A MOBILITY-AWARE RESOURCE ALLOCATION SCHEME IN FEMTOCELL NETWORKS

N. O. Oyie, P. K. Langat and S. Musyoki
Jomo Kenyatta University of Agriculture and Technology, Nairobi, Kenya
E-mail: oyie3nick@yahoo.com

Abstract
Macrocells' coverage deteriorates in indoor environments where most data traffic originate. Use of femtocells has enhanced indoor coverage and network capacity. However, user mobility dynamics in resource allocation becomes a barrier to a successful deployment of this type of network. This paper considered resource allocation in femtocell network with special attention to impact of user mobility on quality of service. Specifically, user mobility dynamics incorporated in existing scheme in terms of connections considering the variation in time of their positions. Mobility-aware Femtocell Cluster-based Resource Allocation (M-FCRA) algorithm is presented. The approach consists of formulation of the resource allocation scheme as a Min-Max optimization problem and an appropriate hybrid centralized/distributed algorithm. M-FCRA outperforms Femtocell Cluster-based Resource Allocation (FCRA) algorithm in terms of throughput satisfaction rate by 5% ± 0.15% at Signal to Interference plus Noise Ratio (SINR) of -25dBm in when mobility of users is considered at a speed of 0.5 to 1km/h. In conclusion, a high congregate of femtocells in urban areas is expected, user mobility becomes an important factor in resource allocation to ensure quality of service is achieved. M-FCRA has improved on throughput rate while considering user mobility in resource allocation in femtocell networks.

Key words: Femtocell, user mobility, resource allocation, clustering, quality of service

1.0 Introduction

The introduction of third generation (3G) technology has been the driver behind customers' demand for more and more data while extracting high quality services. One solution to enhance indoor coverage are so-called femtocell access points (FAPs) or home base stations as in [1]. These are low-power base stations designed for indoor usage that allow cellular network providers to extend indoor coverage where it is limited or unavailable. On the air interface, FAPs provide radio coverage of a given cellular standard such as GSM, UMTS, WiMAX, and LTE, while the back-haul connection makes use of a broadband connection such as optical fiber or digital subscriber line (DSL). The use of femtocells benefits both users and operators by delivery high quality of service (QoS). Users enjoy better signal quality due to the proximity between transmitter and receiver, hence communications with larger reliabilities and throughputs. Moreover, this also provides power savings, reducing electromagnetic interference and energy consumption. This way, more users will access the same pool of radio resources or use larger modulation and coding schemes, while operators will benefit from greater network capacity and spectral efficiency. In addition, since indoor traffic will be transmitted over the Internet Protocol (IP) backhaul, femtocells will help the operator to manage the exponential growth of traffic and increase the reliability of macrocell networks. Moreover, given that they are paid for and maintained by the owners, femtocells will also reduce the overall network cost[2]. However, due to high density of FAPs, many new challenges have not been sufficiently addressed such as resources allocation and interference mitigation. Finding the optimal resource allocation between FAPs in such highly dynamic and dense environment is, in general, a non-linear non-convex NP-hard optimization problem [3]. Hence, an optimal solution can-not be generated in large-sized networks and even in small-sized network with large set of constraints. Consequently, several heuristics have been proposed in the literature, which can be classified as either centralized or distributed [4].

In this paper, we present a new scalable resource allocation algorithm called Mobility-aware Femtocell Cluster – based Resource Allocation (M-FCRA) for OFDMA based femtocells. The use of OFDMA technology is motivated by the fact that next generation networks such as fourth generation (4G) apply it. The goal of this paper is to associate the best spectrum set of frequency/time resources with each FAP in order to deliver the users data, while considering mobility of users, minimizing the gap between the required and allocated tiles and at the same time minimizing interference between FAPs. To achieve this, a resource allocation is formulated mathematically as a Min-Max optimization problem. It is a hybrid of centralized/distributed algorithm called M-FCRA involving three main phases:

(i) Cluster formation.
(ii) Cluster-head resource allocation with user mobility awareness, and
(iii) Resource contention resolution.

First, M-FCRA makes use of a distributed algorithm to build disjoint femtocell clusters. Then within each cluster, a Cluster-Head (CH) is elected, which assigns resources to all FAPs in its cluster taking into account their required bandwidth and mobility dynamics such as position with time. Accordingly, each CH resolves the Min-Max optimization problem and converges to the optimal solution in a timely manner, as shown in this paper. However, users at the edge of two neighboring clusters might still interfere with each other when operating on the same resources. To handle such interference case, a simple algorithm for resource contention resolution is also presented and allows to enhance the overall satisfaction rate of FAPs.

