Research Article

Joint Access Control and Subchannel Allocation Scheme for Femtocell-Based M2M Network Using a Truthful Mechanism

Chengmei Li, Jianjun Wu, Ziqiang Feng, Xi Luan, and Haige Xiang

State Key Laboratory of Advanced Optical Communication Systems and Networks, Peking University, Beijing 100871, China

Correspondence should be addressed to Jianjun Wu; just@pku.edu.cn

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A joint access control and subchannel allocation (JACSA) scheme is proposed in this paper for femtocell-based machine-to-machine (M2M) network to provide better communication services. As short-range and cost-beneficial eNodeBs, femtocells can improve indoor coverage and data transmission, and can further be used for M2M communication. There are two challenges for femtocell network, access control and truth-telling. Femtocell machine-type communication devices (FMD) select femtocell access points (FAPs) according to the reported channel capacities, while the true values are private information of each femtocell. Therefore, selfish FAPs have incentive to report larger capacities to win greater opportunity to be selected. To solve the aforementioned two problems, a JACSA scheme based on the Arrow-d’Aspremont-Gerard-Varett (AGV) is proposed both in open access and hybrid access scenarios, and formula derivations are given. We prove that, compared with the optimal subchannel allocation (OSA) scheme, JACSA scheme has the feature of achieving near optimal performances with much lower computational complexity. Furthermore, we compare the allocation results for open access and hybrid access in the proposed JACSA scheme. Finally, simulations are performed, and the results verify the availability of our proposed scheme.

1. Introduction

Machine-to-machine (M2M) or machine-type communication (MTC) is an emerging technology that allows devices to communicate with MTC server or each other in absence of human intervention or interaction [1]. In the M2M networks, which have the characteristics of large device number and small data transmission, machine-type devices communicate with each other through wired or wireless connections. As smart home and smart grid become popular, such as home security sensing, lighting control, and the sensors of actuators, M2M communications have a widespread and promising coverage [2, 3].

Due to their commercial prospects and properties, M2M networks have been widely studied [4–7]. In [4], the authors briefly review the features of M2M services in the third generation (3G) long-term evolution (LTE) and the advanced (LTE-advanced) networks, and a variety of radio resource allocation schemes are proposed. In [5], focusing on the problem of heavy random access (RA) load caused by accommodating the huge population of M2M or MTC customers/devices in LTE networks, two methods are proposed to solve the RA congestion. Different from [4, 5], where the M2M communications exist in LTE networks, the work in [6] promotes the new paradigm of cognitive machine-to-machine (CM2M) communication, by exploiting cognitive radio technology in M2M communications, and proposes a coordination-based energy-efficient spectrum discovery scheme that can be used in smart grid neighborhood area networks, which is shown to significantly save energy consumption. For the M2M communications of smart meters, cognitive radio (CR) functions based on different multiobjective genetic algorithms are proposed to find out the tradeoff between power efficiency and spectrum efficiency in different operating environments [7].

Recently, there are a few emerging research interests focusing on the femtocell-based M2M networks [8, 9]. Femtocells are small, inexpensive, low-power base stations (BSSs) for better indoor voice coverage and data reception. They connect to their own wired backhaul connections,
and thus can efficiently offload data traffic from macrocell networks, which appeals to operators [10, 11]. Due to the short transmission distance, femtocells require very low transmission power and thus extend battery life of machines. In addition, femtocells can ease the RA congestion problem if M2M traffic is shared among the femtocell base stations [8]. In [8], the authors propose the group-based time control mechanism to improve the network overload and delay performance in the femtocell-based MTC networks. In [9], the potential added values are analyzed, as well as challenges, in augmenting personal telehealth systems with MTC personal health devices with integrated 3GPP interfaces (GPRS, HSPA, LTE, etc.) and operating in a femtocell network environment.

Femtocells have many benefits both for users (e.g., M2M devices) and operators. However, these benefits are not easy to accomplish simultaneously due to many challenges. One of the major challenges in the femtocell network is the access control problem because the choice of access control mechanism directly influences the interference and performance of the network.

Since femtocells provide better coverage and higher data rates for indoor machines, owners of femtocells prefer the closed access mechanism in order to fully use the femtocell resources, while operators are more interested in the open access mechanism, because open access femtocells can help operators offload the data traffic from the macrocell network and thus assist in providing higher network throughput and outdoor capacity. Nevertheless, hybrid access, a tradeoff of the open access and closed access, is the most promising access mechanism which is likely to benefit both users and operators [12, 13].

