SECTION I: RESEARCH PROPOSAL

TITLE: A NOVEL FEMTOCELL ARCHITECTURE VIA INTERFERECE CANCELLATION

I INTRODUCTION AND BACKGROUND

Telecommunications sectors have witnessed the deployment of new data-oriented mobile wireless systems, such as WiMAX and 3GPP Long Term Evolution (LTE), instead traditional circuit switching voice-orient wireless systems. It has been recently identified that over 50% of total phone calls and 70% of data services take place indoors [1]. A lesson learned from early experiences is that it is expensive to support both line-of-sight (LoS) and non-LoS communications in the range of few tens of kilometers, and it becomes less economically viable to build infrastructures with increasing data rates. Furthermore, quality of service (QoS) could be noticeably degraded by the path loss, shadowing, and multipath fading effects due to wall penetration, which result in low data rates and poor voice quality inside buildings, and create challenges for effective wireless services to operators.

One of the recent advances for overcoming indoor communication barriers while taking little infrastructure expenditure is the use of femtocells, which can achieve high data rate and manageable QoS for both users of macrocell and indoor femtocells. A femtocell is a small cellular area covering homes or offices, while a femtocell base station (FBS) is simple, low-cost, and miniature access point BSs designed for indoor wireless service coverage of the corresponding macrocell. As such, femtocell networks are end-user deployed hotspots that underlay the planned macrocell networks of mobile operators. Instead of using wireless transmissions like relays, an FBS is connected to the femtocell control station (FCS) via wired lines, such as fibers or coaxial cables. Here, the FCS serves as a gateway between the FBSs and the cellular backbone, which seamlessly incorporates with the macro base stations (MBS) for achieving an integrated service plan. Thus, a femtocell user equipment (FUE) could consume the resources provided by the FBS at this moment yet switch to the macrocell and become a macrocell user in the next moment due to mobility, possibly by using different radio channels, and vice versa. With this, a two-tier femto architecture is formed, where the MBSs are in tier-one while the FBSs are in the second. Fig. 1 shows the femtocell underlay and macrocell two-tier network architecture, where the FBSs are installed in building complexes and densely populated neighbourhoods, and are connected to the FCS via wireline such as cables and fibers.

The performance gain by femtocells is due to the higher link quality in indoor areas and better spatial reuse. Such advantages, nonetheless, could be impaired due to unplanned management, uncoordinated spectrum access, interoperability with existing handsets and network infrastructure. Co-channel interferences (i.e., interferences between the two-tier users) are considered one of the most challenging issues in achieving scalable and efficient femtocell design [2][3]. Numerous interference management approaches for femtocell networks have been reported, including a power control strategy for femtocell users [4], time hopped CDMA (TH-CDMA) combined with sectorized antenna [5], signal-to-interference-plus-noise based component carrier selection [6], and a centralized scheduling scheme

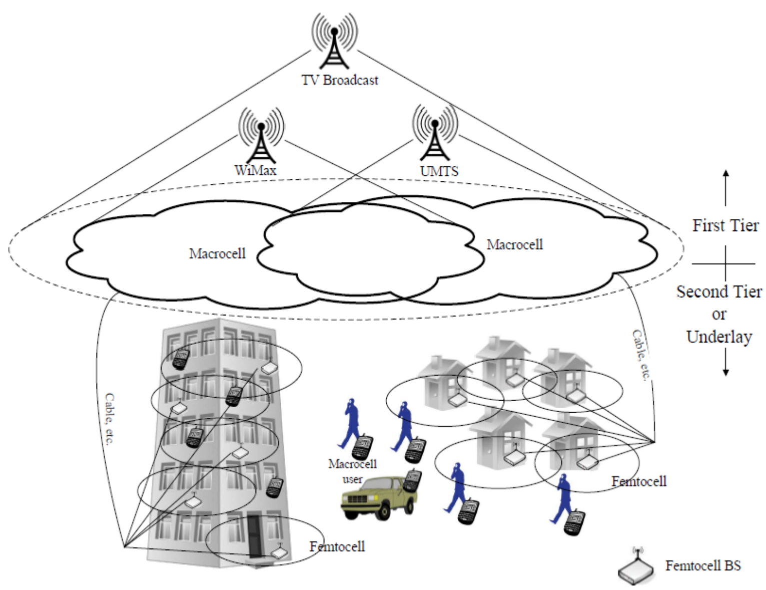

Fig. 1: Femtocell underlay in the two-tier architecture.

that considers the mutual interference of both femtocell and macrocell users [7]. However, due to the design requirement for simplicity with minimum modifications on the macrocell protocols running at the BS, these interference management approaches may not be efficient and scalable.