To evaluate the efficiency of M-FCRA, comparison is done with an existing prominent solution FCRA from the literature [4]. Evaluation and comparison metric is thethroughput satisfaction rate (TSR).The simulation results obtained show that M-FCRA algorithm that incorporates user mobility dynamics converges to the optimal solution and outperforms the FCRA algorithm which does not consider user mobility in both small-sized and large-sized networks when time and position of users are considered.

1.1 Related Work

Several dynamic clustering strategies have been proposed in [5] [6] [7] [8]. The strategies differ in the criteria used to organize the clusters and in the implementation of the distributed clustering algorithms. However, none of them uses prediction of node mobility as a criterion for cluster organization.

The (α, t)-Cluster framework, in [9] defines a strategy for dynamically organizing the topology of an ad-hoc network in order to adaptively balance the trade-off between pro-active and demand-based routing by clustering nodes according to node mobility is presented. However, this framework does not focus on the topology of a Wireless Mesh Network (WMN).

A clustering algorithm for “quasistatic” ad hoc networks, where nodes are static or moving at a very low speed was proposed in [10]. The proposed scheme is more adapted to the Wireless Mesh Networks (WMN) environment. However, it is concerned with one-hop clustering, which defeats the purpose of clustering in WMNs.

In [11], a new heuristic for electing multiple leaders in ad hoc networks called Max-Min Leader Election in Ad Hoc Networks is presented. However, the clusters have the same radius, an additional constraint, which may lead to unsatisfactory results regarding the Radio Resource Utilization (RRU) cost minimization.

In [12], the authors demonstrate how certain geometric properties of the wireless networks can be exploited to perform clustering with some desired properties. Generic graph algorithms developed for arbitrary graphs would not exploit the rich geometric information present in specific cases such as the wireless network environment.

The authors in [13] used connected dominating set (CDS), clustering approach in mobile ad hoc networks, based on graph theory. In this approach, the objective is to identify the smallest set of Cluster Heads (CHs) that forms a CDS. The set of CHs operates therefore as routers and forms a virtual backbone for the ad hoc network. However, the proposed scheme is concerned with one-hop clustering, which defeat the purpose of WMNs.

In [14], clustering algorithms in the context of Wireless Sensor Networks (WSNs) are presented. The common criterion for the selection of CHs with these algorithms is based on the energy consumption constraint. Instead, efficiently using the wireless resources is the main concern in WMNs and is crucial to achieve acceptable performance.

In [15], a clustering algorithm to integrate the WMNs with the wired backbone is presented. The authors investigated the well-known problem of gateway placement in WMNs. In this study, the focus is on each macro-cluster instead of virtual clustering. The distributed resource allocation algorithm namely Distributed Random

Access (DRA), which is more appropriate for medium-wide networks, is described in [16]. The resources, represented as time-frequency slots (tiles) are orthogonalized between macrocells and femtocells based on the gradient ascent/descent heuristic. However, due to its pseudo-random nature, QoS cannot be guaranteed by such an approach and the throughput satisfaction rate of femtocells has not been considered in the analysis.

A fully distributed and scalable algorithm for interference management in LTE-Advanced environments has been presented in [3]. The proposal called Autonomous Component Carrier Selection (ACCS) is executed locally in each femtocell. However, the scheme is highly correlated with the environmental sensing since it mainly relies on measurement reports. In addition, ACCS does not allocate time-frequency slots but only subcarriers, which can be expensive and penalizing in terms of bandwidth.

A decentralized F-ALOHA spectrum allocation strategy for two-tier cellular networks is described in [17]. The proposal is based on a partition of the spectrum between the macrocell and femtocells. However, F-ALOHA cannot guarantee any level of QoS since it is based on a pseudo-random algorithm. In addition, this scheme does not consider time-frequency slots as resources and instead, it focuses on sub-carriers allocation.

Three resource allocation algorithms in OFDMA femtocells are proposed in [2]. The first method is called orthogonal assignment algorithm. It divides the spectrum into two independent sets $S_M$and $S_F$used by the macrocells and femtocells, respectively. The problem is to find the best split that maximizes the satisfaction of the required QoS. However, this scheme does not take into account the femto-to-femto interference, which remains an important issue for indoor performance, especially when femtocells are densely deployed.