Besides, there are some studies on resource allocation using game theory [14–16] and auction theory [17, 18]. Both theories are important mathematical tools that can effectively solve the complex interactions and cheating problems among rational players and guarantee fairness and truth-telling characters. They are widely used in wireless communication [19] and show great advantages in resource allocation problems [20, 21] and access control problems [22–24].

In [22], the paper considers the selfishness of femtocell owners and proposes a utility-aware refunding framework to motivate femtocell owners to adopt hybrid access through refunding. The framework is formulated and analyzed as a Stackelberg game, and the authors prove that maximum utility can be achieved at the unique Nash Equilibrium. In [23], the authors considered the scenario that femtocell owners rent spectrum from the macrocell and proposed a spectrum leasing framework based on game theory. They model the process as a three-stage Stackelberg game and obtain the optimal spectrum leasing price, spectrum leasing ratio, and open access ratio from the Nash equilibrium. The authors in [24] propose a reverse auction in access control problem, and they use Vickery–Clarke–Groves (VCG) mechanism [17] to motivate femtocell owners participate in the auction process and maximize social welfare. Nevertheless, the VCG mechanism cannot implement the budget balance of the network, which means extra cost needs to be paid by the players in the game, and thus, the total welfare is impaired. Compared with the VCG mechanism, the AGV mechanism [17, 25] is an incentive efficient mechanism that can maximize the expected total payment of all the players in the game and achieve budget balance.

In this paper, we consider a femtocell based on M2M network with OFDMA techniques and assume all the subchannels are orthogonal and using the same spectrum. FAPs need to report their channel capacity to MTC devices (FMDs), and these devices select FAPs according to the reported information and pay for the femtocell resource they use. The channel capacity is private information, so femtocells do not know others’ channel information. Since FAP cannot get payment from FMDs unless it is selected, each FAP has an incentive to report exaggerated channel capacity to get more chance to be selected, which may lead to cheating and vicious competition in the access control process and thus decrease the throughput of the network. Under these conditions, we propose a JACSA scheme to solve the problems. By adding a transfer payment to the total payment of each FAP, we prove that there is no incentive for FAPs to report exaggerated channel information. Each femtocell can get its maximum expected total payment when it reports the true information and any cheating behavior leads to a decrease in its expected total payment. Moreover, the subchannel allocation solution based on the truthful mechanism contains two steps. Firstly, FMDs select FAPs according to their reported information. Then all FAPs allocate their subchannels to the linked FMDs aiming at maximizing their own payment. The truth-telling mechanism results in that each FAP reports its real subchannel capacity, which ensures one feature that near optimal performance can be achieved. The subchannel allocation method, with which each FAP (FUE) only chooses FUEs (FAPs) with the largest capacities, decides another feature of low computational complexity of this scheme. Further analysis proves effectiveness of the truthful mechanism and shows the near optimal performance of the subchannel allocation solution with low computational complexity.

This paper is organized as follows. In Section 2, the system model of open access and hybrid access femtocell-based M2M network is described. Then the access control and resource allocation problem are formulated. In Section 3, we propose the JACSA scheme and prove the verity of AGV mechanism in both open and hybrid access scenarios. The simulation results of open access scenario in JACSA scheme versus OSA scheme, hybrid access scenario in JACSA scheme versus OSA scheme, and open access scenario versus hybrid scenario in JACSA scheme are shown in Section 4. Finally, conclusions are drawn in Section 5.

2. System Model

Access control mechanisms in femtocell networks could be classed into three categories [12, 26]. (1) Closed access: in this scenario, only registered user equipments (UEs), which are defined as closed subscriber group (CSG) in the third generation partnership project (3GPP), are able to connect to femtocells. (2) Open access: in this scenario, all public access to femtocells is allowed. (3) Hybrid access: in this scenario,
In this paper, we consider a two-tier femtocell-based M2M network with the open access and hybrid access mechanism and compare these two situations.

1. **Open access**: the system consists of one macrocell base station (MBS), $N_O$ FAPs denoted by $\{F_1, F_2, \ldots, F_{N_F}\}$ which provide services to all $M_O$ FMDs denoted by $\{U_1, U_2, \ldots, U_{M_O}\}$.

