Analysis of Two-Tier LTE Network with Randomized Resource Allocation and Proactive Offloading

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Abstract Heterogeneity in cellular networks comprising multiple base stations’ types imposes new challenges in network planning and deployment. Radio Resource Management (RRM) techniques such as dynamic sharing of the available resources and advanced user association strategies determine the overall network capacity and efficiency. This paper targets a two-tier heterogeneous LTE network consisting of macro and femto tiers. It introduces randomization of the allocated resources on the femto tier, novel proactive offloading scheme in the user association phase and a novel femto tier access control. System level simulation results in terms of rate distribution, i.e. the percentage of users that achieve certain rate in the system, show that an optimal RRM strategy can be designed for different network scenarios. The proposed proactive offloading scheme in the association phase improves the performance of the congested networks by efficiently utilizing the available femto tier resources. Moreover, the introduced femto hybrid access allows up to 20 times higher data rates for the authorized users, compared to the non-authorized users in the network.

Keywords Heterogeneous networks · Femtocells · Randomized RRM · Proactive offloading · Access control

1 Introduction

The continuous growth in users’ demands for better mobile broadband experience leads the development of new network technologies and concepts towards the next generation cellular networks and 5G [1]. One of the key novel paradigms within is the network densification [2] that addresses the increased need for capacity. The densification can be achieved either in space, by increasing the number of network nodes in the system, or in frequency, by utilizing different portions of spectrum in different bands.

The space densification is a prerequisite for reducing the load factor at different network nodes and enhancing overall network performance through the received signal power per user. It can either be achieved by adding new Macro Base Stations (MBSs) or by adding additional pico/femto tier of base stations that differ from the macro tier in terms of transmission power, capacity and base station spatial density. The former approach is an expensive solution not able to solve the problem of indoor coverage whereas the latter one results in network heterogeneity. Femtocells have emerged as a promising solution since the user-centric deployment of Femto Base Stations (FBSs) is less expensive and uncoordinated, making them preferable for coverage improvement (both indoor/outdoor) and data rate improvement [3].

Network heterogeneity adding multiple tiers of small base stations, pico or femto, requires new advanced Radio Resource Management (RRM) and coordination techniques [4]. Unlike the macro tier that is a subject of frequency planning prior to actual deployment, the femto tier is usually deployed sporadically and randomly without any spatial or frequency planning. Additionally, FBSs’ deployment is usually uncoordinated with the macro tier, further complicating the design of intelligent strategies for resource allocation and sharing [5].
Important aspects of RRM in heterogeneous networks are the interference management and the user-to-BS association strategy. The interference can be classified as either cross-tier interference, caused by elements from different tiers (e.g. from a FBS to a MBS) or co-tier interference, between the elements of the same tier (e.g. between neighboring FBSs). Traditional user-to-BS association strategies, such as Nearest BS and Maximum Received Power, are mostly BS coverage based and favor the MBSs for user association. This leads to severe increase of the FBSs’ interference, as the high power transmission from the MBSs greatly limits the FBSs’ coverage areas, leading to a high underutilization of FBSs physical resources. To overcome this problem, 3GPP introduces the Cell Range Expansion (CRE) association strategy with biased handoff boundaries in favor of small cells. However, this approach creates significant downlink interference for users in the CRE region that are served by small cells. The use of advance interference cancelation strategies is advised for co-channel deployments, such as ICIC (Inter Cell Interference Coordination), to control cross-tier interference level and enhance the received signal power in expanding HetNets deployments [6].

This paper introduces a Heterogeneous Network (HetNet) model with randomized RRM on the femto tier and a proactive macro-to-femto offloading scheme for better rate distribution in congested networks. Additionally, the paper proposes a novel hybrid access control approach, embedded at the femto tier, to maximize the date rates for the FBS’ authorized users.

The paper is organized as follows. Section 2 overviews the current related work. Section 3 elaborates the proposed system model in details. Section 4 provides simulation results for different scenarios. Finally, section 5 concludes the paper providing some directions for future work.

