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Analysis of Coverage Range Expansion in Closed Access Cognitive Femtocell Networks

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***Abstract*—Femtocells are low-power nodes which aim to extend high data-rate wireless services in indoor environments. While low power operation allows more frequent spectrum reuse and significant improvement in network capacity, it also suffers from frequent handoffs between the macro and femtocell due to the short distances involved. It can potentially generate considerable redundant control data for handover management. An alternative is to apply handover bias which artificially expands the coverage range of a femtocell to keep a user connected to a *femtocell access point* (FAP). This eliminates the handover problem or ping pong effect, but at the cost of reduced throughput. This paper proposes an *enhanced virtual cluster formation* (EVCF) algorithm that allows the coverage range of the femtocells to be expanded. The impact of FAP coverage expansion on system performance of closed access femtocell networks for various FAP deployments has been analysed and is compared to a random resource allocation system with similar range expansion capability. Results reveal that while FAP range extension inevitably decreases the *signal to interference plus noise ratio* (SINR) and corresponding throughput, the resultant degradation can be minimised by adopting the EVCF model with a commensurate enhancement in the system *quality-of-service* (QoS) provision.**

I. INTRODUCTION

Femtocell networks are increasingly emerging as a viable solution for cellular and high data rate broadband services in indoor environments [1]. They normally comprise a plug and play *femtocell access point* (FAP) and small number of *mobile stations* (MS). The FAP provides conventional cellular and data services similar to a *macrocell base station* (MBS). Since it operates at a low power ($\sim 10dBm$) it covers only a short range of typically $< 10m$. The femtocell network is overlaid on the macrocell network and operates on the same licensed band, with the FAP traffic backhauled via either conventional wired *asynchronous digital subscriber line* (ADSL) or optical fiber networks.

Femtocell technology offers a number of benefits [2]. Due to the short communication distance involved, the transmitter-receiver link is robust and high data rates are achievable by using higher order modulations. It also liberates a number of channels by handing over indoor MS from MBS to the FAP. Since each MS connects to a nearby FAP instead of a relatively distant MBS, the energy for communication is low compared to the macrocell system. As a consequence, MS experience prolonged battery lifetimes. This permits the spectrum to be reused more frequently which in turn significantly increases achievable throughput per unit area.

Although FAP offers a number of benefits, there are technical, regulatory and economic challenges that need to be addressed. A summary of these and their possible solutions are given in [3]. Since FAPs are deployed by the end users, no pre-deployment network planning is possible, unlike in a macrocell system. Due to this uncoordinated deployment, severe interference between the macrocell to femtocell and between femtocells may occur, particularly in dense residential areas. Thus, post deployment network planning including cross-tier resource sharing and femto-tier resource distribution is a crucial design objective [4].

While low power transmission offers many advantages, it can lead to users easily going beyond the coverage range of a femtocell for a short period of time. This means there is the potential danger of triggering a high number of handovers which requires cross-tier control information sharing and negotiation. This increased control data will have a detrimental effect on the efficiency of the network. To avoid such frequent handovers is therefore vital for successful joint macro-femto deployment.

The issue of mobility and handover have been previously addressed in the literature [5] [6]. Dynamic coverage shrinking and expansion techniques for cellular networks have previously been studied to ensure various performance metrics, such as load balancing, system throughput maximization and fairness, coverage hole elimination and energy saving are mentioned . Cell zooming is a technique that adaptively adjusts the cell coverage range depending on the traffic load, channel condition and user requirements [6]. Cell zooming, particularly expansion, cannot however be readily performed to cover areas far away from the cell that lie deep inside neighbouring cells, as this may require higher transmission powers. It also increases the risk of higher traffic in the expanding cell, ultimately leading to a load imbalance in the system.

Existing coverage range modification research which relates to cellular networks has mainly focused upon pre-planned network architectures and coverage, which is typically much higher than FAP coverage. Also as mentioned earlier, unplanned femtocell deployments and their short coverage distance make the handover related problem distinct from the conventional cellular network. This provided the motivation to undertake a detailed study of the coverage range issue in a femtocell network context.