In [18], authors investigated the radio resource utilization efficiency in wireless mesh networks. They propose two clustering schemes to improve the resource utilization in such networks. Clustering in ad-hoc networks mostly focus on efficient handling of the frequent network topological changes due to ad-hoc nodes mobility. The main objective has therefore been to adapt quickly to topological changes, which occurs only occasionally in femtocell networks, due to their relatively static topologies as described in [4].

Resource management in OFDMA-based femtocell networks is an ongoing research area. In [4], FCRA a new scalable resource allocation strategy based on clustering is proposed. A distributed clustering algorithm to form disjoint femtocell clusters was described. The objective is to subdivide the resource allocation problem into sub-problems by means of clustering and the use of optimum centralized spectrum allocation inside each cluster to handle more efficiently the available resources. However, the authors did not incorporate the impact of user mobility to their study.

In this paper, M-FCRA algorithm based on Min-Max Optimization is preseneted to study the impact of incorporating user mobility dynamics in frequency/time allocation algorithm in femtocellular networks.

2.0 System Description

2.1 Network Model

This paper considers a macrocell embedded with a set $F$of femtocells (FAPs) that represent residential or enterprise networks, as shown in Fig. 1. Both FAPs and the macrocell are assumed to operate using the same OFDMA technology. As in [16], an OFDMA frame structure that is populated with time-frequency slots, so-called tiles is considered. In this study, the focus is on the downlink communications. As in [2] [16], assumption is made that resources are split between the macrocell and femtocells, eliminating thus interference between femto/macro users. This kind of spectrum partition aims at maximizing the throughput and fairness within the macrocell and femtocells [2] [16]. The objective of this piece of work is then to find the optimal allocation of resources dedicated for femtocells to deliver the users data, while considering users mobility dynamics, minimizing the interference between femto/femto and at the same time ensuring the required QoS.

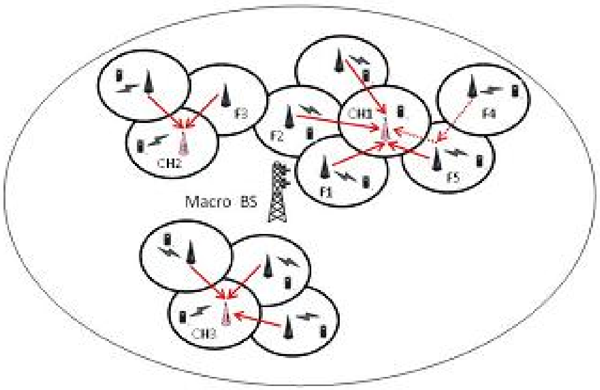

Figure 1. Network model

Problem 1 Min-Max femtocells resource allocation problem

$$\forall F_a \in F\text{:min}\left[\max_a\left(\frac{R_{a-\sum_{i,j}\Delta_a(i,j)}}{|F| \times R_a}\right)\right]$$

$subject\ to$:

(a) $\forall F_a \in F$: $\sum_{i,j} \Delta_a(i,j) \le R_a$
(b)$\forall_{i,j,}$
$\forall F_a \in F, \forall F_b \in I_a : \Delta_a(i,j)$+$\Delta_b(i,j) \le 1$
(c) $\forall_{i,j,}\forall F_a \in F$: $\Delta_a(i,j) \in \{0,1\}$

For each femtocell $F_a \in F$, the set of interfering femtocells defined, denoted byI_a. This set depends on the minimum required Signal to Interference plus Noise Ratio (SINR) values and the indoor path loss model. Similar to [3], the latter is modeled based on A1-type generalized path loss models for the frequency range 2-6 GHz developed in WINNER [19].

In addition, this paper defines for each femtocell F_a the binary resource allocation matrix denoted by Δ_a, with 1 or 0 in position(i,j)according to whether the tile $(i,j)$is used or not.To represent the users' demands, a vector $V_a$is introduced. Its elements correspond to the bandwidth required by users associated with the femtocell F_a.The total number of tiles required by the femtocell F_a to fulfill the attached users' demandswhile considering their position with time is denoted by R_a such that $R_a = S + \sum_{i=1}^{n_a} V_a(i)$, where n_a is the total number of users belonging to femtocell F_a and S is the speed of users in km/h. Obviously, R_a is not constant and depends on the arrival/departure process of end users. Hence, we assume that R_a is updated periodically every epoch δ_t.

The number of end users that can be associated with each femtocell follows a random uniformdistribution with a maxi-mum value of 4 per femto. Moreover, we assume that femto-cells adopt the Round Robin strategy to serve the associated users [3] [16].

