Engineering Science and Technology, an International Journal 19 (2016) 1534–1542

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Contents lists available at ScienceDirect

Engineering Science and Technology, an International Journal

journal homepage: www.elsevier.com/locate/jestch

Full Length Article

A case study on femtocell access modes

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ARTICLE INFO

Article history:
Received 10 February 2016
Accepted 13 May 2016
Available online 27 May 2016

Keywords:
Long Term Evolution
Heterogeneous networks
Macrocell
Femtocell
Access modes

ABSTRACT

Access mode of a femtocell network plays a crucial role in determining the service quality of femtousers and the revenue of network operators. The behavior of a femtocell is not only based on network density, orthogonal or non-orthogonal multi-access technique, frequency reuse strategy, but also on the access mode being adopted. The access mode selection directly influences the performance metrics like handover mechanism, security, resource management and co-channel interference management. In this paper, we analyze the behavior of femtocell networks in three different access modes. We examine the choice of access mode from the aspect of network operator and FC owner. Under various network scenarios, we identify the best access mode analytically in terms of ergodic rate, sum throughput and interference factor. Simulation results indicate that the performance of conventional cellular network can be improvised through proper selection of FC access mode. It indicates that the selection of a particular access mode strictly depends on the performance requirements of network operator and FC owner.

1. Introduction

Every day, there is a growing demand for higher data rate services and the conventional macrocell (MC) network is unable to provide better services to data-rate-hungry users [1]. To handle tremendous traffic burden, the recent heterogeneous network has emerged with an answer in the form of low power femtocell (FC) networks which bring the base station closer to the users. Deployment of many FCs offer higher throughput to network users and bring-down the traffic bottleneck at the MC network [2]. The configuration phase of FCs includes access mode selection as a fundamental task. In general, access mode is regarded as the ability of a femto-base station (FBS) to allow or restrict the nearby network user to access the core network [3].

The FCs or the FBSs can be flexibly configured in any one of the three access modes namely open access mode, closed access mode and hybrid access mode. Among them, the primitive access mode is closed access mode that evolved based on the Closed Subscriber Group (CSG), conceptualized by Release 8 of Third Generation Partnership Program (3GPP) [4]. In the conventional CSG based Home evolved Node B (HeNB), limited number of network users are grouped in an Access Control List (ACL) and only those registered users in the list are offered with a high quality service [5]. In Long Term Evolution (LTE) technology, the CSG is referred as FC and the HeNB is denoted as FBS. The network users in the ACL database are termed as femtousers (FUs), who are allowed to access FC's backhaul resource [6]. Hence, the FCs were initially designed and deployed in closed access mode to serve only certain set of registered users, rather than accepting a cross-tier macrouser (MU).

Subsequently with 3GPP release 9 specifications on inter-tier mobility [7] and security aspects [8], the open access mode has emerged in FC networks. The network operators viewed open access FCs as an attractive solution to extend the service to the MUs present in cell-edge, coverage hole and shadow regions. Hence, they deployed more and more number of open access FCs to support cross-tier users over limited FC's resource. However, in open access mode, FUs who really pay for the backhaul bill experience service outage on the unrestricted camping of cross-tier users [9]. In order to offer preferential access to registered FU, a new functionality was introduced in 3GPP TSG SA WG1 Release 9 [10] in the name of hybrid access mode. With a preferential treatment to the FUs, the hybrid access mode shares *limited amount* of resource with *selective number* of cross-tier users [11].

To define, closed access mode allows only the registered FUs to camp-in, thereby preventing the FBS from the public access. In open access mode, cross-tier MUs are unconditionally allowed to access the FC's resource along with the registered FUs. Hybrid access mode, on the other hand, combines the benefits of closed and open access modes through priority based service to FU and best effort service to MUs. Many literatures have viewed and analyzed the behavior of FC access modes with various schemes

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Peer review under responsibility of Karabuk University.

http://dx.doi.org/10.1016/j.jestch.2016.05.007
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under different environmental conditions. The following discussion enumerates the challenges in access mode selection and the solution for the challenges. Golaup [12] discussed the access control strategy of FCs from the aspect of pre-release 8-Universal Mobile Telecommunication System (UMTS) network, pre-release 8 User Equipment (UE), Third Generation Partnership Project (3GPP) release 8 and LTE standards. In addition to periodic cell reselection method, Golaup proposed two methods namely, autonomous system information acquisition method and manual system information acquisition method for proper identification and selection of FC access mode. The inbound handovers in LTE and UMTS standards were also discussed in [12].

Xia [13] analyzed the uplink capacity of open and closed access FCs over orthogonal and non-orthogonal multiple access schemes. Based on the constraints like FC backhaul, user density and throughput requirement, the choice of access mode was examined. The analyses in [13] concentrated on open and closed access modes, whereas the choice and effects of hybrid access mode were not considered. In general, access mode selection greatly influences the level of interference in co-existing macro-femtocell networks. The closed access mode induces interference to the MU, whereas the open access mode affects the performance gain of the registered FUs. To overcome this performance conflict between access modes, Jia-Shi Lin [14] proposed the hybrid access mode based on pure Nash Equilibrium model. The function of all users was determined on the basis of channel quality, resource scheduling priority and service preference to subscribers, this model [14] offered service to cross-tier MUs. As per [6], hybrid access mode was more flexible as it used Game theoretical model that aided in selecting the appropriate network user to be its home user.

It is remarkable that an MU always chooses to become a home user of good signal quality FC, whereas an FBS always prefers to select an interference-aggravating MU, thereby protecting itself from cross-tier interference. Hence, to regulate the admission strategy in open and hybrid access modes, a Mutual Selection Admission (MSA) algorithm was modeled in [15]. Out of different levels of stability, MSA algorithm chose to serve a weak MU based on limited resource constraint. The MSA algorithm found the stable match using Nash's hard formulation, thereby yielding a rate gain to both MU and registered FU.

