Femtocells for next-G Wireless Systems: the FREEDOM approach

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Abstract: The paper deals with femtocell in context of next generation wireless systems. Actually, in the framework of the ITU, the definition of IMT.ADVANCED systems is on-going and all the candidates already investigate the usage of femtocells to improve system capacity. On the other hand, femtocell market is still at its early stage, facing the competition of low-cost, easy to use WiFi equipments. This paper presents the concept of femtocell and the related challenges and promising technical solutions to make them happen in the framework of next generation of broadband OFDM system.

Keywords: 4G, Femto cell, 802.16m, LTE.ADV, IMT.ADV,

1. Introduction

In the recent years there has been an increasing demand for mobile traffic due to the large nomadic population and the type of applications to be employed. This has motivated that the near-future 4G networks must enhance their efficiency in terms of spectrum, energy and cost as requested by the ITU, in the IMT.ADVANCED framework. One solution is the use of femtocells that has been also considered by several mobile operators (e.g. T-Mobile Europe, TELECOM-Italy and Vodafone in Europe; NTT DoCoMo and Softbank in Japan; O2/Telefonica, Sprint, AT&T Mobility and Verizon in the US; and Chunghwa in Taiwan) and different standards, such as IEEE 802.16m and LTE-Advanced.

In a nutshell, the femtocells are deployed in the households to get better indoor voice and data coverage, improving at the same time the macrocell reliability and promise to be a cost-effective solution, able to improve the spectrum efficiency of the network and additionally, increase the peak-bit rate in low coverage areas. There are many technical studies (e.g. [2], [3], [4], [5]) and business models (e.g. [6], [7]) elucidating the outstanding potential of femtocells in terms of increasing the network capacity, saving energy and providing benefits from the social and economic side, indicating the femto-based networks as a substantial technological breakthrough on future mobile networks. The ever-increasing industrial interest on femtocells is also testified by the boost in patents filed in 2008-09

However, macrocells and femtocells (connected through an IP-based backhaul link) use the same spectrum, originating interference and imposing additional horizontal handover issues that need to be administrated. In addition, the industries are concerned because all the envisaged benefits are not easily achievable, due to following major technical and non-technical challenges:

Technical

- A massive deployment of femtocells will pose serious issues on the radio interference management between the macro and femto layers and among neighbouring Femto Access Points (FAPs).
- There is still no clear effective approach for insuring seamless BS-FAP and FAP-FAP handover.
- Lack of precise engineering solutions for scalability, redundancy and traffic partitioning: the more massive is the deployment, the more impacting are these aspects.

- Access control: solutions in [8] are "open" access paradigms, whereas the "restricted" access in needed. The mechanisms proposed so far (e.g. idle mode mobility with area assignment to each femtocell and service rejection in Location Area Update) are not optimised and are difficult (if not impossible) to handle when the areas assigned to different FAPs overlap (massive deployments).
- There is currently no guarantee that the fixed broadband connection will prioritize the traffic originating from the FAPs for a service without interruptions, call blocking and dropping.

Non-technical

- The major advantages seem concentrated on the operator side and there is no business models that leans also towards end-user interests and make the purchase of a FAP attractive for the end-user.
- WNO prefer not to be tied to a single vendor and current FAP equipment is not likely to interoperate.
- A new type of handset could be required to efficiently operate with FAPs and handset issues may jeopardise the business case, as testified by some unsuccessful UMA deployments such as the BT-fusion service.

The FREEDOM project [1] aims at providing seamless solutions and high bit rate wireless services, based on **F**emtocell-based netwo**R**k **E**nhancement by int**E**rference management and coor**D**ination of inf**O**rmation for sea**M**less connectivity (FREEDOM). The planned activities target at providing a new vision of a femto-based network, giving solutions to the major concerns about the foreseen mid-term (2011-2012) massive deployment of FAPs.

This paper is organized as follows: Section II introduces the market drivers of femtocells while Section III presents the technical approach foreseen by the FREEDOM project. Finally Section IV concludes the paper.

2. Market drivers

The most significant business cases and market analysis developed so far (e.g. [7], [9], [10]) indicate the following major advantages for operators and the consumers, related with the adoption of femtocells.