Recent work relating to range expansion for dual-tier cellular networks predominantly addresses open access multi-tier heterogeneous networks with the focus being upon the mobility and handover issue between the tiers. Mobility management between network tiers with handover and ping-pong effect involved in range expansion has been analysed in detail in [7]. In a randomly deployed open access femtocell scenario, dynamic coverage adjustment is very important for balancing the load among the collocated FAPs, while minimising the overall coverage [8]. Also, along with load balancing, the level of transmission power can be adjusted to provide energy savings. From a design perspective therefore, to achieve individual throughput fairness among the users, both the power and resources need to be carefully allocated.

While some literature [9] has sought to address range expansion within dual-tier heterogeneous networks, the impact on closed access femtocell networks has been largely ignored. In this paper, a pragmatic approach has been adopted where range expansion in closed access femtocell networks is studied. The investigation focuses on analysing the impact of coverage expansion at various FAP deployments, to understand how the throughput or *spectral efficiency*(SE) and *signal to interference plus noise ratio* (SINR) performance varies as the FAP coverage range is expanded and how the FAP deployment density influences the overall system performance. This provided the basis for the development of a cross-tier handover minimisation framework for closed-access femtocell networks.

To evaluate the impact on range expansion on both SE and SINR, a previously developed algorithm *virtual cluster formation* (VCF) paradigm [10] has been enhanced to accommodate range expansion capability. Then the performance of the proposed *enhanced VCF* (EVCF) algorithm is compared with a benchmarking randomly allocated *non clustered system* (NCS) with similar range expansion capability. The performances have been rigorously tested and analysed for various FAP densities. The paper will also make some recommendations with regard to adopting a range expansion (RE) policy for joint macro-femto deployment models.

The rest of the paper is organised as follows: the system model will firstly be discussed in section II, before a rigorous analysis on the corresponding coverage range expansion performance is presented in section III. Finally, section IV concludes the paper with some recommendation for future work.

II. SYSTEM MODEL

A joint macro-femto deployment model is considered in this paper, where the femtocell network is overlaid upon the macrocell network. The MBS is located at the centre of the cell with the layout following the traditional hexagonal pattern. Each cell comprises three sectors with MSs connected to MBS being uniformly distributed in each sector. Femtocells have omnidirectional coverage and they are uniformly distributed inside the coverage of the macrocell. The FAP is assumed to be located at the centre of a femtocell and the MS are uniformly distributed across the femtocell coverage. Both FAP and MBS transmission powers are fixed. A closed access mechanism is adopted for all femtocells so if a user moves out of the coverage of femtocell, they are handed over to the macrocell only. Similarly, once a macrocell user reaches the coverage of femtocell, then it will be handed over to the femtocell. Since the focus of this paper is to analyse the impact of RE, for simplicity only those users that are already connected to a FAP are considered in the ensuing evaluation.

Both macrocells and femtocells are operating in the same 10MHz spectrum, which is divided into 180KHz wide equispaced channels in an analogous way to the 3GPP LTE definition. The sharing between the macro and femto tiers is performed according to the dynamic *fractional frequency reuse* (FFR) technique described in [11]. Dynamic FFR updates the femto-tier at regular intervals with spectrum usage information about the macro-tier in different macrocell sectors. The femto-tier then makes its own allocation ensuring mutually exclusive channels are used by both macrocell and femtocell in any particular location.

For indoor scenarios the WINNER II [12] path loss channel model is utilised, with (1) and (2) giving the indoor path losses (PL) for the Line of Sight (LOS) and NLOS cases respectively. In *Non Line-of-Sight* (NLOS) situations where there are walls between the transmitter and receiver, an extra wall penetration loss (L_{WP}) component is included.

$$PL_{LOS} = 18.7\log(d) + 46.8 + 20\log\frac{f_c}{5} \quad (1)$$

$$PL_{NLOS} = 20\log(d) + 46.4 + 20\log\frac{f_c}{5} + L_{WP} \quad (2)$$

where f_c is the carrier frequency (GHz), d is the distance (m) and L_{WP} is the wall penetration loss (dB).