2.2 Problem Formulation

To find the optimal resource allocation of a set of tiles in each femtocell to deliver the users data, while minimizing the interference between femto/femto and at the same time ensuring the required QoS, the paper introduces a new metric, called throughput satisfaction rate per femtocell, which is defined as the ratio of the received number of allocated tiles to the total requested ones for each femtocell. The aim is to maximize this metric. In other words, the objective function will be to minimize the maximum gap between the number of allocated and required tiles in each FAP. Given the set of interferer femtocells I_a,$\forall F_a \in F$ and for every epochδ_t, hence the problem can be formulated as illustrated in Problem 1. Condition (a) denotes that the resource scheduler must guarantee that femtocells cannot obtain more than the required spectrum, and inequality (b) ensures that two interfering femtocells cannot use the same tiles.

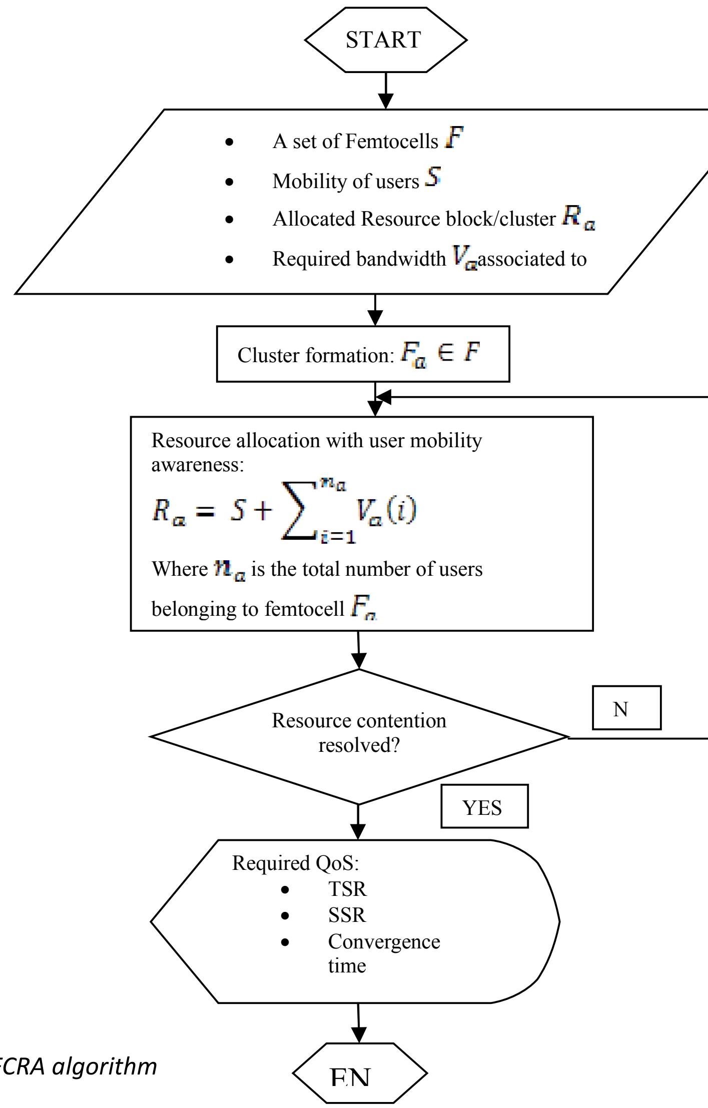

Figure 2: M-FCRA algorithm

3.0 M-FCRA Algorithm

Fig. 2 presents the flowchart of ahybrid M-FCRA algorithm for OFDMA femtocell networks. This scheme is based on three main components:

(i) Cluster formation,
(ii) Cluster-head resource allocation with user mobility awareness and
(iii) Resource contention resolution.

First, M-FCRA builds disjoint clusters within the network. Then, a cluster-head allocates resources for all femtocells within its cluster by resolving the above problem (Problem 1). Each cluster may interfere with its neighbors and the cluster-head resolution does not consider the neighbor clusters allocation. Hence, a resource contention avoidance is also considered to resolve collision in subsequent frames. The three stages detailed as follows.

3.1 Cluster Formation Stage

Each femtocell starts by creating its one-hop neighbor list containing the identity of its interfering femtocells (i.e., causing interference to its users). This can be reached by sensing the environment exploiting users' measurement reports. The list is then transmitted and shared with the corresponding one-hop neighbors. Therefore, every FAP can compute the number of interfering femtocells (i.e., interference degree) of each of its one-hop neighbors.