2. **Hybrid access**: besides the FAPs and FMDs described in the open access scenario (which we call OFAP and OFMD for short), there are $N_C$ additional FAPs denoted by $\{F_{N_O+1}, F_{N_O+2}, \ldots, F_{N_O+N_C}\}$ and $M_C$ FMDs in CSGs denoted by $\{M_{M_O+1}, M_{M_O+2}, \ldots, M_{M_O+M_C}\}$ (which we name as CFAP and CFMD), with each FAP $F_{N_O+n}$ providing service only to $M_C$ FMDs denoted by $\{U_{M_O+1}, U_{M_O+2}, \ldots, U_{M_O+M_C}\}$ with $M^n_O = M_O + \sum_{i=1}^{n} M_C$. This means that only FMDs belonging to the CSG of corresponding FAP have authorization for this access access point. The total numbers of FAPs and FMDs are $N = N_O + N_C$ and $M = M_O + M_C$, respectively.

For hybrid access scenario, there exist three cases:

1. **OO case**: OFAPs $F_n$ ($n = 1, 2, \ldots, N_F$) report capacities to OFMDs $U_m$ ($m = 1, 2, \ldots, M_O$), and each OFMD may choose one OFAP to access.

2. **OC case**: OFAPs $F_n$ ($n = 1, 2, \ldots, N_O$) report capacities to CFMDs $U_m$ ($m = M_O + 1, M_O + 2, \ldots, M$).

3. **CC case**: Each CFAP $F_n$ ($n = N_O + 1, N_O + 2, \ldots, N$) reports capacities to CFMDs $U_m$ ($m = M^{n-1}_O + 1, M^{n-1}_O + 2, \ldots, M^n$) in its own CSG. Each CFMD may choose either one OFAP or one CFAP to access.

The open access scenario can be regarded as a special case of the hybrid access scenario with $N_C = 0$ and $M_C = 0$. For simplicity, we only introduce the hybrid access scenario below and consider the open access scenario as its special case.

The interference analysis model is shown in Figure 1. M2M communications have the characteristics of dealing with a huge number of devices. A large amount of MTC device will increase congestion in the network. As a result, only part of MTC devices can access the network. Here we only discuss the truth-telling problem of MTC devices which are able to access the network. The interference exists when the MBS and all FAPs share the same $K$ subchannels with equal bandwidth of $W$. Here we consider the worst condition that interference exists in all the subchannels. The transmission power of MBS and FAP (e.g., $F_n$) over the $K$ subchannels can be denoted by vectors $P = \{P_1, P_2, \ldots, P_K\}$ and $P_n = \{P_{n,1}, P_{n,2}, \ldots, P_{n,K}\}$ [27]. For additive white gaussian noise (AWGN) with variance of $\sigma^2$, the signal to interference plus noise ratio (SINR) of $F_n$ to $U_m$ in subchannel $k$ is

$$\text{SINR}_{n,m,k} = \frac{P_{n,k}|h_{n,m,k}|^2}{\sum_{i=1}^{N} P_{i,k}|h_{i,m,k}|^2 + P_{k}|h_{m,k}|^2 + \sigma^2}, \quad (1)$$

with $h_{n,m,k}$ and $h_{m,k}$ the channel frequency responses of the $k$th subchannel from $F_n$ to $U_m$ and from MBS to $U_m$, respectively, where the path loss and Rayleigh fading factor are contained. The channel capacity of $F_n$ to $U_m$ in subchannel $k$ is

$$C_{n,m,k} = W \log (1 + \text{SINR}_{n,m,k}). \quad (2)$$

During the access control and subchannel allocation processes, the FAPs first report to FMDs their channel state information (CSI), which may be false information. According to the quality of CSIs, FMDs select FAPs by comparing the capacities they report, where we assume that each FMD can only access one of the FAPs to enjoy the service. Based on the true subchannel information, FAPs distribute the capacities of all subchannels to one or more FMD(s) to maximum their profits, and each FMD pays for the sum of the subchannel capacities provided by the FAP. Therefore, the sum of the subchannel capacities of $F_n$ used by $U_m$ can be written as

$$C_{n,m} = \sum_{k \in \kappa_{n,m}} C_{n,m,k}, \quad (3)$$

where $\kappa_{n,m}$ is the set of subchannels of $F_n$ allocated to $U_m$. The throughput of the network is given by

$$C = \sum_{n=1}^{N_O} \sum_{m=1}^{M} C_{n,m} + \sum_{n=N_O+1}^{N} \sum_{m=M_O+1}^{M} C_{n,m} \quad (4)$$

$$+ \sum_{n=N_O+1}^{N} \sum_{m=M_O+1}^{M} C_{n,m}.$$ 

The three terms on the right side of (4) represent the throughput of OO, OC, and CC cases, respectively. The main problem here is to maximize the throughput of the network.