2 Related work

Current researches in the field use stochastic geometry tools for modeling and analysis of multi-tier cellular networks [7]. Analysis of a generalized K-tier downlink heterogeneous cellular network is presented in [8], focusing on coverage probability and average user data rate with derived closed-form expressions under different network setups. An important part of the overall network performance is the User-to-BS association. Ref. [9] analyzes rate distribution under generalized cell selection, assuming that shadowing impacts cell selection, while fading does not. Ref. [10] shows that the maximum Signal-to-Interference-and-Noise Ratio (SINR) association is suboptimal in HetNets, because it leaves unutilized resources in the BSs with smaller coverage. Ref. [11] presents load-aware downlink modeling, which outperforms standard user association strategies. Load distribution and balancing challenges in heterogeneous cellular networks are presented in [12], while the traffic offloading solutions between different tiers are analyzed in details in [13]. An overview of the access control mechanisms, with technical implementation issues and business models for CDMA and OFDMA femtocells, is given in [14]. Ref. [15] presents a throughput optimization of the spectrum allocation in two-tier hybrid cellular network.

Unlike previous work, this paper introduces a new hybrid access control at the femto tier where all spectrum resources are shared among users divided into two groups: authorized users (subscribers) and non-authorized users (non-subscribers). The available resources are primarily used by the associated subscribers that experience guaranteed preferential access. If no subscribers are associated, then the resources are divided among the associated non-subscribers. This approach maximizes the throughput of femtocell subscribers. The proposed novel two-step macro-to-femto offloading scheme is used proactively in the user association phase as a viable tool for improvement of the data rate distribution in congested network.

3 System model

The network model under consideration in this paper represents a HetNet with two tiers of BSs, macro and femto. The tiers mainly differ in the transmit power, as the MBSs have higher downlink transmit power than the FBSs. Therefore, FBSs coverage regions are much smaller when they are nearby a higher power MBSs. The paper analyzes the impact of the available bandwidth on the network performances of both tiers.

The MBSs are distributed using regular distribution, in a grid, so that each MBS is at the center of hexagonal cell and the distance between two adjacent BSs is denoted as $d$. We are using the regular grid deployment on the macro tier as the most frequently used in system-level simulations. It is easy to simulate and closely approximate the usually centrally planned cellular deployment where the BSs are distributed according to a previous network planning process, which is a common practice in real cellular network deployments. Another approach employs a macro tier distribution according to a random spatial process, mainly using Poisson Point Process [7, 8]. Both of these models have their advantages and disadvantages in many regards, which we address in details in section 3.5.

The FBSs are randomly distributed over the same area, uncoordinated with the MBSs. Poisson Point Process (PPP) models the randomized and uncoordinated deployment of FBSs, as one of the most frequently used statistical distribution for modeling stochastic two-dimensional point processes with spatial density $\lambda_f$. The use of PPP is most appropriate in
modeling irregular placements of BSs, where all locations are i.i.d with an exponential PDF for the number of BSs per area (an average number of $N_f = \lambda_f A$ FBSs, where $A$ denotes the observed area).

The mobile users are also randomly distributed according to an independent PPP with intensity $\lambda_u$ and average number $N_u = \lambda_u A$ (Fig. 1).

### 3.1 Access control on femto tier

Access control mechanisms play an important role in mitigation of cross-tier interference and number of handover attempts. The proper selection of the FBS access control mechanism has significant effects on the overall network performance, mainly due to its role on the definition of the interference. There are three different approaches already proposed for access control mechanisms [15]:

- **Open access:** all customers of the operator’s network have the right to make use of any of the available femtocells.
- **Closed access:** only a subset of the users, which is defined by the femtocell owner, can connect to the femtocell. This is also referred to as a CSG (Closed Subscriber Group).
- **Hybrid access:** compromise between authorized and non-authorized users as a limited amount of the femtocell resources are available to all users, while the rest are operated in a CSG manner.

The users are divided into two categories so that the femtocell is able to distinguish the authorized users that have privileged access, in a closed or a hybrid access control scenario:

- **Subscriber,** referring to a user that is registered in the femtocell’s CSG, also known as authorized user.
- **Non-subscriber,** referring to a user that is not registered in the femtocell’s CSG.