Benefit	**Description**	**Operator**	**Consumer**
Increased coverage and data rates	Femtocells can insure better coverage in indoor environments and data rates limited to the ISP backhaul capacity		X
Reduced network cost	The cost associated with the data transport through a FAP is less than the cost faced by the operator for the wireless macrocell and a part of this cost is faced by the consumer	X	
Reduced congestion under peaks of high service request	Areas with high density of users and proportionally low density of BSs (sport grounds, skyscrapers, convention centres, etc.). Deployment of FAPs drain traffic from the macrocell to the xDSL connection	X	X
Delivery of advanced services and reduced tariffs	The possibility of locating the user within the home enables the provision of dedicated services and the application of discounted tariffs		X

Table 1:Operator and consumer benefit

The foreseen market impact is not negligible, also considering that 60% of the wireless voice traffic and 70% of the wireless data traffic originates in home/office environments [11] and that the 19% of the European users complain about the poor voice coverage at home (58% of which in every room). In addition reducing the cell size boost in the data rates.

However the benefits claimed so far can be achieved only if and when the deployment of femtocells will be massive (e.g. 100 FAPs per macrocell, so that the drain of bandwidth request from the macrocell is significant) and the consequent major issues about the interference generation, seamless handover and scalability will be solved. This is precisely the direction of FREEDOM. We believe that the combination of the new paradigms employed in the project constitute a realistic and technologically viable set of solutions to enable the achievement of the targeted high density in FAPs deployment. FREEDOM will thus benefit to the at-home/office customers that will have access to higher bit rate services, dedicated advanced applications and possible cheaper tariffs policies (see table 1). At the same time, the data flows routed through the ISP backbone by the FAPs will proportionally relieve outdoor macrocells of a substantial traffic load, lowering the congestion peaks and insuring better connectivity and QoS for the other subscribers.

The benefits for the operators are even more significant, as the achievement of dense FAPs deployments will translate in a direct financial benefit proportional to the bandwidth routed on the ISP backhaul; in addition the possibility of offering new dedicated services for the home/office will enlarge the market segment, attracting new customers.

Beside the above, it has to be considered that serving indoor users from outdoor macrocells has a disproportionate drain on network capacity and power consumption [12]. In this perspective, the advanced PHY techniques for interference avoidance as well as the advanced RRM employed by FREEDOM will further decrease the energy consumption and the EM (Electromagnetic) pollution of the whole system: topics highly impacting on the EC policies about the green issues.

The FREEDOM project targets to new concepts and techniques beyond the conventional cellular paradigm. The technical approach of FREEDOM project is described in the next section.

3. Technical approach to enable massive Femtocell deployment

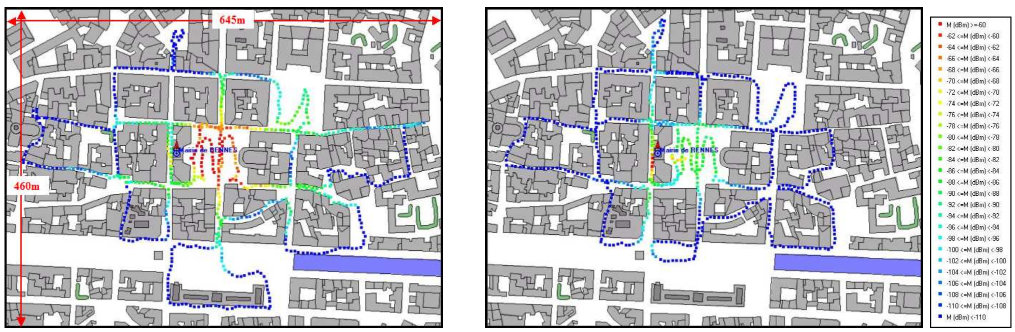
The femtocell is a wireless network which shares the licensed wireless spectrum with the macrocell. Both networks are connected through an IP-based backhaul link. In contrast to the optimized deployment of base stations in the macrocell, the FAP is installed in the households by the end-user without the supervision of the macrocell. Under those circumstances, the deployment of a large number of femtocells imposes an efficient administration of the interactions between both types of networks. FREEDOM will investigate advanced interference-aware PHY techniques (scaling as the quality of the backhaul link) and the enhancement of the control plane procedures. The devised algorithms will be evaluated at system level, outlining the benefits of the femto-based networks and giving some network planning recommendations. Additionally, the candidate algorithms/protocols will be assessed in terms of hardware feasibility and on-field demonstration.