Flexible spectrum allocation in closed and open access FC networks was discussed in [16]. In a densely populated area, MUs and closed access FUs were assigned with disjoint set of sub-channels, whereas in less populated area, joint set of sub-channels were assigned to MUs and open access FCs [16]. The joint sub-channel assignment strategy in open access FCs provided higher throughput than the disjoint sub-channel assignment strategy in closed access FCs. Tarasak et al. [17] examined Inter-carrier Interference (ICI) between fixed number of MUs and FBSs. With fixed distance of separation between MBS and FBS, Tarasak [17] derived the closed-form expression for the probability of an MU causing ICI to the open access FCs. For a fixed number of FC deployment, their analyses showed that the probability of ICI in open access mode was lesser, whereas for the same number of closed access FCs, the probability of MU experiencing ICI was more.

Jo et al. [18] presented the mathematical model for zone-wise SINR distribution with respect to distance between FBS and MBS. For open and closed access FCs, the sum throughput of FU and MU were arrived in [18]. They proposed a shared access approach in which each FC had a time slot gap to serve between the FU and the MU. The optimal value of the time slot gap met the Quality of Service (QoS) requirement of home user, thereby maximizing the overall network throughput. The shared access approach yielded 80% better network throughput than open access mode and whenever the QoS requirement of home user was higher, the overall throughput of shared access approach degraded similar to open access mode.

Bernal [19] developed an analytical model to study the activity profile of FUs and MUs in open access FCs. In an uncommon way, Bernal assumed that the FUs as primary network users and MUs as secondary network users, where MUs were supposed to vacate the channel of interest on FUs' arrival. In addition, based on the experienced SINR, the attainable data rate of each channel was determined and from the data rate, the best channel was chosen for the operation of open access FCs [19].

The relationship between access policy and the performance contribution of access modes in overall network was explored in [20]. A specific attention was imposed on understanding the relationship between traffic burden and respective quality of service. Choi [21] presented the mutual interaction between mobile stations and nearby open access FCs. It was shown that the performance improvement was attained over closed and open access approaches with an adaptive FC access policy with respect to network load. The work presented in [22] discussed the benefits and the challenges of access methods from the business aspect. The technical impact of access mode in macro-femtocell networks was provided in [22], with an emphasis on the need for hybrid access mode.

The discussion of Lopez-Perez [23] presented a framework for the study of Worldwide Interoperability for Microwave Access (WiMAX) in comparison with macro-femtocell hybrid scenarios. An in-depth description of the necessary radio coverage prediction and system-level simulation for the above scenarios were introduced. Simulations and numerical results were presented in [23] for the downlink side communication with public (open) and private (closed) access methods. Ko [24] studied the resource sharing aspect over different FC access modes. Over an IP based network, FC's resource allocation algorithm [24] controlled the private traffic information of the FUs to travel through the secured gateway. Fair resource sharing was attained even in open access FCs, thereby guaranteeing high quality service to registered and non-registered users.

Many of the literatures dealing with FCs concentrate on proposing solutions for the challenges associated with each of the FC access modes. To understand the effects of FC access modes in the overall network performance, we examine all the three access modes under certain network and system operating conditions. We focus on studying the importance of appropriate access mode selection in an FC network. The subsequent sections are organized as follows. Section 2 elaborates on the three different access modes of FCs. We discuss the choice of access mode from the aspect of FC owner and the network operator in Section 3. Section 4 presents the mathematical formulation to analyze the consequences of not identifying proper FC access mode. Section 5 examines the performance of FC access modes and highlights the merits associated with each access modes. Section 6 briefs out the conclusion.

2. Types of femtocell access modes

In macro-femtocell heterogeneous networks, the service quality experienced by co-existing FU and MU is greatly dependent on FC access modes. The permissible number of network users and the level of service guarantee to the cross-tier users are purely based on access mode adopted by an FC [25]. The interests of registered FU and unregistered MU in selecting an access mode are conflicting, that is, the indoor FUs choose closed access mode and the outdoor MUs prefer open access mode [26]. To mitigate this conflict, hybrid access mode has evolved. The following discussion elucidates on the three access modes of FCs.

2.1. Closed access mode

Closed access mode monopolizes the FC backhaul for the benefit of FUs [27]. This mode prevents an unregistered user from accessing the FC, thereby offering privacy and security features to FU's information. It facilitates high quality coverage and higher rate multimedia services to indoor subscribers [28]. Even with growing network density, FUs in closed access mode enjoy higher service success probability. This mode regret to share its limited resource with the non-subscribers and hence, most of the FC owners choose to operate in closed access mode [29].

Tedious handover mechanisms are not required in closed access FCs, as they are not bothered of accepting unregistered users. However, this mode introduces the threat of co-tier and cross-tier co-channel interferences, which deteriorate the efficacy of the FC network [30]. Careful frequency planning and good network administration protocols are required in closed access FCs. As well, the overall macro-femtocell heterogeneous network throughput obtained in closed access FCs is less compared with that of open access FCs [31].

2.2. Open access mode

Open access mode provides service even to unregistered MUs. Through open access FCs, MUs enjoy all-time connectivity with the core network [32]. Network operators strictly prefer open access mode because this mode extends the coverage to MUs with less threat for co-channel and adjacent channel interferences. Besides, out of many nearby open access FCs, the MUs are intended to connect to an FC that offers best service quality [33].