In order to solve the access control and subchannel allocation problem, we need to construct a mathematical model to describe it. During the accessing process of femtocell
network, each FAP aims at increasing its own revenues by providing larger capacities, while the FMDs prefer better communication quality by selecting FAPs with larger capacities. However, the information shared by FMDs and FAPs is unbalanced, and the FMDs have incomplete information: they do not know either the real channel capacity of the each FAP or the real capacity of each subchannel. They have no other choice but to trust the FAPs of their reported information, and can only select the FAPs according to their reported capacities. For the FMDs, to select the FAPs with largest reported average capacities is always a good idea. After all, FAPs with larger average capacities are more probably to provide subchannels with larger capacities. Furthermore, the FMD can guarantee that it has larger opportunity to attain a subchannel when it select to attach the FAP with largest capacity rather than a smaller one, since the FAP always grants its subchannels to those FMDs with largest capacities. In a simple scheme, the FAPs are paid by FMDs only when they are selected. If no FMD selects the FAP, it will get nothing. This result may drive the FAPs to report better channel information to FMDs in order to win greater opportunity to be selected, causing unfairness in subchannel allocation and reduction of the throughput of the network

\[ \bar{C} \leq \bar{C}_n \]  

with \( \bar{C} \) and \( \bar{C}_n \) representing the throughput of the network calculated according to the reported and real information, respectively. Considering the maximization of the throughput, the FAPs should all report true information.

When FMDs select FAPs according to their reported information, the truth-telling problem needs to be solved effectively to maximize the throughput of the network.

### 3. Joint Access Control and Subchannel Allocation Scheme

To formulate the problem above, we denote the real and the reported subchannel capacities of \( F_n \) to \( U_m \) as \( (\bar{C}_{n,m,1}, \bar{C}_{n,m,2}, ..., \bar{C}_{n,m,K}) \) and \( (\tilde{C}_{n,m,1}, \tilde{C}_{n,m,2}, ..., \tilde{C}_{n,m,K}) \), respectively. Similarly, the averaged real and reported subchannel capacities of \( F_n \) to \( U_m \) can be expressed as \( \bar{C}_{n,m} \) and \( \tilde{C}_{n,m} \), respectively. The FMD pays \( \xi \) to FAP per unit channel capacity, and the revenue of \( F_n \) from \( U_m \) can be expressed as

\[ R_{n,m} = \begin{cases} \sum_{k=1}^{K} \xi \bar{C}_{n,m,k}, & \text{if } F_n \text{ is selected by } U_m, \\ 0, & \text{otherwise}. \end{cases} \]  

The total revenue of \( F_n \) can be expressed as

\[ R_n = \begin{cases} \sum_{m=1}^{M} R_{n,m}, & \text{for } \text{OO, OC cases}, \\ \sum_{m=M+1}^{M_n} R_{n,m}, & \text{for } \text{CC cases}. \end{cases} \]  

Here we consider \( F_n \) and \( U_m \) as an example and neglect whether they are OFAP (OFMD) or CFAP (CFMD), which does not influence the following discussion. The real capacity of each subchannel for any FAP obeys a certain probability density function (PDF) defined as \( f(C_{n,m,k}) \), and the real average subchannel capacity obeys the PDF which is expressed as \( p(\bar{C}_{n,m}) \), which is known by all FAPs. The information enjoyed by \( F_n \), \( \bar{F}_n \), \( U_m \), and \( \bar{U}_m \) (where \( \bar{F}_n \) represents any one in the sets of all FAPs except \( F_n \), and \( \bar{U}_m \) in the sets of all FMDs except \( U_m \) is

1. \( F_n \) enjoys its real channel capacities to \( U_m \) \( (\bar{C}_{n,m,1}, \bar{C}_{n,m,2}, ..., \bar{C}_{n,m,K}) \) as private information belonging to its own, just the same situation as \( \bar{F}_n \). \( F_n \) reports its channel capacities to \( U_m \) as \( (\tilde{C}_{n,m,1}, \tilde{C}_{n,m,2}, ..., \tilde{C}_{n,m,K}) \), which is not known to \( \bar{F}_n \). Besides, \( F_n \) knows well about the PDF of the real capacities of all FAPs as \( \bar{F}_n \).
2. \( F_n \) does not know either real or reported channel capacities of \( \bar{F}_n \), which is also private information belonging to \( F_n \) itself.
3. \( U_m \) only knows the capacities all FAPs have reported to it and treats them as real capacities, according to which it selects one FAP to access. It does not know either reported or real capacities of FAPs to \( \bar{U}_m \).
4. For \( \bar{U}_m \), the situation is the same as \( U_m \).