By considering data and multimedia services provisioned in 4G cellular networks, we expect femtocells will be widely and densely distributed similar to that of WiFi routers nowadays, such that a macrocell may cover hundreds of (or even more) FBSs. This makes the existing femtocell technologies based on centralized scheduling and resource allocation inefficient. A desired situation should be scalable to the number of FBSs, and each FBS works in a highly distributed and autonomous manner.

II PROPOSED IDEA TO INNOVATION

The proposed idea to innovation is on a femtocell wireless over cables (FemtoWOC) architecture for resolving the problem. Instead of any store-and-forward process via standard physical layer (PHY, or "L1" in the following context) and medium access control (MAC, or "L2" in the following context) protocol stacks, each FBS is simply equipped with a FemtoWOC device and is connected to the Femto Control Station (FCS) served as the gateway to the macrocell network via wires (e.g., coaxial cables or fibers), as shown in Fig. 2. The FemtoWOC device can be as simple as an antenna along with an analog modulator/demodulator. Fig. 3 gives a simplified system diagram for FemtoWOC with three FBSs (i.e., FBS-1, FBS-2, and FBS-3), where the cross-tier and intra-tier interferences on the uplink traffic of each FBS is linearly added on the original signal, x_i. The signals flowing via the cables/fibers are denoted as y_i, which is given by the equations right to the figure.

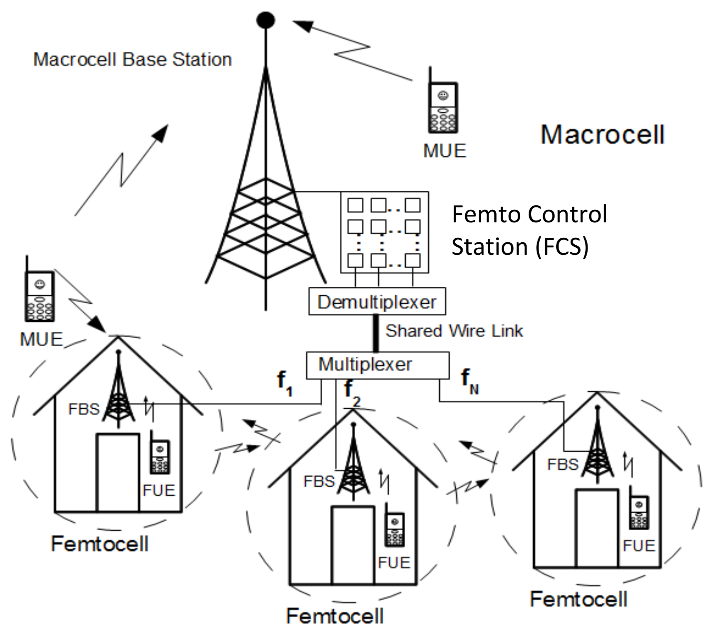

Fig. 2. An illustration of femtocell network architecture.

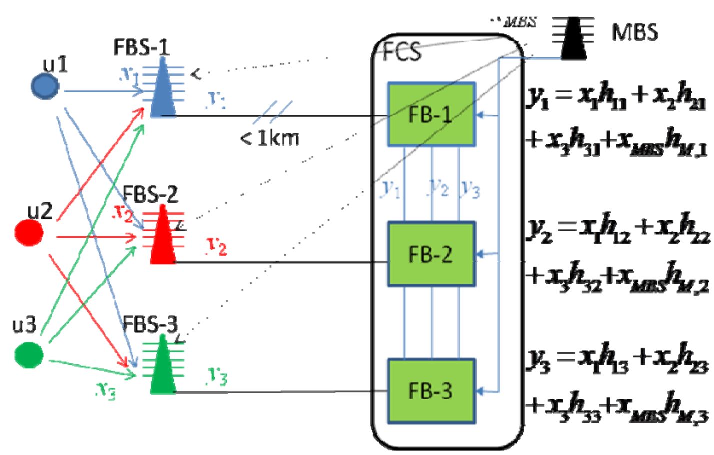

Fig. 3. A diagram of the WOC architecture. The signals (y_i) along the cables/fibers are due to the interferences from adjacent FBSs and the MBS.