3.1. Advantages of advanced interference-aware PHY techniques

The challenges faced at the PHY layer in FREEDOM are:

- human activity impact on the channel models in a femtocell context;
- synchronization (time, carrier frequency and carrier phase);
- interference power modelling;
- transmission/reception schemes based on the quality of the backhaul link.

Since the femtocells are installed inside of the buildings, the moving people will block intermittently the signal transmitted from the femtocell or the interfering signals coming from the macrocell. Those issues are currently investigated in the IEEE 802.11n and COST2100. One of the objectives pursued by FREEDOM is to get a realistic channel model for indoor and outdoor-to-indoor transmissions. Thus two coherent approaches will be followed. On one side a propagation model will be proposed to determine the indoor and outdoor coverage resulting from indoor femto transmitter. The impact of the transmitter location inside the building will lead to different outdoor coverage. This will model the observation made on initial measurement campaigns represented in Figure 1. In this Figure, the transmitter is located deeply inside the building or close to the window. The possible range of interference of the femtocell in the surrounding environment may be observed.



(a) (b)

Figure 1: Femtocell outdoor coverage for a transmitter located a) close to the window b) deep inside the buidling

On the other side, a realistic channel model is derived by combining RF measurement campaigns and by a large set of deterministic simulations in typical configurations. This channel model is then used in system simulators.

The synchronization can be tackled from two different points of views: time synchronization and carrier frequency/phase synchronization. The femtocells are autonomous (cheap) entities connected to the macrocell through an IP-based backhaul. At the macrocell, the base stations have high-accuracy oscillators calibrated periodically by timing signals sent from a central controller over T1 lines (more reliable than IP lines). The accuracy of the oscillators installed at the FAPs is significantly lower than the BSs in the macrocell. The lack of time synchronization among femtocells motivates the generation of the interference due to the uplink/downlink transmissions. FREEDOM will consider the adoption of distributed techniques for time synchronization at frame level and will evaluate how the synchronization is related with the generated interfering power. The second type of synchronization (carrier frequency/phase) is required for implementing distributed precoding solutions when two or more network elements (nodes) decide to cooperate in transmission. The promising gains of the distributed precoding techniques can be dramatically reduced when the nodes are not synchronized.

The derivation of a statistical model for the interfering power received at the femtocell and macro-cell is necessary to design robust transmission schemes for minimizing the impact of the outage events associated to the current (unknown) values of the interference. Moreover, this model will be useful for the system level evaluations of the femto-based network.

The transmission/reception techniques are grouped as a function of the quality of the IP-based backhaul link: minimal, medium and high quality. When the quality of the backhaul link is minimal it is not possible to exchange much information among nodes (femto-femto, femto-macrocell), so the signals received from neighbouring femtocells and/or macrocells are tackled as interference. To this end, intelligent sensing algorithms will be developed, exploiting the compressive sensing and resource allocation can be designed under a game-theory approach as a competitive game. Under the assumption of a medium-quality level of the backhaul link, the nodes are capable of exchanging messages at control-plane level, deriving coordinated strategies, where several nodes can collaborate in order to identify the interference. Finally, a high-quality backhaul link allows exchanging messages at data-plane level. Hence transmitter cooperation strategies can be devised such as distributed beamforming (under carrier frequency/phase synchronization) or space-time coding, where all the cooperative nodes must know all the messages.

With respect to this kind of cooperation mechanisms in the infrastructure, FREEDOM project aims to find practical methods that make cooperation worth doing. A first issue that may be raised here is to find the threshold above which the data plane cooperation has to be triggered. The threshold value will be chosen according to a compromise between the spectral efficiency enhancement and the complexity of the required processing and signalling. Based on this threshold it would be possible to define geographic regions where cooperation is worth doing. This problem has been investigated in similar situations of distributed antenna systems using standard cellular technologies.

Figure 2 draws an example of results obtained for a WiMAX network where base-stations are deployed according to a regular hexagonal grid. Several cooperation modes have been defined: single BS (no cooperation single user), intra-BS cooperation (denoted IntSec) which involves different sectors within the same base-station, and inter-BS cooperation (denoted IntBS), where 2 or 3 sectors cooperate to process one, two or three users. The cooperating sectors are located in two or three neighbouring cells. The colour of each point corresponds to the best mode according to a compromise made between spectral efficiency and joint processing complexity. This compromise is defined through a set of complexity triggers. A cooperative mode is preferred only if it brings significant gain compared to other modes with lower complexity. The figure shows that more than 50% of the cell area is covered by cooperative modes. Such result gives a first insight about the relevance of cooperation in a femtocell deployment. An extension to this work will investigated in the framework of the Freedom project by taking into account the backhaul limitations. Furthermore, appropriate low complexity physical layer schemes and MAC signalling will be investigated in order to ensure the competitiveness of the femtocell concept.