Note that we are not dividing mobile users based on different tiers, macro or femto users, but only according to their preferential access on the hybrid femtocell. Each user can initially send an association request to its ‘best’ BS, either MBS or FBS, regardless of the embedded access control on the femto tier.

The proposed femtocells access control is based on the previously stated hybrid access control, with adequate modifications to utilize the whole available bandwidth at the FBS. In case there is at least one subscriber association request at the FBS, the available resources are fairly allocated among the associated subscribers. If there are no subscribers’ requests, the FBS allocates all resources among associated non-subscribers. This approach maximizes the average rate per subscriber. However, it might result in higher number of rescheduled users on the femto tier, as the hybrid FBS reschedules non-subscribers on the next time slots if there is an associated subscriber. We expand this case with employing a proactive offloading mechanism to reduce the number of rescheduled users on the femto tier, detailed in section 3.4.

### 3.2 RRM and user resource allocation

The implemented radio access technology is OFDMA (Orthogonal Frequency-Division Multiple Access). The smallest resource unit that can be allocated to a single user is referred to as a Physical Resource Block (PRB) with 180 kHz of frequency bandwidth and 2 slots in time. No intra-cell interference is considered, i.e. orthogonal multiple access is employed within a cell. Also, OFDMA FBSs allow orthogonal resources to be allocated to nearby FBSs and MBSs for a fine-tuned interference management. In theory, a network-wide optimization could be done where FBSs get just as much resources as they need, with the MBSs avoiding using those time and frequency slots.

We are using Hard Frequency Reuse (HFR) with Frequency Reuse Factor $K=1$, as is usually used in FDD LTE networks [3, 10, 16]. Thereby, the whole available bandwidth is reused by each MBS, with the number of PRBs per MBS denoted as $N_{PRB,m} = N_{PRB}$.

The femto tier employs uncoordinated approach for resource allocation in order to mitigate co-tier interference and alleviate cross-tier interference, as it requires minor coordination with the macro tier to determine the overall network traffic state. The available system bandwidth is divided in $n_f$ spectrum fragments, each consisting of $N_{PRB,f} = N_{PRB}/n_f$ PRBs. Each FBS choices randomly one fragment from the available pool.

User resource allocation strategy requires each BS (on both tiers) to distribute the available physical resources fairly, using equal power allocation to each PRB, so that each user gets the maximal possible data rate with respect to the network settings and traffic load.
3.3 User association for downlink

The user-to-BS association strategy determines which BS the user associates for downlink transmission. The common approach is that each user associates to the BS, macro or femto, that maximizes a predefined association rule.

Let \( V = M \cup F \) denote the set of all BSs in the network, where \( M \) denotes the subset of all MBSs and \( F \) denotes the subset of all FBSs. Each user associates with the BS \( k \), in accordance with the following association rule:

\[
 k = \text{argmax}_{i \in V} \{ T_i Z_i^{-\alpha} \} 
\]

where \( Z_i \) is the distance between the \( i^{th} \) BS and the user, \( \alpha \) is the path loss exponent and \( T_i \) is the association weight that defines the association strategy. This paper analyzes several association strategies, depending on the value of \( T_i \):

- **Nearest BS association** (MBS or FBS): \( T_i = 1 \), \( \forall i \in V \)
- **Femtocell range modification**: \( T_i = P_i B_i \), where \( P_i \) denotes the transmit power and \( B_i \) denotes the bias factor. The femtocell range is extended if the bias factor \( B_i > 1 \), \( \forall i \in F \) and \( B_j = 1 \), \( \forall j \in M \)
- **Maximum received power association**: if the bias factor \( B_i = 1 \), \( \forall i \in V \) then \( T_i = P_i \), \( \forall i \in V \)

The use of the association rule (1) leads to an opportunistic scheduling in the frequency domain. If the number of users that want to associate to a given BS, either macro or femto, is higher than the number of available PRBs on the targeted BS, the system associates the maximum number of users on the BS, the ones with the highest values according to the association rule (1). The remaining users are dropped and rescheduled for later transmission in subsequent time slots.