Open access FCs improve the overall network throughput and hence find application in public areas like airports, office-based buildings, stadiums, shopping malls and universities [34]. Nevertheless, this mode encounters abrupt service degradation on sharing the limited resource among potentially large number of users. A few more challenges with the open access mode are huge handover mechanisms between under-laid MC and open access FC, non-guaranteed QoS to FUs, security threats and traffic bottleneck with large billing amount [35].

2.3. Hybrid access mode

The closed access and open access modes are inflexible access modes that restrict the service to certain types of users. To counterbalance the characteristics of open and closed access modes, hybrid access mode has evolved [36]. Hybrid access mode allows certain number of *outage-experiencing* MUs to access the limited amount of FC backhaul without compromising the service quality of FUs. As hybrid access FCs provide minimum rate service to MUs, the overall network throughput is maintained above the usual throughput level attained by MC alone [37].

Hybrid access mode has the provision to choose and add the guest network users along with the registered home users. The interfering MUs are readily selected and served by hybrid access FCs, thereby minimizing the threat for co-channel and adjacent channel interferences [38]. However, this mode is easily vulnerable to privacy and security challenges [39]. Similar to open access mode, the hybrid access mode undergoes complex signaling overheads and huge backhaul billing procedures. For a dense MU growth, hybrid access FCs experience traffic bottleneck and gradual service outage analogous to open access FCs [40].

3. Choice of femtocell access modes

Apart from an indoor user purchasing a personal FBS from a network operator, the network operator may also commit to deploy massive FBSs in coverage holes, shadow regions and in large revenue harvesting cell sites to expand their network capacity. FC owners and network operators may differ in their access mode preference. One access mode may perform better than the other access modes based on the network driving parameters like multiple access schemes (CDMA/OFDMA), location of FCs with reference to the co-channel MU, frequency reuse factor and radius of FC networks. These parameters determines interference factor, ergodic rate and sum throughput of macro-femtocell networks. The following sub-sections display our analysis on the choice of access modes from the aspect of FC owner and network operator with respect to network driving parameters.

3.1. OFDMA scheme based access mode selection

In OFDMA based macro-femtocell networks, the network users are assigned with a portion of the spectrum for a sub-frame duration, which can be reused with the spatially apart cross-tier users simultaneously. Such frequency reuse phenomenon influences interference in OFDMA based FC networks [29]. Under this circumstance, the access mode preference of an FC owner and the network operator is highly dependent on network user density. Thus, the favorable access mode choices of the network operator and FC owner in OFDMA based macro-femtocell network are exhibited in Table 1 based on network user density.

On lesser network user density, the chance of two *co-channel* users coming closer to one another is less due to which the OFDMA based network acquires minimal level of co-channel interference. Thus, network operators prefer to operate in closed access mode on lesser user density. On medium and higher network user densities, the probability of co-channel users getting closer increases gradually. Furthermore, simultaneous service requisitions originating from the users necessitate the need for extra base stations. Hence, to collectively address the co-channel interference and network user growth, the network operators prefer hybrid and open access modes on moderate and higher network densities, respectively [41].

It is remarkable that the indoor users always desire to have a high-quality service at their provinces and hence, FC owners strictly prefer to operate in closed access mode irrespective of network density. On the whole, for an OFDMA based network, the most favorable FC access mode for a network operator is open access mode, whereas closed access mode is usually preferred by an FC owner.

3.2. CDMA scheme based access mode selection

In CDMA scheme, all network users transmit and receive over the common spectrum by using a unique set of pseudo noise code. With novel coding and signal spreading schemes, the burst traffic of CDMA users is efficiently handled over the same spectrum. The complete spectrum exploitation in CDMA based network improves the on-average bandwidth efficiency [42]. In case of CDMA based FC networks, the interests of network operator and

Table 1
Access mode selection in OFDMA based FCs.

Density conditions in OFDMA based network	Network operators	FC owners
Lower network user density (No. of network users <500)	Closed access	Closed access
Moderate network user density (No. of network users = 500–1000)	Hybrid access	Closed access
Higher network user density (No. of network users = 1000–2000)	Open access	Closed access

FC owner to choose an access mode are quite similar. The open access mode turns out to be the favorable choice of both network operator and FC owner for the whole range of network user density. The reason is that the cross-tier and co-tier users utilize distinctive code to spread their data, which allows the co-existence of heterogeneous network users on same frequency band. Hence, in CDMA based FC networks, the resource similarity has no role in influencing co-channel interference; besides, they yield more revenue to the network operators without affecting the service quality requirements of FUs. These appreciable benefits avoid the necessity of adaptive resource allocation at the CDMA based FBSs. Therefore, from the aspect of network operator and FC owner, open access FCs are conclusively preferred for CDMA based FC networks.

3.3. Location of MU with respect to MBS

Closer an MU to its MBS, better the experienced service quality. For 1000 m of MC coverage, an MU enjoys excellent coverage quality within 600 m. If an MU moves farther away from MBS, the radio link quality degrades gradually and the service failure rate becomes higher. The necessity of service enhancing FCs in cell edge regions become a reality in the next generation cellular networks [43]. Table 2 indicates the FC access mode preference over the three different vicinities of an MC.

The MUs nearer to MBS (1–600 m) would enjoy better service quality and the presence of FC at this zone is not beneficial to MUs. Hence, network operators will not prefer to deploy open/hybrid access FCs in the cell zones having excellent signal strength. However, a group of indoor users who desire higher rate multimedia services in the range between 1 and 600 m can prefer closed access FCs. As well, when FCs are deployed at a distance of 600–800 m from MBS, the need for hybrid or open access FCs is not significant because the MC signal strength is still sufficient to uphold the service quality of MUs. Hence, under such coverage zones, the most preferred mode of network operator and FC owner is closed access mode.