Based on the PDF of capacities, \( F_n \) can calculate its expected revenue from \( U_m \) as

\[ R_{n,m}(\bar{C}_{n,m}) = \xi \bar{C}_{n,m} P(n,m) \]  

where

\[ P(n,m) = \begin{cases} \int_{0}^{\infty} p(x) dx N_o^{-1}, & \text{for } \text{OO case}, \\ \int_{0}^{\bar{C}_{n,m}} p(x) dx N_o, & \text{for } \text{OC, CC cases} \end{cases} \]  

is the probability of \( F_n \) selected by \( U_m \). We can easily know that when \( \bar{C}_{n,m} \to \infty, P(n,m) \to 1 \). As the expected revenue is monotone increasing function of the reported capacities, \( F_n \) has an incentive to report larger average subchannel capacity. More important, if \( F_n \) thinks that all FAPs have the same motivation, it will get nothing if it does not report \( \infty \). In this situation all information received by FMDs is false, making all FMDs blind on selecting the FAPs.

In order to solve the above problem, a truthful mechanism AGV in JACSA scheme can be employed to prevent FAPs reporting false information, when each FAP gets its maximum expected total revenue when it reports the real capacities. We will introduce the AGV mechanism in the next chapter.

Here we assume that all FAPs would report their real capacities to FMDs, and the next problem to be solved is how the FAPs allocate their subchannels among linked FMDs to maximize the throughput. Global optimum can not be
reached, since each FMD only knows its own choices of FAPs, and it cannot learn other FMDs’ choices, and those FMDs who select the same FAP may compete for subchannel resources. For the optimal subchannel allocation (OSA) scheme which maximizing the throughput of the whole network, all subchannel information (which, of course, should be the true values) and allocation probabilities should be concerned, and the complexity of the algorithm is $O(N^M K)$. In a rapidly changing wireless communication environment, this process is too time-consuming and cannot be achieved. Besides, as all FAPs may be so selfish that they only care about maximize their own throughput, an additional entity must be included to allocate the subchannels globally, which raises the total cost of the network. With the JACSA scheme, however, the complexity is only $O(N^M K)$, which is much lower than the OSA scheme, especially when $N$ and $M$ are very large. From the following simulation results, we can see that, in the current JACSA scheme, as long as each FAP maximizes its own utility, the maximum throughput of the whole network can be well approached with a percentage of about 90%. The whole process of JACSA scheme is described as follows.

(i) Based on the truth-telling mechanism, all FAPs report real average capacities to FMDs. OFAP $F_n$ reports $\overline{C}_{nm}$ to any FMD $U_m$ ($n = 1, 2, \ldots, N_O$ and $m = 1, 2, \ldots, M$), and CFAP $F_n'$ reports $\overline{C}_{nm'}$ to CFMD $U_{m'}$ ($n' = N_O + 1, N_O + 2, \ldots, N$ and $m' = M'^{-1} + 1, M'^{-1} + 2, \ldots, M'$) in its CSG.

(ii) According to the reported information, FMDs select one FAP with the largest average capacity to access. OFMD can only access $N_O$ OFAPs, while CFMD can access $N_O$ OFAPs and one additional CFAP.

(iii) According to the accessing information, FAPs allocate their subchannel resources among FMDs who select them. For each subchannel, FAP will allocate it to the FMD with the most capacity to maximize its throughput. OFAPs will allocate their subchannels among all FMDs, while CFAPs only allocate among CFMDs in their CSGs.

(iv) Subchannel allocation finished. FMDs will access the FAPs who have allocated resources to them.

4. AGV Mechanism

Truth-telling is achieved by adding a transfer payment to the expected revenue $\mathcal{R}_{nm}$, which is different for the OO, OC, and CC case.

(i) For OO case, the transfer payment is

$$
\mathcal{T}_{n,m} (\overline{C}_{1,m}, \ldots, \overline{C}_{N_O,m})
= \Gamma_{nm} (\overline{C}_{nm}) - \frac{1}{N_O - 1} \sum_{i=1, i \neq n}^{N_O} \Gamma_{im} (\overline{C}_{im}),
$$

where the externality

$$
\Gamma_{nm} (\overline{C}_{nm}) = \sum_{i=1, i \neq n}^{N_O} E [\mathcal{R}_{jm} (\overline{C}_{nm})]
$$

represents the sum of other FAPs’ expected payment from $U_m$ when $F_n$ has reported $\overline{C}_{nm}$.