At the FCS, an array of *femtoboxes* (FBs) corresponding to each FBS is devised, which centralizes the signal processing for y_i and x_{MBS}. The functional diagram of the *i*-th FB is shown in Fig. 4. In addition to the conventional L1 and L2 units (that could virtually be considered as on-the-shelf devices for standard L1 and L2), each FB is equipped with an interference identification/cancellation (IIC) module for interference correlation and cancellation.

The FemtoWOC device is positioned as a home device that performs bi-directional analog relaying of the signals to/from the FCS without any L1 and L2 processing. A careful look at IIC in Fig. 4 shows that the signal of the i^{th} FB goes through co-channel interference identification and cancellation with signals from the interfering FBSs and the MBS. Since no store-and-forward process is involved in the datapath, the signals from the FBSs are subject to constant delays due to the signal propagation over fixed distances. Thus, we can manage to achieve symbol-level synchronization at the FCS for all the FBS signals through proper compensation. Therefore, IIC is expected to effectively mitigate both intra- and cross-tier interferences at the i^{th} FB. Once interferences are removed, the signals are fed into the L1 and L2 units of the corresponding FB for conventional femtocell uplink receiver processing.

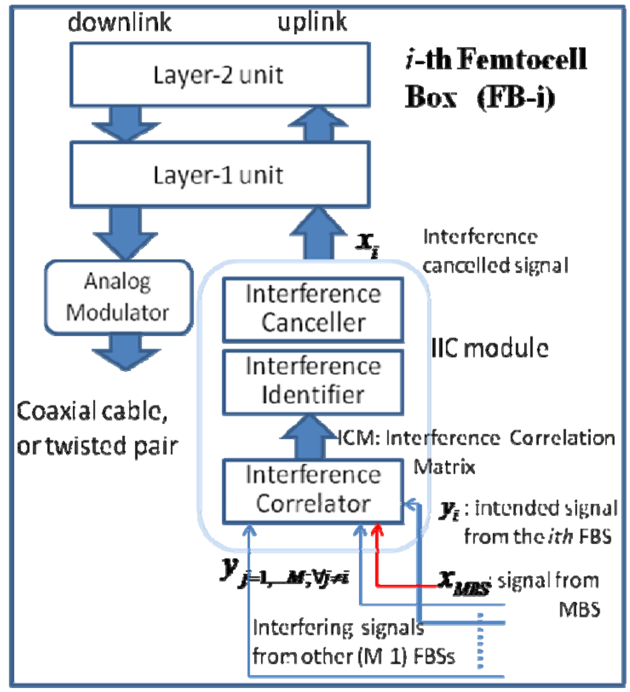

Fig. 4. Diagram of the *i*-th FB in FCS.

II.A Distributed FemtoWOC

It is clear that FemtoWOC is a promising option to the next-generation cellular systems; nonetheless, it seriously deviates from the current industry practices due to the centralized baseband processing. In addition, using customized analog/digital transmission of user data along the cables/fibers may achieve very low bandwidth, which will not be able to support data and multimedia services envisioned in the future femtocell systems. Thus, a distributed version of the proposed FemtoWOC architecture, namely D-FemtoWOC, is introduced, such that the interference cancellation can be performed transparently to the standard femtocell systems, while the user data is still transmitted through the cables/fibers using the standard carriers and protocols. Note that a consensus in the current standards is that the L1 and L2 units in the FBS should talk to the L1 and L2 units in the FCS, which ensures the transmission quality and control of the FBSs and FUEs over standard protocols.