The open and hybrid access FCs come into picture when an MU surviving beyond 800 m demands a high quality multimedia service. A football stadium at the MC's edge can be marked as an example to understand the scope of open access mode. To handle the big traffic originating from the football stadium, network operators deploy open access FCs. Such access mode preference enhances the service quality at cell edges with a revenue-bonus to network operators. On the other hand, cell edge FC owners who bear small organizations and home-based businesses deploy their FCs in closed access mode to experience high quality indoor network coverage and services.

3.4. Frequency reuse factor

In OFDMA based heterogeneous networks, frequency reuse factor is defined as the number of times the same frequency is reused between two tier network users simultaneously [44]. Single frequency reuse is termed as the assignment of same frequency band to a spatially apart MU and FU, whereas double frequency reuse is the assignment of same frequency to an MU and two FCs on dense FC deployment. Triple frequency reuse is a rare case in heterogeneous networks, where the same set of frequency is allotted to a spatially apart MU and three FCs [45]. Thus, triple frequency reuse strategy necessitates complex resource management algorithms. Table 3 shows the choice of network entities over various frequency reuse strategies.

When the network utilizes single and double frequency reuse strategies, an easy and clear frequency planning induce less chance of co-channel interference [46]. Due to this reason, revenue oriented-network operators prefer open access FCs and the FC owners may agree to operate in hybrid or closed access modes as indicated in Table 3. The effect of co-channel interference increases with an increase in number of frequency reuse. On triple frequency reuse, FC owners play safely by adopting closed access mode, as they do not want to indulge in service outage. The network operators choose to deploy hybrid or open access FCs, thereby handling the anticipated interferences on account of higher degree of frequency reuse and network density. At the outset, the overall favorable choice of network operator with respect to frequency reuse is open access mode and for the FC owner, the favorable choice is closed access mode as always.

3.5. Cell radius and cell capacity

Cell capacity is defined as the maximum number of associated users served concurrently and successfully by a cellular network over the available amount of resource. In general, the pursuit of FC network is due to the following fact. The capacity of a cell depends on the cell radius. From inverse square law, the total cell capacity is inversely proportional to the square of the cell radius [47].

$$\text{Capacity of a cell} \propto \frac{1}{(\text{Cell radius})^2} \tag{1}$$

From Eq. (1), it is understood that if the cell radius is halved, the cell capacity is quadrupled. Since FC is the smallest cell among the prevailing cellular family (FC radius = 15 m, picocell radius = 100–300 m, microcell radius = 250 m to 1 km and MC radius = 1–2 km), FC is regarded as the best-known candidate to offer higher cell capacity to next generation cellular networks. The three access modes of FCs project the FBSs as the flexible base stations that not only yield extra cell capacity to the conventional MC, but also offload MC traffic burden [48]. Table 4 illustrates the scope of access modes in improving MC and FC capacities. The closed access mode is purposively designed to enhance the indoor service quality and cell capacity. Consequently, outdoor users are left un-served in closed access mode. Thus, the closed access FCs do not take part in enhancing the MC capacity. On the other hand, hybrid and open access FCs support cross-tier users, thereby enhancing the overall MC's capacity.

4. Constraints on the choice of FC access mode

Based on spectrum availability, multi-access technique (OFDMA/CDMA), frequency reuse and the proximity of co-channel MU and FU, the FC networks are anticipated to experience interference. In

Table 2
Access mode selection based on the distance between FBS and MBS.

Macrocell zones (1000 m)	Network operators	FC owners
Femtocells nearer to MBS (1–600 m)	Closed access	Closed access
Femtocells away but not far (600–800 m)	Closed access	Closed access
Femtocells at cell edge (800–1000 m)	Open access	Hybrid/closed access

Table 3
Access mode selection with respect to frequency reuse factor.

Frequency reuse factor	Network operator	FC owners
Single frequency reuse	Open access	Hybrid access
Double frequency reuse	Open access	Closed access
Triple frequency reuse	Hybrid/open access	Closed access

Table 4
Impact of access modes on MC and FC capacities.

Access mode	Macrocell capacity	Femtocell capacity
Closed	Not significant	Maximum
Hybrid	Better than closed access mode	Less than closed access mode
Open	Better than hybrid access mode	Less than hybrid access mode

addition to the limitations posed by interference, the choice of FC access mode plays a major role in determining the ergodic rate and sum throughput of co-existing macro- and femtousers. To study the effects of FC access mode choice, we examine the performance of three different FC access modes in terms of interference factor, ergodic rate and sum throughput. The analyses are substantiated through simulations as given in Section 5.

4.1. Interference factor

Interference is one of the serious challenges in heterogeneous networks. The major reasons for interference are frequency reuse, dominant transmit power of FBS and/or co-channel MU in close proximity, random and dense FC deployment, seamless mobility of MU and non-realistic access mode selection with respect to prevailing environmental conditions [49]. We examine the interference factor or interference rate experienced by MU in each access modes, so as to identify the performance implication of FC access modes in the macro-femtocell networks.

Let Z be a heterogeneous network in which FCs are overlaid on MC and there are $'M'$ MUs denoted as $A_1, A_2, \ldots A_M$ grouped under an MBS. Let $B_1, B_2, \ldots B_N$ be the group of $'N'$ FUs served by a FC which is overlaid on the heterogeneous network Z. All the $'M'$ MUs are considered to follow independent and identical distribution (i.i.d) and the position of $'N'$ FUs is deterministic as they are communicating within the indoor area.

Let the path loss exponent of the MU and FU be α and β, respectively. The channel model with such path loss exponent can be represented as

$$H(|x|) = \begin{cases} |x|^{-\alpha} & \text{outdoor transmission} \\ |x|^{-\beta} & \text{indoor transmission} \end{cases} \tag{2}$$

where $|x|$ is the distance from the network user to the respective base station. Due to shorter distance between the indoor FU and FBS, the value of indoor path loss exponent is lesser than the value of outdoor path loss exponent observed between MU and MBS, i.e., $\beta < \alpha$ [13].