(2) For OC case, the transfer payment is

$$
\mathcal{T}_{n,m} (\overline{C}_{1,m}, \ldots, \overline{C}_{N_O,m}, \overline{C}_{N_O+q,m})
= \Gamma_{nm} (\overline{C}_{nm})
- \frac{1}{N_O} \left[ \sum_{i=1, i \neq n}^{N_O} \Gamma_{im} (\overline{C}_{im}) + \Gamma_{N_O+q,m} (\overline{C}_{N_O+q,m}) \right],
$$

where the externality is

$$
\Gamma_{nm} (\overline{C}_{nm}) = \sum_{i=1, i \neq n}^{N_O} E [\mathcal{R}_{jm} (\overline{C}_{nm})]
+ E [\mathcal{R}_{N_O+q,m} (\overline{C}_{nm})],
$$

(3) For CC case, the transfer payment is

$$
\mathcal{T}_{N_O+q,m} (\overline{C}_{1,m}, \ldots, \overline{C}_{N_O,m}, \overline{C}_{N_O+q,m})
= \Gamma_{N_O+q,m} (\overline{C}_{N_O+q,m})
- \frac{1}{N_O} \sum_{i=1}^{N_O} \Gamma_{im} (\overline{C}_{im}),
$$

where the externality is the same as OC case.

The expected total payment or the expected utility of $F_n$ from $U_m$ is

$$
\mathcal{U}_{nm} (\overline{C}_{nm}) = \mathcal{R}_{nm} (\overline{C}_{nm}) + \mathcal{T}_{nm}.
$$

The existence of transfer payment can effectively prevent the FAPs from reporting false information. The FAPs who report larger capacities than their real values can be punished, and the loss of any FAPs revenue caused by exaggeratedly reported capacities of other FAPs can be compensated. If $F_n$ reports its subchannel capacities with larger values ($\overline{C}_{nm} > \overline{C}_{nm}$), it has more chance to be selected by $U_m$, but the transfer payment is even larger, decreasing its expected total revenue. On the contrary, if $F_n$ reports its true values but one of the other FAPs reports larger capacities than its real values and is selected by FMDs instead of $F_n$, it will have to pay $F_n$ some transfer payment. On the other hand, if $F_n$ reports smaller average capacities ($\overline{C}_{nm} < \overline{C}_{nm}$), it has smaller probability to be selected by $U_m$, and the transfer payment from other FAPs does not compensate the reduction, making its expected utility decreasing.
Proposition 1. Each FAP maximizes its expected utility from FMDs only when it reports its real information

\[ \hat{C}_{nm} = \bar{C}_{nm}. \]  

**Proof.** Without loss of generality, we consider the expected utility of \( F_n \) paid by \( U_m \), which can be expressed as follows.

(1) For OO case

\[
E \left[ \mathcal{U}_{nm} \left( \hat{C}_{nm} \right) \right] = E \left[ \mathcal{R}_{nm} \left( \hat{C}_{nm} \right) + \mathcal{F}_{nm} \left( \hat{C}_{1m}, \cdots, \hat{C}_{Nm}, \hat{C}_{N_O+q,m} \right) \right];
\]

inserting (10) into the above equation, we get

\[
E \left[ \mathcal{U}_{nm} \left( \hat{C}_{nm} \right) \right] = E \left[ \mathcal{R}_{nm} \left( \hat{C}_{nm} \right) \right] + E \left[ \sum_{j=1, j \neq n}^{N_O} \mathcal{R}_{jm} \left( \hat{C}_{nm} \right) \right] - \frac{1}{N_O - 1} \sum_{j=1, j \neq n}^{N_O} \Gamma_{jm} \left( \hat{C}_{jm} \right).
\]  

(2) For OC case

\[
E \left[ \mathcal{U}_{nm} \left( \hat{C}_{nm} \right) \right] = E \left[ \mathcal{R}_{nm} \left( \hat{C}_{nm} \right) + \mathcal{F}_{nm} \left( \hat{C}_{1m}, \cdots, \hat{C}_{Nm}, \hat{C}_{N_O+q,m} \right) \right];
\]

inserting (12) into the above equation, we get

\[
E \left[ \mathcal{U}_{nm} \left( \hat{C}_{nm} \right) \right] = E \left[ \sum_{i=1}^{N_O} \mathcal{R}_{im} \left( \hat{C}_{nm} \right) \right] + E \left[ \mathcal{R}_{N_O+q,m} \left( \hat{C}_{nm} \right) \right] - \frac{1}{N_O - 1} \sum_{j=1, j \neq n}^{N_O} \Gamma_{jm} \left( \hat{C}_{jm} \right) + \Gamma_{N_O+q,m} \left( \hat{C}_{N_O+q,m} \right).
\]  