In most cases, the general user association rule (1) results in high number of users being associated to the MBSs. This is critical in congested networks, where there are high number of denied users by the macro tier and high portions of the physical resources of the femto tier unused. Forcing more traffic routing to the femto tier might also result in congested FBSs, depending on the available femto resources. There is a need for a trade-off between the number of associated/denied users, implementing load balancing between the different tiers of the networks.

3.4 Two-step macro-to-femto offloading scheme

We propose a simple two-step macro-to-femto offloading scheme as a compromising solution of the aforesaid issues regarding the user traffic balancing. The basic idea is to allow each user to initially to send association request to their ‘best’ BS (MBS or FBS) in accordance with the association rule (1). The offloading scheme allows the overloaded MBSs to associate as much users as it can (the best ones) and offload the remaining users to the femto tier. The offloaded user will perform association with their respective ‘best’ FBS (according to the association rule (1)). The offloading scheme uses the following algorithm:

**Algorithm**: Two-step, macro-to-femto offloading scheme

1: Number of users that send association requests to BS \( i \) using (1) \( \rightarrow N_{u,i} \)
2: Step 1: Macro layer user association
3: If \( N_{u,i} \leq N_{PRB,m} \) \( \rightarrow \) associate all users with MBS \( i \)
4: If \( N_{u,i} > N_{PRB,m} \)
5: Step 2: Femto layer offloading
6: \( \rightarrow \) Associate the best \( N_{PRB,m} \) users to the MBS \( i \)
7: \( \rightarrow \) Forward the rest \( N = N_{u,i} - N_{PRB,m} \) users to their closest FBSs and use (1) for association

Existing solutions for load balancing reactively offload the user traffic between the tiers. They are often time consuming and inefficient. Note that in the above algorithm, the offloading is performed in the association phase and can be can be regarded as proactive scheme. Additionally, the algorithm avoids time and resource consuming re-associations of the dropped users by forwarding them to the femto tier. Due to its simplicity and lack of control information overhead, the proposed algorithm is well suited for scenarios with high number of user association requests at a time, such as public gatherings.

3.5 SINR distribution and coverage analysis

One of the most important metrics in a cellular network is the SINR distribution. Standard SINR calculation formulae, assuming complete spectrum sharing and reuse, are not applicable in the above-described system. The SINR calculation in OFDMA based systems requires incorporation of the number of overlapping PRBs with other MBSs or FBSs in the area. We conduct the analysis on the SINR distribution on a typical mobile user located at the origin. The channel fading between a typical user at location \( x_j \) and a BS is assumed to be Rayleigh fading, so that the channel gain coefficient to be i.i.d exponential. The standard path loss function is given as \( PL(x) = \|x\|^{-\alpha} \), where \( x \) denotes the BS-user distance and \( \alpha > 2 \) is the path loss exponent.

This paper introduces SINR calculation formula that uses novel approach to calculate the interference from surrounding
BSs with overlapping PRBs. In such baseline two-tier network model with no interference management, the SINR threshold for that tier \( \gamma \) base station in any tier can provide a SINR higher than the \( \gamma \) Therefore, the outage probability is simply the event that no \( P_c \) probability in such case will only depends on the SINR target relative power levels and the fading distribution. The coverage \( \eta \frac{W_{PRB}}{PRB} \) number of tiers, the number and density of different BS tiers, their \( \omega \) coverage/outage probability \( \eta \), independent of the number of tiers, the number and density of different BS tiers, their \( \omega \) coverage probability in such case will only depends on the SINR target value, the path loss exponents and the embedded access control.