Based on this information, a cluster-Head (CH) needs to be elected as the one deciding on the resource allocation, which is then notified to the other Cluster-Members (CMs). To do so, each FAP will determine whether it can act as CH or CM. Indeed, a femtocell is elected as CH if it has the highest interference degree among its one-hop neighbors. In this case, all associated one-hop neighbors will act as CMs and are attached to the elected CH. Otherwise, the femtocell is considered as CM and will be attached to the elected CH among its immediate neighbors (if it exists). If more than one unique CH is chosen by the neighborhood's femtocells, the one with the highest interference degree is considered as CH in order to minimize the tiles' collision between femtocells (if an equal degree, a random tie-break is used). However, if no CH is chosen by the neighborhood's femtocells (i.e., all neighbors act as CMs and are associated to other clusters), the FAP is attached to the cluster of the neighbor with the highest interference degree. More formally, the cluster formation stage is described by the pseudocode in Algorithm 1.

3.2 Cluster-Head Resource Allocation with User Mobility Awareness Stage

Once the femtocell network partitioned in clusters, the second step is to jointly allocate resources to all femtocells within each cluster with user mobility awareness by considering position with time i.e., in km/h. The objective is to satisfy as much as possible the femtocells' requirement in terms of tiles while avoiding interference within the cluster while the user is mobile. To achieve this, each CH resolves individually the above resource allocation problem (Problem 1) every epoch δ_t. It is worth noting that, since the obtained clusters' size is not large, the CH resolution using a solver such as ILOG CPLEX [20], would still converge within a short time period T_{conv}. This allows femtocells to serve their attached users in a timely manner (as will be shown in Section VI).

However, it is noted that users at the edge of two neighboring clusters might still interfere when they operate on the same resources. This could indeed happen since each CH resolves the above mentioned problem independently from its neighboring clusters. Consequently, two interfering femtocells attached to different clusters could use the same allocated tile. To resolve such collision, a simple coordination mechanism can be realized and detailed in the next subsection.

3.3 Resource Contention Resolution Stage

Two femtocells may have been assigned the same tiles from their respective CHs and interfering with each other. Thus, interference occurs between their associated end users. In this case, each user suffering from contention will send a feedback report to its associated femtocell to notify about the collision on the selected tile. Then, each femtocell tries to resolve contention on the collided tiles by sampling a Bernoulli distribution. Accordingly, it decides whether the attached user would keep using the tile or would remove it from the allocated resources. It is worth noting that if collision occurs, M-FCRA converges to a stationary allocation within a small number of frames, as will be shown in Section VI. This makes the solution practically feasible.

4.0 Throughput Satisfaction Rate (Tsr)

The performance of M-FCRA can be evaluated building on the output of the above optimization problem resolution for each constructed cluster.The QoS metric considered is throughput satisfaction rate (TSR).

TSR denotes the average degree of satisfaction of a femtocell with respect to the requested resources. For each femtocell $F_a, TSR\ (F_a)$is defined as the ratio of the received number of allocated tiles to the total requested ones and can be expressed as follows:

$\forall F_a \in F$ $\qquad TSR\ (F_a) = \left(\sum_{i,j} \Delta_a(i,j)\right)/R_a$

The TSR metric can be given by:$TSR = \sum_{F_a \in F} TSR\ (F_a)/|F|$

5.0 Performance Evaluation

In this section, M-FCRA efficiency is evaluated. FCRA scheme [4] is used as benchmark to which the M-FCRA potential benefits are compared. This paper studied the gain of M-FCRA when the users are mobile under various interference level scenarios. The reported results are obtained using the solver"ILOG CPLEX" [20]. 30 simulations were run and mean value calculated and its confidence level fixed to 99 .70%. Note that in each simulation, we vary the number of mobile nodes attached to each femtocell and their position with time.

The analysis is achieved using a typical OFDMA frame (downlink LTE frame) consisting of M = 100 tiles (time-frequency slots), as in [6]. Users are distributed randomly within the femtocells with a maximum value of 4 per FAP. Each user uniformly generates its traffic demand (required bandwidth), which is translated into a certain number of tiles V_a ($0 \leq V_a \leq 25$). The study considered different network sizes: 20 and 100 FAPs, which are representative of small and large femtocell networks, respectively. The N femtocells are distributed randomly in a 2-D 400*m* × 400*m* area, with one FAP randomly placed in each 10*m*× 10*m* residence. Then, based on the SINR values and the path loss model [19], the interference matrix $I_a$for every femtocellF_a is derived. In our simulations, we considered different SINR thresholdsto show the impact of the interference degree on the evaluated metrics.