Wall penetration losses vary according to different factors such as: signals angle of arrival, transmission frequency, wall thickness and the construction materials used. So to simplify the calculations, $L_{WP} = 5dB$ and $L_{WP} = 10dB$ are respectively considered as the internal and external wall penetration losses.

Channel Allocation: It is assumed each FAP is responsible for allocating channels to its member MSs. It achieves this based upon feedback from the MSs on the received SINR. Each FAP calculates the *carrier-to-interference ratio* for all the MS attached to it and for all the channels available to it and then assigns the best channel to the MS using the following relationship:

$$\frac{C}{I} = \frac{P_{t0}h_0}{\sum_j P_{nj} + N_0} \quad (3)$$

where C is the carrier power, I the interference-plus-noise power, P_{t0} the transmit signal power, h_0 the channel power gain, P_{nj} the received interference power on channel n from user j and N_0 is the noise power.

In the next section, a brief overview of the the EVCF network management model is presented.

A. Enhanced VCF Paradigm

The key characteristic of the VCF framework is the generation of virtual FAP clusters, which are formed according to a minimax criterion by combining FAPs operating on the same set of channels, while concomitantly maximising the closest FAP distance. The rationale for the VCF algorithm is that as power exponentially decays with distance, the FAP furthest away from a particular FAP will correspondingly generate the lowest interference. Hence, by maximising the distance of the closest FAP operating on the same channels the interference can be minimised. The logical block diagram of the VCF paradigm is shown in Figure 1.

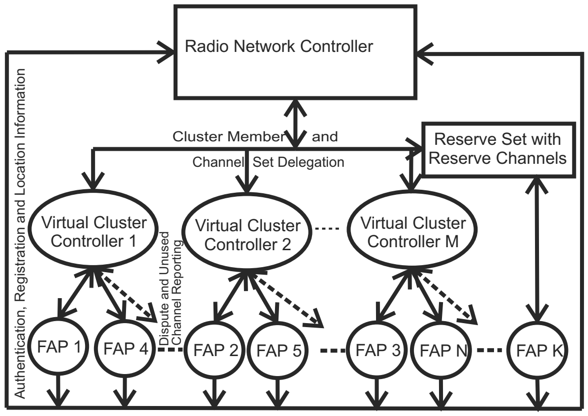

Fig. 1. Virtual cluster formation block diagram for femtocell networks

In order to manage the femtocell networks, the VCF model creates a number of *virtual cluster controllers* (VCC) to control the FAPs which are grouped into virtual clusters. The number of VCC is calculated as follows:

$$M_V = \left\lfloor \frac{C_f}{\max(N_k^f)} \right\rfloor \tag{4}$$

where M_V is the number of VCC, C_f is the number of channel available for the femtocell networks and N_k^f is the number of MS connected to k^{th} FAP.

Cluster membership is determined using a Euclidean distance criterion, with the inter-FAP distance between femtocells being represented by the distance matrix D:

$$\mathbf{D} = \begin{pmatrix} d_{11} & d_{12} & \dots & d_{1N} \\ d_{21} & d_{22} & \dots & d_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ d_{N1} & d_{N2} & \dots & d_{NN} \end{pmatrix} \tag{5}$$

where d_{ij} is the Euclidian distance between FAP i and FAP j. Note, all diagonal elements of **D** are zero and are excluded from the minimum distance calculations. Also, $d_{ij} = d_{ji}$.