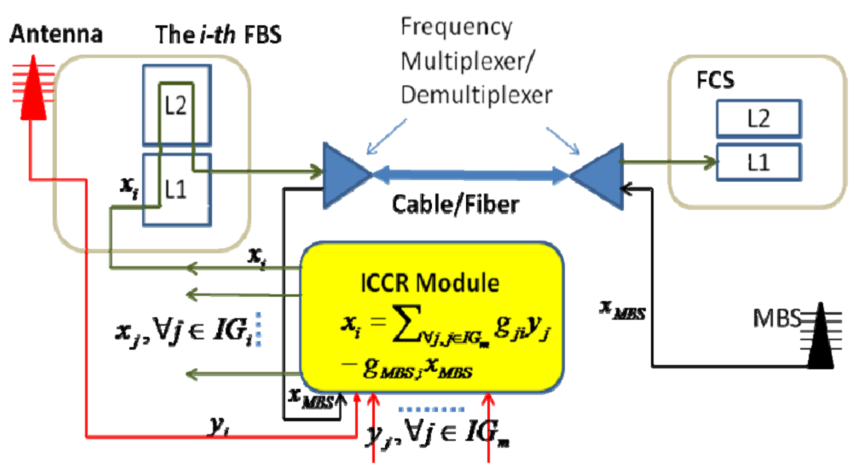

Fig. 5. Diagram for the proposed distributed WOC architecture.

To achieve D-FemtoWOC, a device called Interference Correlator/CancelleR (ICCR) as shown in Fig. 5 is proposed, which performs completely the same as IIC in original FemtoWOC. However, rather than located at the central FCS as IIC, multiple ICCRs are distributed in a macrocell, and each performs interference correlation/cancellation for a group of geographically adjacent FBSs. For example, an ICCR could be allocated at a curb of the access network beside a business complex, in a residential community, or at any location where the nearby associated FBSs are subject to non-trivial interferences with each other and/or with MBS. An *interference group* (IG) is defined as a set of FBSs associated with a common ICCR. The ICCR should be near the geographic center of the set of FBSs in order to erase any possible near-far problem, and is responsible for removing both intra- and cross-tier interferences for the uplink traffic of each FBS in the group. This can be achieved because the ICCR is connected to all the FBSs in the IG, and is fed with the raw signals from the FBSs and MBS. Thus, interference correlation/cancellation can be performed locally at the ICCR for the set of FBSs in the IG.

To enable cross-tier interference cancellation, the FCS has to real-time multicast the baseband signal x_{MBS} in the downlink direction through the cable/fiber to all the ICCRs. Note that any customized digital processing (i.e., sampling, quantization via A/D and D/A conversion, and even line coding, etc.) could be in place for the transmission of x_i, y_i, and x_{MBS}, as long as the resolution is high enough such that the feature of interferences carried in the signals is sufficiently in detail to enable effective interference correlation and cancellation at the ICCR. In some circumstances, each FBS is initially assigned with a fixed set of sub-bands which are orthogonal to that assigned to its neighbor FBSs. This is a viable approach for resolving intra-tier interferences when most FBSs have small numbers of neighbor FBSs. In this case the ICCR only needs to deal with the cross-tier interferences for the corresponding FBSs, which can be simply done by setting $g_{ji} = 0$ at the ICCR.

In summary, the proposed D-FemtoWOC is a distributed version and strategic implementation of the original FemtoWOC in terms of better industry acceptability and compatibility, and higher achievable bandwidth/throughput due to the use of standard protocols and digital systems along the datapath from FBS to FCS. It is compatible with the existing commercial and standard femtocell systems because the required signal processing at the ICCR can be totally transparent to the upper layer protocols.

III Significance of the Proposed Technologies

The centralized FemtoWOC architecture has merits and is novel in a number of aspects. Firstly and most importantly, it enables the mitigation of both intra- and cross-tier interferences in uplink via state-of-the-art signal processing techniques, which demonstrates a completely new design dimension and solution plane toward interference mitigation in femtocell networks. Secondly, since each FBS is simply an analog relay device that consists of an antenna, amplifier, and analog modulator/demodulator, it is inexpensive, generic and protocol independent, which can be with different standards and technologies (e.g., WiMAX, LTE, or any other). On the other hand, instead of being allocated in the user side, the L1 and L2 units in each FB at the FCS can be managed in a centralized manner (such that the FCS can virtually be multi-standard to guarantee vertical handover). Note that the L1 and L2 units of an FBS are usually software-based and protocol-dependent, which could incur extensive maintenance efforts in case they are allocated in home devices. Therefore, a much reduce maintenance overhead (e.g., upgrade and fault identification) can be achieved compared with the conventional femtocell design where protocol dependent and software based FBSs are scattered across the macrocell area.

Rather than via centralized processing, D-FemtoWOC defines IGs of FBSs and performs interference cancellation in a distributed manner within each IG, which is considered with better scalability, flexibility, and cost-efficiency. D-FemtoWOC also serves as a transition from the current standard/practice with a L1 and L2 modules in the FBSs, to the FemtoWOC architecture where each FBS is a simple an analog device.