Equation (2) represents the received SINR at the \( i \)th user that is associated to the \( j \)th BS \( j \) is either in \( M \) or \( F \). Parameter \( \rho_j \) is a random variable that represents the number of PRBs allocated to the user. The total transmit power from the \( j \)th base station to the \( i \)th user is \( P_j/N_{PRB,j} \), where \( P_j/N_{PRB,j} \) is the transmit power on one RB from the \( j \)th base station. Parameters \( h_{ij} \) and \( x_{ij} \) are the channel fading and the distance between the \( i \)th user and the \( j \)th BS, respectively. The first sum in the denominator denotes the interference from MBSs in the system, while the second sum denotes the interference from FBSs in the system. The random variables \( \beta_{im} \) and \( \beta_{ij} \) represent the number of overlapping PRBs between the \( i \)th user and the interfering BSs, both macro and femto, respectively. The parameter \( N_0 \) is the noise power.

Once the SINR distribution is known, the coverage and outage probabilities can be defined and easily computed. To ease the analysis we impose certain assumptions, that are likely to be met in realistic HetNets scenarios, such as that each mobile user connects to the base station with the strongest signal, which is not necessarily the closest one (e.g. max received power association (1)). Also we assume that the SINR targets are equal for each tier, \( \gamma = \gamma \) under Rayleigh fading (exponential distribution of the channel gain coefficients). Therefore, the outage probability is simply the event that no base station in any tier can provide a SINR higher than the threshold for that tier \( \gamma \) [7]. The coverage probability \( P_c \) is the probability that the maximum SINR over all BSs is greater than some threshold value \( \gamma \), with a typical SINR target of 0 dB (cell-edge users) for LTE HetNets.

The SINR distribution, coverage probability and the outage probability \( 1 - P_c \) analysis of our model is numerically evaluated using system-level simulation (with Monte Carlo) in MATLAB, with respect on the network parameters (density of the FBSs and density of the users PPP).

Stochastic geometry tools allow simply closed-forms for the coverage/outage probability [8], independent of the number of tiers, the number and density of different BS tiers, their relative power levels and the fading distribution. The coverage probability in such case will only depends on the SINR target value, the path loss exponents and the embedded access control.

If a closed access control mechanism is employed on the femto tier, the FBSs can represent coverage holes in the network, assuming that the strongest BS to which a random non-subscriber is a closed access FBS. The proposed hybrid access control allows each user to initially send an association request to its ‘best’ BS regardless on the tier to which it belongs (FBSs are not representing coverage holes). The FBSs’ interference will not deteriorate the SINR distribution and will maximize the coverage probability.

### 4 Performance analysis

The envisioned scenario is deployed over a targeted area with a size of \( 25 \times 25 \) km, with a total number of 33 MBSs regularly distributed over the area with BS-to-BS distance of 5 km. The FBSs and the users are randomly distributed according to their respective PPPs. The system uses an overall bandwidth of 15 MHz, corresponding to 75 PRBs. Different scenarios are simulated, dividing the whole bandwidth at the femto tier into different number of fragments 1, 3, 5, 15 or 25, each containing 75, 25, 15, 5 or 3 continuous PRBs, respectively. Each FBS randomly chooses one fragment from the overall pool. To evaluate the network performance we are using system-level simulation in MATLAB.

We are using Eq. (2) for the calculation of the SINR distribution, previously described in details in Sec. 3.5. The rate for the \( j \)th user in the system, knowing the received SINR from the \( j \)th BS, which the user is associated to, is calculated as:

\[
R_{ij} = \alpha_{ij}W_{PRB}\log_2(1 + \text{SINR}_{ij})
\]

where \( \alpha_{ij} \) is random variable that represents the number of PRBs allocated to the user and \( W_{PRB} = 180kHz \) denotes the bandwidth per PRB.
The rate distribution \( \Psi \), defined as the probability that certain percentage of users achieve rate higher than a predefined threshold, is calculated as:

\[
\Psi = \Pr \{ R > \delta | R > 0 \}
\]  

(4)

The system model allows for service denial and user rescheduling in subsequent time slots. The goal is to maximize the average rate in the system that can be guaranteed to any associated user.