After calculating the matrix, the VCF finds the nearest neighbours from **D** and allocates them to two different empty VCC, before excluding these from the allocation list and **D**. The next closest pair of FAP is then considered from **D** and allocated to another empty VCC, if any exist. Otherwise, the distance from the cluster members of each VCC is taken from **D** with the minimum distance from each VCC being chosen. Finally, the FAP is assigned to the VCC which has the highest minimum distance with the candidate FAP. The process continues untill all the FAPs are allocated. Full details of the VCF algorithm are provided in [10] including the cluster formation process and FAP assignment methodology together with the corresponding SE and SINR results.

In the original VCF algorithm, the coverage range of the femtocell was fixed. Any user moving out of the fixed range was handed over to the macro cell. The EVCF algorithm enhances the previous algorithm to include range expansion capability by introducing handover bias to the system. It allows the user to remain connected until certain extended distance is reached or the *Quality of Service*(QoS) falls below a given threshold regardless of the handover bias required for it. The objective is to keep the users connected to it as long as the performance is satisfactory. The performance of the EVCF will be analysed in the next section.

III. SIMULATION AND RESULTS ANALYSIS

To evaluate the performance of the EVCF algorithm, a 200m by 200m area of one sector in a hexagonal macrocell was considered, for three specific FAP node deployments of 50, 100 and 200. It was assumed 20 channels were available for femtocell downlink operation, so according to (4), the requisite number of VCC was 5. As a performance comparator for EVCF, a distributed resource allocation framework was implemented where each FAP independently chooses its operating spectrum and whenever it encounters an interferer, it randomly hops to a new channel, so no clustering is involved i.e., NCS. The simulation test platform was designed and implemented in MATLAB$^{\text{TM}}$, with all the various network environment parameters being given in Table I.

TABLE I
NETWORK ENVIRONMENT PARAMETERS USED IN ALL SIMULATIONS.

System Parameter	Value (Range)
Femtocell Radius (R)	6m to 18m
Macrocell Radius	500m
Experimental Area	200 m × 200 m
Number of Femtocell in experimental area	50, 100, 200
Maximum number of MS per FAP	4
MS Noise Figure	9 dB
Shadowing	6 dB
Macrocell Transmission Power	46 dBm
FAP Transmit Power	10 dBm
MS Min. Power Requirement	$\geq$ 0 dB
Total Bandwidth	10 MHz
Channel width	180 KHz
Total Number of Channels	50
Number of Channels for FAP in the given area	20
Number of VCC	5
Number of Simulations	10000

Firstly, the performance of the NCS and EVCF systems at various coverage ranges was evaluated at a 100 FAP deployment density. The *cumulative distribution function* (CDF) for both the SINR and corresponding SE are shown in Figures 2 and 3 respectively. It is clear that both the SINR and throughput (SE) decrease as the FAP coverage range, R expands. When the coverage range, $R = 6$m the NCS system achieves on average, an SINR of 18dB. This reduces to 13.5 dB and 10 dB when R is further expanded to 12m and 18m respectively. The range expansion allows users to move relatively further away from the FAP which results in a higher transmitter-receiver distance so the signal becomes weaker because of increasing propagation loss. Also, the user may become closer to FAPs operating on the same channel and receive stronger interference.

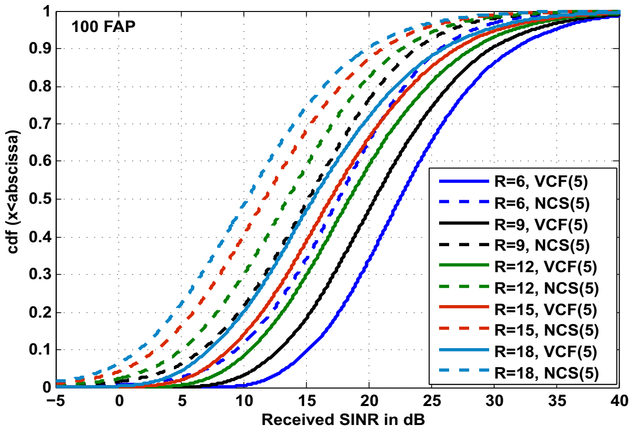

Fig. 2. CDF of SINR performance with various range expansion values (R) for 100 FAP when $VCC = 5$ and for an equivalent channel sets for NCS.