We assume that the MBS is not responsible for resource and power co-ordinations to the overlaid FCs. It is noteworthy that MUs operate at higher uplink power to reach their associated MBS, whereas FUs utilize less uplink power to reach their nearby residing FBS. Let h and g be the channels to the FBS and MBS, respectively and the received power at MBS and FBS from their corresponding users be P_m and P_f accordingly.

As MBS and FBS follow independent resource and power co-ordinations, an MU A_j and a closely located FU B_i (where $j \in M$, $i \in N$) may happen to operate at same uplink channel with different power levels. This scenario may lead to co-channel interference. That is, when a high power MU transmits on the same channel which is also adopted by a nearby low powered FU, the associated FBS experiences co-channel interference as the FBS receives the dominantly powered MUs signal over the less powered FUs signal. The interference experienced by FBS due to nearby MU A_j is

$$I_j = \frac{P_m h_j}{g_j} \tag{3}$$

h_j is the channel of A_j to FBS and g_j is the channel of A_j to MBS. The interference between FU and MBS is neglected, as the complete communication of a low powered FU ends at indoor itself. Hence, the overall interference caused by a low powered FU to the MBS is much smaller than the interference caused by a high power outdoor MUs to the FBS. The interference to be excluded at MBS due to FU B_i is

$$I_i = \frac{P_f g_i}{h_i} \tag{4}$$

Also, the interference between the indoor FUs and a neighboring FBS is considered to be minimum, as the indoor path loss exponent is smaller.

Definition [13]

For $A_j \in \{A_1, A_2, \ldots, A_M\}$, the interference factor I_j due to an MU A_j is defined as $\frac{h_j}{g_j}$. The interference factors $\{I_1, I_2, \ldots, I_M\}$ are considered as i.i.d. random variables and their ordered statistics can be written as

$$I_{(1)} = \min(I_1, I_2, \ldots, I_M), \tag{5}$$

$$I_{(M)} = \max(I_1, I_2, \ldots, I_M) \tag{6}$$

For any kth user ($1 < k < M$), the interference factor $I_{(k)}$ is

$$I_{(k)} = \min(\{I_1, I_2, \ldots, I_M\} / \{I_{(1)}, I_{(2)}, \ldots, I_{(k-1)}\}) \tag{7}$$

The interference factor takes a value between 0 and 1 inclusive. The value of interference factor is different in each access mode. With the increasing number of open and hybrid access FCs, the chance of an MU to encounter a service providing FBS becomes greater. In other words, the open and hybrid access FCs allow a certain number of cross-tier MUs to access the FC resource. Hence, the interference raised by the nearby cross-tier user is minimum in open and hybrid access modes and the value varies based on the network density. On the other hand, closed access FCs do not care about the nearby service-demanding MU, rather becomes a victim to interference caused by high powered co-channel MU. Thus, closed access FCs are more vulnerable to interference.

4.2. Ergodic rate

In the heterogeneous network, MBS and FBS do not follow shared resource allocation strategy and the MUs and FUs are subjected to independent backhaul allocation based on their service requirements. In general, the backhaul capacity of MBS is larger compared with the backhaul capacity of FBS. As the backhaul capacity of FBS is lesser, FC cannot accommodate more number of home users (FUs) over the limited resource.

Resource limitation and unsuitable access mode selection has a direct impact on the ergodic rate and the quality of service enjoyed by indoor FUs. Specifically, open and hybrid access FCs need special care in backhaul allocation, as these access modes serve additional $'L'$ MUs along with its existing $'N'$ FUs. Let the initially assigned backhaul resource to an FBS be λ. If μ is the portion of resource shared with service requesting MU, the backhaul fraction for open or hybrid access modes is given as $\lambda < 1$ and $\mu > 0$. In closed access mode, the backhaul fraction is considered as $\lambda = 1$ and $\mu = 0$. When $'L'$ additional MUs are added up with registered FUs in a open or hybrid access FC, the fraction of resource allocated to FU decreases such that

$$\lambda_0 > \lambda_1 > \lambda_2 \ldots > \lambda_L, \text{where} L \in N \tag{8}$$

Let S_L be the event of FBS serving L additional cellular user. The allocated backhaul capacity to FBS be λC_b and the target rate of MU be C. Thus, the required rate of an FU in open or hybrid access mode will be

$$R_f = \min(C,\ \lambda C_b) \tag{9}$$

Based on the rate requirement, the target SINR varies for each and every FU. The success probability of a service is determined based on the target SINR and rate requirement. Let the service success probability of indoor FU, femto-assisted L MUs and the remaining $M-L$ outdoor MUs be p_f, p_L and p_{M-L}, respectively, with the target SINR of Γ_f, Γ_L and Γ_{M-L} accordingly. Thus, the ergodic rate is defined as the product of rate required and success probability of the service [13]. It is denoted as E_o and as per [13], E_o is given by

$$E_0 = \min(C, \lambda C_b) p_f \tag{10}$$

$$E_o = \min(C, \lambda_o C_o) F_I \left(\frac{P_F}{P_M \Gamma_L} - \frac{\sigma^2}{P_M}\right) \tag{11}$$

where F_I is the interference factor of an FU. P_M and P_F are received powers at MBS and FBS, respectively and σ^2 is variance of white Gaussian noise.