The rate distribution for different number of FBSs and FBSs’ resources is shown at Fig. 2, using the Nearest BS association strategy. The average number of users over the area is 10,000. Figure 2a shows the rate distribution when the average number of FBSs is 500, which corresponds to a congested network as the number of available PRBs and the number of downlink user association requests in a single slot is of the same order of magnitude. It is evident that the spectrum division on smaller fragments in this case results in better rate distribution and better inter/intra tier interference mitigation. However, smaller spectrum fragments also result in more service denied users. This requires rescheduling of the dropped users in subsequent time slots. Figure 2b shows the rate distribution when the average number of FBSs is 1000. There is a trade-off between attaining high data rates per user and the percentage of users that are guaranteed to achieve those rates. If the operator targets high data rate for small percentage of users, then the femto tier should use larger spectrum fragments. If the operator wants to guarantee a predefined, lower data rate to higher number of users, the femto tier should use smaller spectrum fragments. Therefore, the femto tier can dynamically adjust the spectrum fragment size depending on the network state for optimized spectrum allocation and sharing. This requires femto/macro tier coordination about the network traffic state using standard network interfaces (e.g. X2 [10]).

Figure 3 shows a comparison of the performance for different user association strategies in terms of the rate distribution in a congested network. The femto tier uses the smallest spectrum fragment possible, i.e. 3 PRBs per FBS. The two-step macro-to-femto offloading scheme significantly outperforms all other user-to-BS association strategies around 1 Mbps for this scenario. This suggests that the two-step offloading scheme provides better utilization of the available spectrum resources (i.e. higher spectrum efficiency) at the
femto tier for high amount of scheduled downlink traffic in a single time slot in a congested network. However, the improvement of the two-step offloading diminishes for higher data rates since the LTE air interface is a channelized system with limited physical resources.

Figure 4 shows the gains in the average data rate for the associated subscribers and non-subscribers for the proposed hybrid access control approach, depending on the association strategy and the spectrum allocation. We compared results for different association strategies according to association rule (1) and the proposed macro-to-femto offloading scheme. Additionally we include the max-SINR association strategy (that maximizes the received user SINR, according to Eq. (2)) using it with the proposed offloading scheme. When a smaller amount of bandwidth is available for the femto tier (5 and 3 PRBs per FBS), max SINR association shows highest gains due to the lower number of associated users and thus lower cross-tier interference (i.e. less overlapping PRBs between the FBSs and the MBSs) compared to all others. When a larger bandwidth is available for the femto tier (75, 25 and 15 PRBs per FBS), the femto CRE approach shows highest gains as most users usually associate on an FBS that is not their ‘best’ BS in terms of achieved data rate. Associated subscribers in such case outperform such users by a large margin. Usage of max-SINR in this case leads to a major load imbalance and lower gains in the subscribers’ data rates since larger bandwidth is shared between both tiers. Overall, the femto hybrid access allows subscribers’ data rates gains in all cases.

5 Conclusion

This paper analyzes spectrum resource allocation, sharing and utilization efficiency in two-tier heterogeneous networks, with macro and additional uncoordinated femto tier. The femto tier uses simple spectrum fragmentation and random fragment allocation to determine the operating resources. The results show that the rate distribution of the system depends on the fragment size for varying network conditions and suggests that the femto tier can dynamically adjust it. The paper also proposes novel, two-step, macro-to-femto offloading scheme for user-to-BS association for efficient utilization of the femto tier resources. The scheme provides better rate distribution compared to existing user association strategies.
From operators’ perspective, the results can be used to implement an intelligent RRM, where the fragment size at the femto tier can be dynamically adjusted according to the congestion in the network. It requires loose coordination with the macro tier, with optimized load balancing factor depending on the appropriate fragment size to fully utilize all available femto tier resources. Furthermore, the access control on the femto tier improves overall network performances and targeting of specific user groups with different requirements. The embedded femto hybrid access control mechanism allows higher data rates to be guaranteed for the authorized femtocell users. Operators can guarantee minimal average rates and preferential access for subscribers, offering an opportunity for implementation of newer and richer services and used it to motivate the usage of femtocells, especially in indoor environments such as homes, offices etc.

Future work may comprise frequency-domain interference coordination, extension towards the analysis of millimeter wave RAN etc.

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