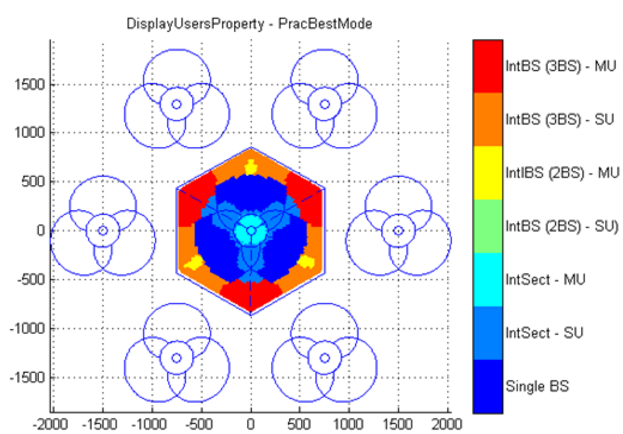


Figure 2: Cooperation worth doing geographic regions in a WiMAX cooperative network

Among the various PHY options, antenna selection will be jointly investigated with cooperative mechanisms. In fact, when data plane cooperation is possible, it is obvious that the best scheme is to use all antennas to process (in DL or UL) all users. However, this may be non-feasible in practice. In order to guarantee scalability, the cooperation needs to be restricted to a small number of base-stations and FAPs. The antenna selection algorithms can be of two types: BS/FAP selection and antenna selection. The former consists in finding the macro-BSs and FAPs whose cooperation is worth doing, and the latter consists in selecting antennas within the same BS/FAP.

Antenna selection has been extensively investigated in single BS single user processing [14][15][16]. However, very few contributions have focused on this problem in the distributed case (multiple-base stations and multiple users). The entity selection has been considered in [13] where several algorithms have been proposed. However in the proposed schemes, the limitation of the backhaul rate has not been taken into account. In order to ensure scalability of the femtocell concept, Freedom will provide practical backhaul aware BS and antenna selection mechanisms. These schemes will be tightly related to the complexity triggers and the backhaul rate threshold mentioned above.

3.2. Enhancements in the control plane procedures

Strategies for seamless handover: the fast seamless handover generating minimum signalling overhead for femto-based networks with coordinated femtocells will be designed. This procedure should allow handover among macro and femtocells as well as among femtocells. The femtocells have some specifics (such as fast decrease of signal strength) that will be reflected in the proposed handover management procedure. Therefore, advanced methods for handover decision and initialization will be designed considering either parameters from different layers or passive scanning. Also in this case the exploitation of the coordination paradigm enables the design of significantly more promising femto-specific coordinated handover mechanisms. However, as in the case of the interference management, also not-coordinated solutions will be proposed, as the lack of sufficient quality of the backhaul is a worst-case, but still valid, working hypothesis. Finally, since the femtocells can support both 4G candidates, LTE-A and WiMAX, procedures for movement of users among networks with different radio access technologies will be also supported.