The achievable ergodic rate of an FU depends on the number of resources offered by the core network against the requested number of resources (physical resource blocks). If the number of resources offered to an FU is equal to the requested number of resources, the service success probability will be higher and the ergodic rate of FU will be greater. As FCs are allotted with only fractional amount of resource, the resource will not be sufficient for open and hybrid access FCs to handle growing number of MUs. Under the circumstances of increasing network density, open and hybrid access FCs should be equipped with robust resource and mobility management algorithms. Such algorithms aid FCs to offer resource only to the dominant outage experiencing MU, whereas the less outage experiencing MUs are left un-served or handed over to neighboring open and hybrid FCs. Closed access FCs neither require a resource management algorithm nor a mobility management algorithm, as it acts as an independent base station with fixed number of registered FUs.

4.3. Sum throughput

Sum throughput is defined as the sum of all MUs' ergodic rate achieved through the open and hybrid access FCs [50]. The sum throughput of MU is denoted by E_{sum} and from [50], it is given as

$$E_{sum} = M \times C \times p_L \tag{12}$$

$$E_{sum} = \lambda_L C F_I \left(\frac{P_M}{\frac{P_F}{I_o} + \sigma^2}\right) \tag{13}$$

where I_o is the interference power experienced by an MU. Higher the number of open or hybrid access FCs, greater will be the chance of a service degrading MU getting served. Closed access FCs will not contribute much in enhancing the sum throughput of the heterogeneous network as this mode restricts its service only to the registered FUs. Hence, open and hybrid access FCs serve the purpose of improving overall network throughput.

5. Performance analysis

The performance of FC networks in three different access modes is analyzed in Rayleigh fading environment through MATLAB simulations. The macro-femtocell heterogeneous networks follow 3GPP-LTE standard and the coverage area of randomly deployed FCs is considered to overlap. Table 5 lists the simulation parameters involved in our performance analysis. For varying number of FCs, the characteristics of access modes is analyzed in terms of interference factor, indoor FUs ergodic rate and the sum throughput attained by MUs due to FC deployment. Our simulation results reveal the advantages and disadvantages of each access mode.

Interference factor, one of the important performance metrics of macro-femtocell networks, is the ratio of the interference power to the signal power received by cross-tier users at the given location, when all the base stations are transmitting at same power [51]. The interference factor scales up or down based on the choice of FC access mode and the density of network user. Higher the interference factor in co-existing macro-femtocell network, greater the service outage and lesser the network capacity and throughput.

It is observed from the Fig. 1 that even at the absence of FCs, MUs experience some degree of interference, which is due to channel impairments like noise, signal fading and attenuation. With 10 FCs per cluster, the level of interference experienced by a cross tier MU from a closed access FC is 0.97, whereas hybrid and open access FCs manage to uphold the MUs service quality by maintaining the interference level at 0.54 and 0.43, respectively. On deploying 20 FCs per cluster, the interference factor in open and hybrid access FCs are 0.24 and 0.35, respectively, ensuring the co-existence of MU in FC vicinity without interference. For the same condition, the closed access FCs induce an interference factor of 0.99, which indicates that the nearby non-associated MUs experience higher interference level and service outage. Similarly for the co-existence of MUs with 30 FCs, the interference factor experienced by a MU in closed access mode is maximum, whereas for hybrid and open access FCs, interference factor is decreasing to 0.27 and 0.16, respectively. This highlights the advantage of open and hybrid access FCs compared with the closed access FCs.

With reference to the Fig. 1, the quantitative results are indicated in Table 6 which shows that with an increase in closed access FCs, the interference factor becomes exorbitantly higher. Particularly in closed access mode, the constraints like network density, resource similarity, dominant transmit power and close proximity of co-channel users maximize the interference factor. As well, Table 6 shows that the interference factor in open access mode is lesser compared to hybrid and closed access modes. The reason for this is the selfless service grant nature of open access mode. Hence, open access mode can handle loud (interfering) neighbors effortlessly. When the density of open or hybrid access FCs increases, the chance of a weak radio-link MU getting served by an FC becomes adequate. Thus, the overall interference factor of an MU reduces with an increasing number of open and hybrid access FCs and comparatively, the most favorable access mode choice of FCs with respect to interference factor is open access mode.

Offering high quality multimedia services to the indoor subscribers is the ultimate goal of FCs. Though the open access FCs yield interference-free service to cross-tier MUs, the data rate

Table 5
Simulation Parameters.

Parameters	Values
Number of FCs/cluster	40
Number of FC clusters/MC	3
Number of MUs/MC	500
Number of FUs/FC	5
Carrier frequency of MC and FCs	2.5 GHz
Bandwidth	10 MHz
Number of sub bands	50
Modulation scheme	64 QAM (3/4)
Frame duration	10 ms
Frame structure	FDD
Radius of FC	10meters
Radius of MC	1000meters
Deployment type	Random
Traffic model	ON/OFF with Markov property

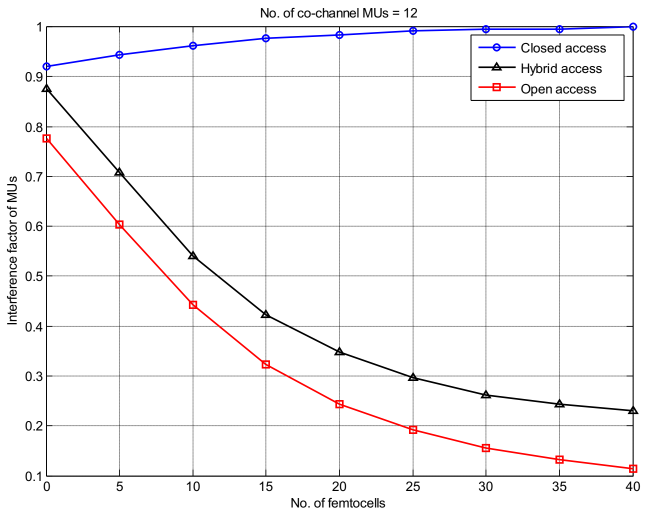

Fig. 1. Interference factor experienced by MUs in three different access modes of FC.