(3) For CC case

\[
E \left[ \mathcal{U}_{N_O+q,m} \left( \hat{C}_{N_O+q,m} \right) \right] = E \left[ \mathcal{R}_{N_O+q,m} \left( \hat{C}_{N_O+q,m} \right) \right] + \mathcal{F}_{N_O+q,m} \left( \hat{C}_{1m}, \cdots, \hat{C}_{Nm}, \hat{C}_{N_O+q,m} \right).
\]

inserting (14) into the above equation, we get

\[
E \left[ \mathcal{U}_{N_O+q,m} \left( \hat{C}_{N_O+q,m} \right) \right] = E \left[ \sum_{i=1}^{N_O} \mathcal{R}_{im} \left( \hat{C}_{N_O+q,m} \right) \right] + \mathcal{R}_{N_O+q,m} \left( \hat{C}_{N_O+q,m} \right) - \frac{1}{N_O} \sum_{j=1}^{N_O} \Gamma_{jm} \left( \hat{C}_{jm} \right).
\]  

The terms on the right side of (18), (20), and (22) represent the expected revenue of all FAPs paid by \( U_m \) when \( F_n \) reports \( \hat{C}_{nm} \) to \( U_m \) and the average externality of other FAPs except \( F_n \), which is independent on \( \hat{C}_{nm} \) to \( U_m \). Therefore, the first term describing the expected total revenue of all FAPs determines the expected utility of \( F_n \) from \( U_m \). Note that according to (8), the expected total revenue is decided by the reported capacities which may not be true. Besides, we easily know that if there exist FAPs who cheat about their capacities, the selections of FMDs may be misled, leading to decreasing of the expected total revenue. Therefore, only when all FMDs select FAPs according to the real capacities, the whole network can get the maximum total revenue. The maximum of the whole network also means that the utility of \( F_n \) from \( U_m \) reaches its maximum value. The coincidence between the global maximum and the individual optimum ensures that \( F_n \) has no incentive to report false information and the equilibrium can be achieved.

**Proposition 2.** The network pays no extra costs for the truthful mechanism.

**Proof.** From the transfer function equations (10), (12), and (5) we can obtain the sum of the transfer payment of all FAPs with \( U_m \) (Vnm) as follows:

(1) for open FMDs (OO case)

\[
\mathcal{F}_{nm} \left( \hat{C}_{1m}, \cdots, \hat{C}_{Nm}, \hat{C}_{N_O+q,m} \right) = \sum_{n=1}^{N_O} \Gamma_{nm} \left( \hat{C}_{nm} \right) - \frac{1}{N_O - 1} \sum_{n=1}^{N_O} \sum_{i=1}^{N_O} \Gamma_{jm} \left( \hat{C}_{jm} \right) + \frac{1}{N_O - 1} \sum_{j=1}^{N_O} \Gamma_{jm} \left( \hat{C}_{jm} \right).
\]

(2) for closed FMDs (CC case)

\[
\mathcal{F}_{N_O+q,m} \left( \hat{C}_{1m}, \cdots, \hat{C}_{Nm}, \hat{C}_{N_O+q,m} \right) = \frac{N_O}{N_O - 1} \sum_{j=1}^{N_O} \Gamma_{jm} \left( \hat{C}_{jm} \right) - \frac{N_O}{N_O - 1} \sum_{i=1}^{N_O} \Gamma_{jm} \left( \hat{C}_{jm} \right) = 0.
\]
(2) For closed FMDs (OC and CC case)
\[
\sum_{n=1}^{N_O} T_{n,m}(\hat{C}_{1,m}, ..., \hat{C}_{N_O,m}, ...)
= \sum_{n=1}^{N_O} \Gamma_{n,m}(\hat{C}_{n,m}) - \frac{1}{N_O} \sum_{n=1}^{N_O} \sum_{m=1}^{M} \Gamma_{j,m}(\hat{C}_{j,m})
+ \sum_{j=1}^{N_O+q,m} \frac{1}{N_O} \sum_{m=1}^{M} T_{n,m}(\hat{C}_{N_O+q,m})
+ T_{N_O+q,m}
= 0.
\]

The total transfer payment of all FAPs with \( U_m \) equals zero. Therefore, the total transfer payment of the whole network also equals zero.  