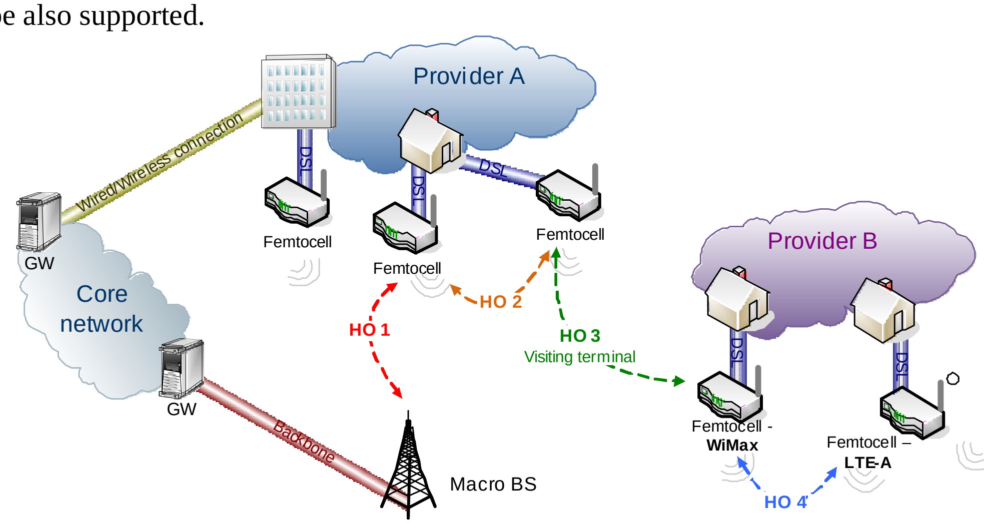


Figure 3. Handover scenarios

Generally, four handover scenarios are taken into account as depicted in Figure 3. The first one (HO 1) refers to scenario where a MS performs handover between macrocell and femtocell (and vice versa). Both, macrocell and femtocell, belongs to the same service provider. The second scenario (HO 2) corresponds to case when a MS executes handover from one femtocell to another one. Both femtocells are assumed to be served by the same service provider and both femtocells are placed at the same location (e.g. same house), however at different places (e.g. different floors). The third scenario (HO 3) represents case of handover between two femtocells of different service providers. The HO 3 requires to enable an access through visited femtocell. Last case of handover (HO 4) corresponds to a vertical handover. It means the handover between femtocells based on the different technologies (e.g. LTE-A and WiMAX).

***MAC control procedures*:** the control procedures for radio resource management in networks with femtocells should manage radio resources despite the limited backbone capacity. To achieve an effective utilization of backbone capacity new scenarios will be considered for routing of data among users served by same FAP. Besides routing, spectrum-efficient techniques for power control, scheduling and broadcast services transmission will be designed. Additionally, novel user admission policies and FAPs identification techniques will be defined keeping in consideration the scalability of the system. The designed control procedures will respect FREEDOM environment and will get the benefit from cooperation and coordination among femtocells and macrocell as investigated in parallel.

3.3. Indications from the system level evaluation

The impact and the benefits of the advanced PHY techniques for the interference avoidance and the control plane procedures must be tested at system level and this poses new challenges such as the adoption of realistic interference system-level models, the system scalability in case of sense deployments and the optimisation of the routing and security mechanisms to be implemented on the ISP backhaul. It is proposed to adopt a systematic approach that will consider the dynamic femtocells clustering as a viable route to cope with the scalability issues by introducing cluster-aggregated metrics, in order to minimise the impact on the ISP backhaul bandwidth requirements.

3.4. Hardware demonstrator

The devised algorithms will be implemented and verified through a hardware prototyping. The hardware feasibility study will suggest which techniques are chosen as a basis of the first femto access point (AP) prototype realization. The latter will address the selected interference mitigation techniques and routing mechanisms to be proven in order to refine the engineering rules of the femtocell deployment. The manufacturers will test and verify the implemented techniques in standalone manner so that there is no requirement to integrate the FAPs with the LTE/WiMAX core networks. These will prove the chosen techniques individually without considering the integration issue.

Another approach will further enrich the proof of concept activities. A laboratory trial will be performed to study the interference characteristics, power control mechanism and handover performance (if applicable) between femto-to-femto and/or femto-to-macro cell and their impact to the system coverage and capacity in a reduced-scale environment. The integration between femtocell and xDSL/Metro-Ethernet network system will be provided within a R&D Centre testbed facility provided by an operator. The trial activities goal may not be limited to prove the selected new techniques implemented in the prototypes (due to the interoperability issue), but extended to refine the engineering rules of the femtocell deployment.

5. Conclusion

Currently, femtocells and macrocells are seen as isolated networks, competing for the resources available in the common spectrum band, at the cost of injecting interference to the whole system. FREEDOM project will address key technical and industrial concerns about the foreseen mid-term massive deployment of femtocells by adopting a new approach based on cooperative/coordination paradigms, enabled by the quality-limited ISP backhaul link. The project will not disregard the approach of isolated networks because it is met when there is not enough backhaul link connecting the femtocells and macrocell. In order to guarantee a strong focus and efficiency, FREEDOM will focus on: advanced interference-aware cooperative PHY techniques, improvement of the control plane procedures for seamless connectivity, system-level evaluation and hardware demonstrator of the proposed femto-based network architecture.

Acknowledgement

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