuse since second adjacent floors can always use the same frequency.

In the following, we use the robinT-wI scheduler to represent the femto-CoMP scenario due to its simplicity and scalable frequency reuse. When the number of UE units per room ranges from 2 to 4, as shown in Fig. 5, we observe persistent throughput advantage of femto-CoMP over independent-HetNet.

Scheduling Delay

We can observe in Fig. 6 that the scheduling delay for any UE is bounded within 10 ms. In independent HetNet, at each time slot, six RBs can be used to schedule at most four UE units, thus incurring smaller delays than femto-CoMP with the robinT-wI scheduler.

The above simulation results demonstrate the advantage of femto-CoMP approach over independent HetNet in both system throughput and fairness. While the scheduling delay of femto-CoMP becomes larger, they still remain bounded by 10 ms in systems configured with up to four UE units per room.

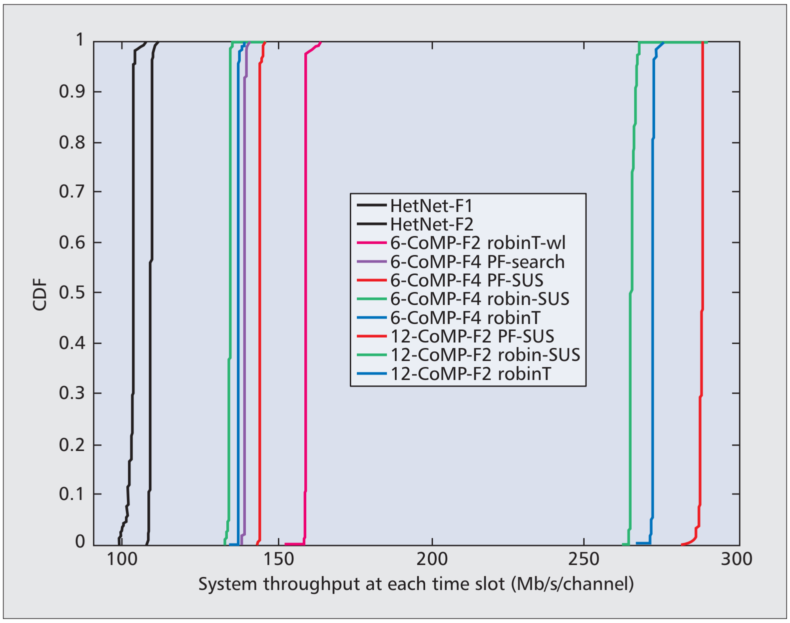

Figure 4. *CDF of system throughput at each time slot assuming two UE units per room.*

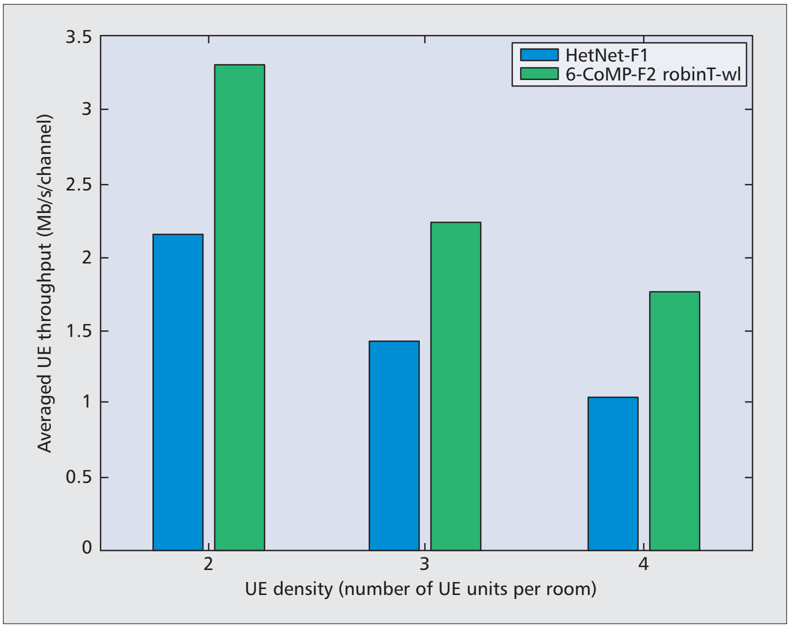

Figure 5. *Average UE throughput: HetNet-F1 vs. 6-CoMP-F2 robinT-wI. Number of UE units per room varies in {2,3,4}.*

Conclusions and Future Work

We have introduced a novel wireless-fiber integration design named broadband wireless access with fiber-connected massively distributed anten-

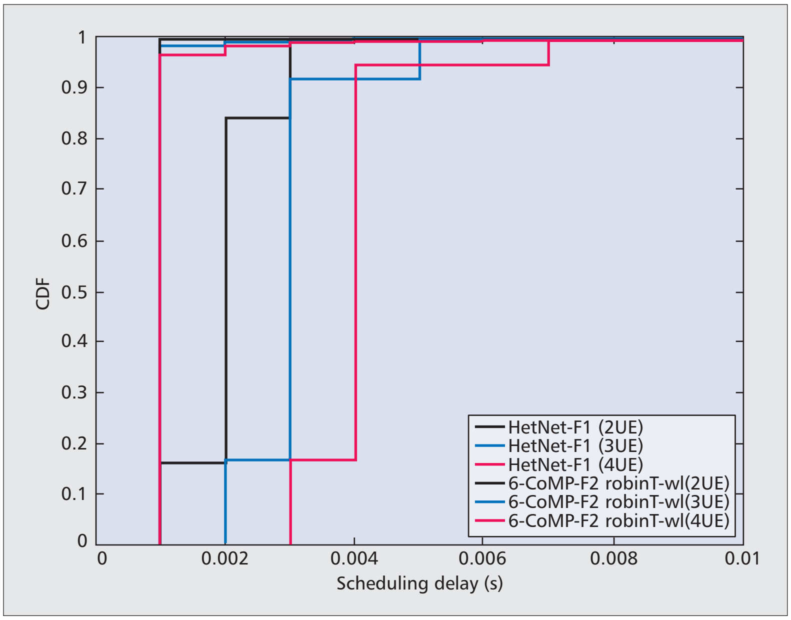

Figure 6. *CDF of scheduling delay among UE units. Number of UE units per room: {2,3,4}.*

nas (BWA-FMDA) which provides an efficient framework for HetNet implementations. More specifically, we have outlined a UMTS LTE HetNet architecture based on the proposed solution. We have further studied resource allocation and interference management opportunities facilitated by our design. Cooperative transmissions of signals from several femto and pico nodes to multiple users via beamforming, to which we refer as femto-CoMP mode, is a promising resource allocation technique in the proposed HetNet setting. Through extensive simulations, we have shown that performance gains are achieved in system and link throughput even under a simple round-robin scheduler design, while the scheduling delay remains bounded. For future research we intend to analyze more complex resource allocation strategies such as interference alignment to further improve system capacity.

Acknowledgment

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