In contrast, the EVCF model performs much better compared to NCS at the same 100 FAP at all expansion range values as evidenced in Figures 2 and 3. For EVCF, the average achieved SINR is approximately 22.5dB when the coverage range is 6m and decreases to 18dB and 16dB at ranges of 12m and 18m respectively. This means for the 100 FAP deployment density, the EVCF outperforms NCS by a margin of 4.5dB when the coverage is 6m and by 6dB when the coverage is extended to 18m. Similar improvements are observed when a comparison is made of the throughput (SE) performance of the EVCF and NCS approaches.

The central idea behind the EVCF paradigm is to maximise the average spectrum reuse distance among FAPs operating on the same spectrum, thereby reducing the interference and increasing the network performance in terms of SINR and SE. MSs moving away from the FAP to which they are connected, will be less close to the FAP operating on the same spectrum, so compared to the NCS they are better able to handle the inherent losses which occur during coverage range expansion.

Similar CDF performance trends for both SINR and SE are observed at lower (50) and higher (200) FAP deployments, though these are not included in this paper because of page restrictions. Instead, the comparative system performance is presented in terms of two alternative measures, namely the average received SINR and corresponding SE. These are presented in Figures 4 and 5 respectively.

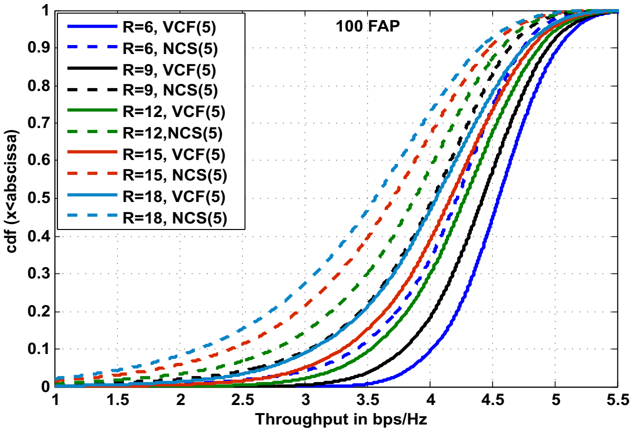

Fig. 3. CDF of SE performance with various range expansion values (R) for 100 FAP when $VCC = 5$ and for an equivalent channel sets for NCS.

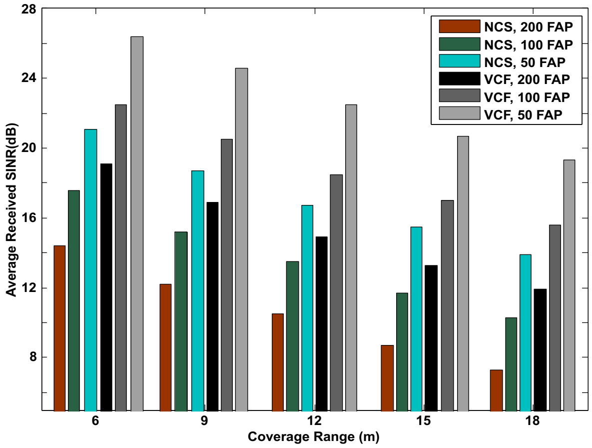

Fig. 4. Average SINR Performance Comparison for EVCF and NCS at various coverage range

Predictably the performance of both EVCF and NCS progressively deteriorates at higher FAP deployments within a given area as reflected in Figures 4 and 5 for 50, 100 and 200 FAP deployments. For example, when NCS is considered for the coverage range of 9m, the average received SINR drops from 19dB to 12dB when the FAP deployment density in the given area increases from 50 to 200. For the EVCF model, the corresponding received SINR falls from 24.5dB to 17.5dB. This means that despite the degraded performance of both systems, EVCF at 200 FAP achieves analogous performance to that of NCS at a 50 FAP deployment. This highlights that the VECF model is much better suited to higher FAP density scenarios.