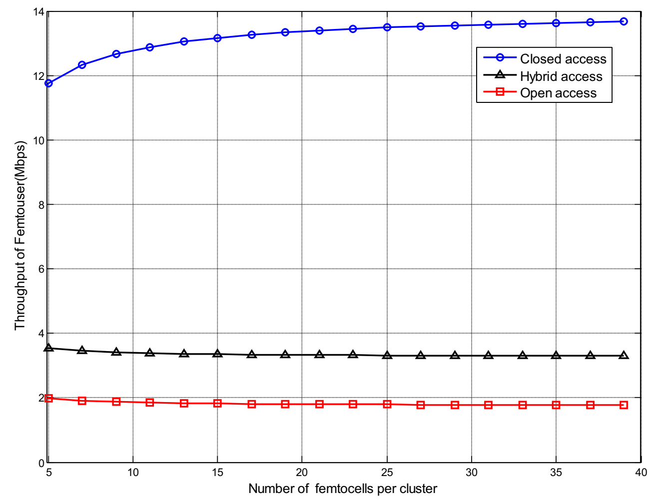

Fig. 2. Indoor users' throughput enhancement due to FC deployment.

Table 6
Access mode selection with respect to interference factor.

No. of FCs	Interference factor of MUs		
	Closed	Hybrid	Open
10	0.97	0.54	0.43
20	0.99	0.35	0.24
30	1	0.27	0.16
Open access mode			

or throughput attained by FUs in open access mode is not so significant.

Fig. 2 illustrates the reward of FCs, when deployed in closed access mode. With the densification of closed access FCs, the throughput of indoor FU ranges between 11.8 Mbps and 13.7 Mbps. The open access FCs, on the other hand, can promise guaranteed service only to certain number of registered FUs, in which the associated FUs and non-associated MUs compete for the limited amount of FC's resource. This in turn creates a traffic bottleneck at FBS. Hence, the throughput of a registered FU in open access FCs is only 1.9 Mbps, even though the maximum attainable throughput of an FU in an FC is around 14 Mbps. Similarly, in hybrid access FCs, the throughput of FU is slightly higher than open access FU's throughput, that is, 3.6 Mbps, as they give priority to serve a registered FU. Hence, it is evident that the closed access FCs are greatly preferred for improving the indoor users' throughput.

Fig. 3 and Table 7 show an analysis on FUs' ergodic rate with respect to the varying scale of offered resource. If the FUs are offered with lesser number of resources than the requested, the ergodic rate in closed access FC is 0.810, which is appreciable. As the offered resource is not shared with any of the cross-tier MU, it is well sufficient for closed access FCs to serve the registered indoor user alone. On the other hand, when hybrid and open access FCs are assigned with insufficient number of resources, the ergodic

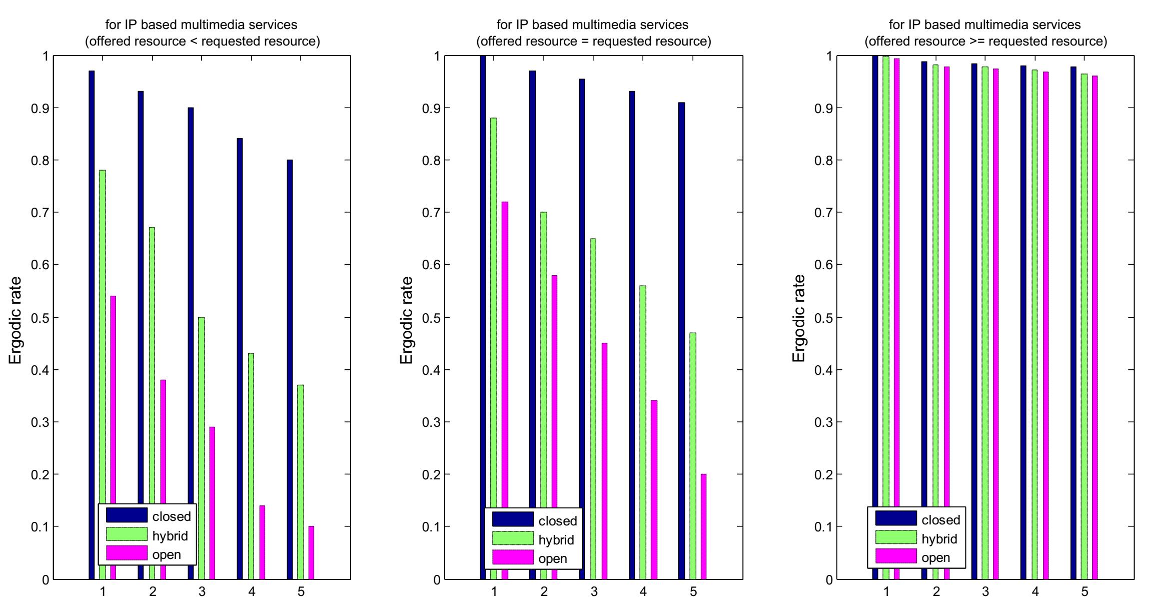

Fig. 3. Ergodic rate for a varying scales of offered resources in three different access modes.

Table 7
FUs' ergodic rate based on the choice of access mode.

Access modes	Offered resources		
	Less than required	Equal to required	Greater than required
Ergodic rate of FUs in FCs with 5 femtouser			
Closed	0.810	0.911	0.977
Hybrid	0.367	0.471	0.964
Open	0.112	0.202	0.960
Favorable choice	Closed access mode		

Table 8
Access mode selection to improvise the sum throughput of MU.