IV Proposed Research and Milestones

With the proposed femtocell architectures and methods, we will undergo a series of research and development activities in order to explore its feasibility and potential of commercialization opportunities. As the first and the most important milestone (**Milestone 1**), an effective approach implemented in the IIC and ICCR module should be developed, which plays a key role in the co-channel interference mitigation for the proposed FemtoWOC architecture. We aim at a robust and efficient interference estimation method that can enable the interference cancellation. All the estimates are put together into an *interference correlation matrix* (ICM) to refine the interference canceller, possibly in an iterative manner with decoding (e.g., turbo IIC). In specific, let the i^{th} FB placed within the FCS that is fed with signals from the i^{th} FBS, be denoted as y_i, and the interfering femtocells' signals be denoted as y_j for $\forall j \neq i$, and the MBS's signal be denoted as x_{MBS}. With all these signals, the interference identifier will estimate the contribution of the interferences onto the i^{th} FB by correlating y_i and y_j for $\forall j \neq i$, and enable an effective interference cancellation.

To achieve the above goal, we will formulate the task into a simplified multi-user detection (MUD) problem at each FBS. Different from legacy MUD problems, FemtoWOC has the adjacent FBSs to form a distributed antenna system, such that the existing MUD schemes cannot work efficiently. For example, FemtoWOC takes a completely different approach in the side information acquisition from that of a CDMA system. Further, the purpose of MUD in FemtoWOC is for interference correlation instead of serving as a multiple access mechanism, which leads to a much different problem formulation. Since the conventional CDMA system is for achieving multi-user access at a single BS with improved channel gain, the near-far phenomena of each user becomes an important issue since all the signals need to be identified. On the other hand, FemtoWOC aims to correlate and cancel the interferences for each distributed FBS, where very weak signals can be ignored.

With the solution for interference correlation, we will create a prototype for D-FemtoWOC on a WiMAX system (**Milestone 2**). Although WIMAX is not a typical cellular network commercially employed, it has a similar operational principle with 3GPP networks and achieves an excellent environment for the purpose of proof of concept. We will firstly build the ICCR module based on a customized circuit board (**Milestone 2-a**); then a set of software defined radio (SDR) systems (NI PXIe-8108 controller) will be employed to form the testbed for the proposed FemtoWOC network (**Milestone 2-b**). With our previous experiences in manipulating the NI SDR systems, we expect that the uncertainty and risk in the prototyping process will be minimized.

While prototyping, we will perform a series of sensitivity analysis and error propagation due to random noises and signal misalignment under the proposed architecture (**Milestone 3**). This research effort aims to gain deeper understanding of the system performance and properly select important system parameters, such as the ICCR allocation and estimation of the ICM entries. In addition, as a related research initiative (**Milestone 4**), we will investigate the ICCR allocation and its impact to the overall cellular network performance. We plan to formulate it into an optimization problem according to the given FBS distribution, fault tolerance requirement, and near-far constraint, etc.

REFERENCES

[1] 3GPP R4-091976, LTE-FDD HeNB interference scenarios, RAN4 #51, May, 2009.

[2] 3GPP TS 36.214 V8.6.0, Evolved Universal Terrstrial Radio Access (E-UTRA); Physical layer - Measurements, Sept. 2009.

[3] K. –C. Chen, *et. al.*, 3GPP R4-093196, Institute for Information Industry (III) and Coiler Corporation, Interference mitigation for HeNBs by channel measurements, RAN4 #52, Aug. 2009.

[4] H. Claussen, "Performance of Macro- and Co-sub-band Femtocells in A Hierarchical Cell Structure", *Proc. IEEE PRIMRC*, Sept. 2007.

[5] V. Chandrasekhar and J. G. Andrews, "Femtocell Networks: A Survey", *IEEE Communication Magazine*, vol. 46, no. 9, Sept. 2008.

[6] L. G. U. Garcia, K. I. Pedersen, and P. E. Mogensen, "Autonomous Component Carrier Selection: Interference Management in Local Area Environments for LTE-Advanced", *IEEE Communication Magazine*, vol. 47, no. 9, Sept. 2009.

[7] V. Chandrasekhar and J. G. Andrews, "Uplink Capacity and Interference Avoidance for Two-Tier Femtocell Networks", *IEEE Transactions on Wireless Communications*, vol. 8, no. 7, July 2009.