Turning now to the throughput performance when 200 FAP are deployed. For NCS, the achieved average SE falls from 3.9bps/Hz to 3.2bps/Hz when the coverage is extended across the full analysed range from 6m to 18m. In contrast for EVCF, the achieved average SE is between 4.3bps/Hz and 3.7bps/Hz at 200 FAP density, so across the entire coverage range EVCF consistently outperforms NCS by a margin of at least 0.5bps/Hz. Similar performance trends are observed at the other FAP densities.

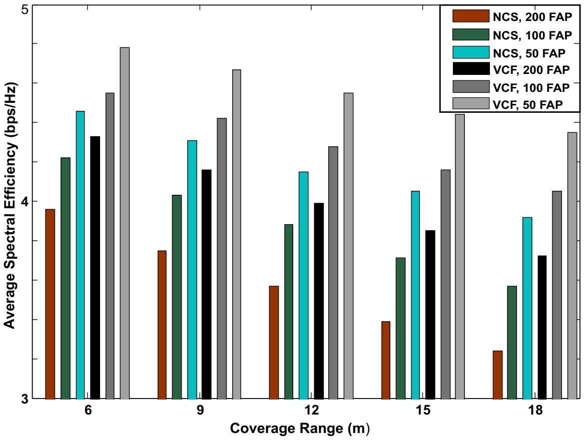

Fig. 5. Average SE Performance Comparison for EVCF and NCS at various coverage range

Interestingly, Figures 4 and 5 can be used to ensure the required *quality-of-service* (QoS) provision mandated by different applications is upheld, along with the maximum permissible coverage range expansion at a defined FAP density. For example, if an application has a QoS requirement of 12dB average received SINR at a FAP density of 50 FAP, then the maximum allowed coverage range is 18m for both NCS and EVCF. If however, the same QoS level is defined at a 200 FAP density, then the allowable coverage range is 9m and 18m for NCS and EVCF respectively, that is double the FAP coverage range. Hence, although at lower FAP densities both NCS and EVCF are able to maintain the QoS requirement, at higher FAP densities VCF is much more flexible in terms of allowing users to remain connected over a wider coverage area.

A look up table (LUT) implementation can be formed using the above results for various QoS settings in terms of the average received SINR at different FAP deployments. Similar LUT can be formed from the CDF plots (including Figures 2 and 3) for different FAP deployment densities and various percentile values, such as the 90th percentile which is another widely adopted QoS measure.

In summary, the EVCF model incorporating a FAP coverage range expansion capability offers both greater flexibility and handover reduction. It also provides superior intra-tier interference management while maintaining the desired QoS performance compared to the non-clustered solution.

IV. CONCLUSION

This paper has analysed the influence of *femtocell access point* (FAP) coverage range expansion on the system performance of closed-access femtocell networks at various densities scenarios and network resource management settings. As FAP are deployed in an uncoordinated fashion, a randomly allocated system is unable to sustain the QoS, particularly at higher FAP densities, with both SINR and spectral efficiency (SE) deteriorating rapidly with increased coverage range. In contrast, judicious post-deployment resource planning using the *enhanced virtual cluster formation* (EVCF) paradigm significantly improves both the SINR and SE. While performance falls at higher FAP densities, EVCF mitigates the impact with results corroborating the clustering model is more flexible and robust in managing different FAP scenarios. The work in this paper has been evaluated under the assumption of fixed channel availability in the femto-tier. Combining the coverage range expansion and FAP deployment density with varying channel availability will introduce further flexibility into the EVCF model as well as enabling femtocell networks to select the most appropriate selections for the crucial FAP nexus between resources, density and range, which is the focus of future research.

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