Access modes	Number of FCs		
	25 FCs	50 FCs	100 FCs
Sum throughput of MU due to FC deployment (bps/Hz)			
Closed	0	0	0
Hybrid	27	46	84
Open	36	55	95
Favorable choice	Open access mode		

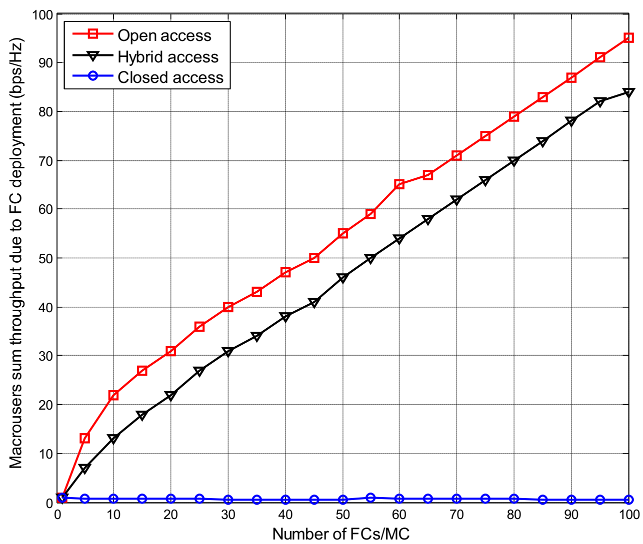

Fig. 4. MUs sum throughput on account of FC deployment in three different access modes.

rate is 0.367 and 0.112, respectively, which are inferior to that of closed access mode. The reason is that the open and hybrid access FCs share the residual resource with the MUs also. If the closed access FCs are assigned with equal or greater number of resources than the requested number, the associated FUs enjoy superior QoS and ergodic rate between 0.911 and 0.977. However, due to resource sharing phenomenon, the ergodic rate of FUs in open access mode is limited to a lesser value (0.202) compared with the ergodic rate attained through hybrid and closed access FCs (0.911 and 0.471, respectively). Apparently, closed access mode is treated as a beneficiary mode for indoor FUs.

The access mode selection determines whether the service is offered only to the indoor users (FC owners) or extended even to the nearby, service demanding MUs. Network operators prefer to deploy open and hybrid access FCs, as they serve extra number of service demanding network users. This contributes in overall sum throughput enhancement.

Fig. 4 illustrates gradual sum throughput enhancement on increasing number of open and hybrid access FC deployment. For 50 number of FCs per MC, the contribution of closed access FCs is almost negligible, whereas hybrid and open access FCs provide a network throughput of 46 bps/Hz and 55 bps/Hz, respectively on serving both tier network users. As well, it could be observed that the closed access mode does not participate in enhancing the sum throughput of a cross-tier MU, as this access mode reserves its complete resource only to the registered FUs. The rest of the quantitative values of Fig. 4 are enumerated in Table 8, followed with the inferences.

The open and hybrid access modes yield better sum throughput to MUs on deploying more and more number of such FBSs. Obviously this is due to the fact that the hybrid and open access FCs share a part of backhaul resource with the cross-tier MUs. To highlight, the open access FCs bring the network closer to the dead zone-surviving MUs and hence, this mode plays an integral part in next generation wireless communication networks.

It is noteworthy that the open access mode has no limitations on allowing the cross-tier MU to access an FC resource unlike hybrid access mode. Therefore, compared with hybrid access mode, the open access mode provides significantly higher sum throughput to MUs irrespective of the number of indoor FUs. Higher is the number of open access FCs, greater is the sum throughput enjoyed by MUs.

Table 9 summarizes the favorable access mode choices of network operator and FC owner for different network strategies. To generalize from Table 9, network operators might prefer and promote open access FCs to bring-up the network experience of associated FUs and non-associated MUs. Closed access FCs are deployed by FC owners who demand higher rate indoor services. Also, some FC owners, who work in or run a business premise, may select hybrid access FCs to connect a selected set of outdoor users to core network, thereby supporting the co-existence of MUs and FUs under the same coverage. At the outset, FCs play a key role in all the three access modes through anytime anywhere multimedia service grant to heterogeneous users, thereby shifting the cellular network to a new arena of advancement.

6. Conclusion

To accommodate MUs and FUs under same coverage, the FCs are favorably designed to operate in the three different access modes namely, closed, open and hybrid access modes. Our case study on FC access modes reveals that the open access FCs are capable of fulfilling the service requirements of network users present in indoors, cell-edges, dead zones and shadow regions. Closed access FCs are dedicated to indoor users who demand higher rate multimedia services. Hybrid access mode incorporates flexibility

Table 9
Favorable access mode choice from the aspect of FC owner and network operator.

Network Entities	Favorable access mode choices at moderate network density							
	OFDMA	CDMA	Zone separation	Frequency reuse factor	Cell capacity	Interference factor	FUs' ergodic rate	MUs' sum throughput
FC owners	Closed	Open	Closed	Closed	Closed	Closed	Closed	Open
Network operators	Open	Open	Open	Hybrid/open	Open	Closed	Closed	Open

in FCs that jointly meets the QoS requirement of FUs and extended coverage requirement of outdoor MUs. Our work will act as a guideline to understand the constraints and the consequences associated with the access mode choice from the aspect of network operator and FC owner. Though the perspectives of network operator and an FC owner on selecting an access mode are different, our case study projects open access mode as the preferable access mode that enhances the overall network throughput of next generation heterogeneous cellular networks. As well, our simulation results show that each access mode plays an important role in improving the service quality of a user under various network conditions, thereby offering all time connectivity between the user and the core network.

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