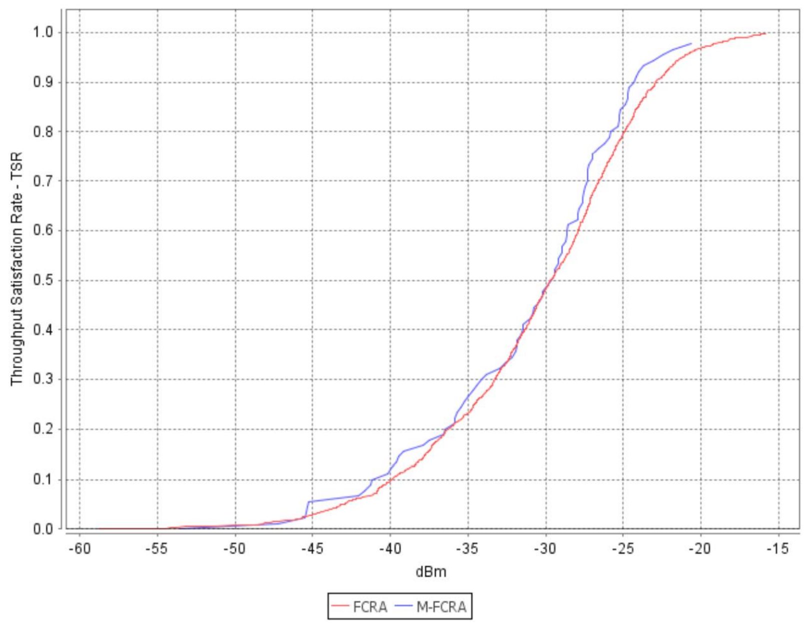

Figure 3: CDF of throughput satisfaction rate under various SINR

Figure3 shows the cumulative distributed function (CDF) of thethroughput satisfaction rate of the strategies under different values of SINR.It can be seen that M-FCRA converges to the optimalsolution as FCRA since both of them satisfy allthe users' traffic demands regardless of the interference level(SINR). The reason is that in small-sized networks, whereinterference is not high, the clusters constructed by M-FCRAapproach often contain a small number of nodes (one or twoFAPs). Hence, each FAP can use the whole spectrum satisfyingthe users demand. However in FCRA, due to the static nature of users, some users are not fully satisfied especially whenthe SINR threshold is high. Indeed,at -25 dBm of SINR, the throughput satisfaction rate – TSR of FCRA is 80% while that of M-FCRA is >80% as depicted in Figure 3.The observation that is made is that M-FCRA scheme outperforms FCRA schemefor all interference levels. The median satisfaction rate (at 50%) when SINR = -30dBm for exampleis 50% ± 1.5% for both M-FCRA and FCRA. This means that M-FCRAandFCRA often satisfy the users demand equally at about SINR value of -30dBm.However, increasing the interference leveldecreases the satisfaction rate of FCRA schemes. Indeed,as shown in Figure 3, the TSRfor all schemes is below 10% when the interference is high. However, for low values ofSINR, this metric evaluates to96% ± 3.0% for both schemes.

6.0 Conclusion

In this paper, the resource allocation problem inOFDMA-based femtocell networks was studied and a new allocation scheme called Mobility-Aware Femtocell Cluster-based Resource Allocation (M-FCRA) is presented. M-FCRA is based on a hybrid centralized/distributedapproach and involves three main phases: (i) Construction ofdisjoint clusters; (ii) Optimal cluster-head resource allocation with mobility of user awarenessby resolving a Min-Max optimization problem; and (iii) Re-source contention resolution. The obtained simulation resultsshow that M-FCRA outperforms theFCRA scheme. The results concern the throughput satisfaction rate.M-FCRA outperforms

FCRA algorithm in terms of throughput satisfaction rate by 5% ± 0.15% at Signal to Interference plus Noise Ratio (SINR) of -25dBm in when mobility of users is considered at a speed of 0.5 to 1km/h. A high congregate of femtocells in urban areas is expected, user mobility becomes an important factor in resource allocation to ensure quality of service is achieved. M-FCRA has improved on throughput rate while considering user mobility in resource allocation in femtocell networks.In the future, user equipments power variations will be incorporated to studyits impact on the analysed scheme.

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