5. Simulation Results

Based on the analysis in previous sections, simulation results are given to evaluate the performance of the proposed JACSA scheme. Generally, the reported subchannel capacity of each FAP is assumed to obey the exponential distribution described by PDF \( f(x) = e^{-x} \), and thus the average subchannel capacity of each FAP follows Erlang distribution with PDF \( p(x) = K^x e^{-Kx}/(K-1)! \). As in our scheme, the FMDs deal with the information got from the FAPs in an easy way: they only care about the average capacities reported by FAPs instead of detailed subchannel capacities. For simplicity, we assume that each FAP calculates its own average subchannel capacity and reports a value to each FMD, from which FMD selects FAP. We consider two scenarios here, the open access and the hybrid access. Now we will give the simulation results of verification of the truth-telling mechanism, the open access scenario in JACSA scheme versus OSA scheme, the hybrid access scenario in JACSA scheme versus OSA scheme, and the open access scenario versus hybrid access scenario in JACSA scheme, respectively.

Firstly, we focus on verification of truth-telling mechanism. For the open scenario, we investigate the performance of the truth-telling mechanism and consider a femtocell network with the settings of \( M_O = 5, N_O = 2, K = 8 \). We also assume that the price per unit of channel capacity \( \xi = 1 \) and a random sample of the real average channel capacity is obtained as

\[
\bar{C}_{\text{open}} = \begin{pmatrix}
\bar{C}_{1,1} & \bar{C}_{1,2} \\
\bar{C}_{1,3} & \bar{C}_{1,4} \\
\bar{C}_{1,5} & \bar{C}_{1,6} \\
\bar{C}_{1,7} & \bar{C}_{1,8} \\
\bar{C}_{1,9} & \bar{C}_{1,10} \\
\bar{C}_{1,11} & \bar{C}_{1,12} \\
\bar{C}_{1,13} & \bar{C}_{1,14} \\
\bar{C}_{1,15} & \bar{C}_{1,16} \\
\bar{C}_{1,17} & \bar{C}_{1,18} \\
\bar{C}_{1,19} & \bar{C}_{1,20}
\end{pmatrix} = \begin{pmatrix}
1.00 & 0.85 \\
0.82 & 0.84 \\
1.26 & 0.58 \\
1.07 & 0.71 \\
0.97 & 1.04 \\
0.86 & 0.59 \\
0.97 & 1.04 \\
0.97 & 1.04 \\
0.97 & 1.04 \\
0.97 & 1.04
\end{pmatrix}.
\]

For the hybrid access scenario, besides the channel capacities above, the open and closed FAPs also report to the closed FMDs. We consider that \( N_C = 1, M_C = M_C = 2, \) and \( K = 8 \). The channel capacity reported to closed FMDs is then

\[
\bar{C}_{\text{closed}} = \begin{pmatrix}
\bar{C}_{1,6} & \bar{C}_{2,6} & \bar{C}_{3,6} \\
\bar{C}_{1,7} & \bar{C}_{2,7} & \bar{C}_{3,7}
\end{pmatrix} = \begin{pmatrix}
0.68 & 0.95 & 1.11 \\
1.22 & 1.49 & 0.54
\end{pmatrix}.
\]

Without loss of generality, we consider \( U_4 \) as an example for the open access scenario and \( U_6 \) for the hybrid access scenario.

In Figure 2, we demonstrate the variation of \( F_n \)'s expected total payment paid by the open FMD \( U_n \) (\( n = 1, 2 \)) and closed FMD \( U_n (n = 1, 2, 3) \), when the reported information changes in the proposed mechanism. Given that the other nodes are honest, we find that \( F_n \) gets its maximum expected total payment only when it reports the true information, which is proved in Proposition 1. There is no incentive for FAPs to report exaggerated information.

In Figure 2, in the hybrid access scenario, the open FAP \( F_1 \), \( F_2 \) and closed FAP \( F_3 \) get their largest expected total payments, whose values are 0.3008, 0.2471, and 0.1977, respectively, at subchannel capacities at \( \bar{C}_{1,6} = 0.55, \bar{C}_{2,6} = 0.96, \) and \( \bar{C}_{3,6} = 1.13 \) for FMD \( U_6 \), respectively. These capacities are very close to their true capacities, whose values are 0.68, 0.95, and 1.11, respectively. The expected total payments are 0.2993, 0.2429, and 0.1956, respectively, which differ from their maximum values of less than 0.5%. These derivations from their true values are due to the fluctuations of the calculated expected total payments for limited simulation times. Among all FAPs, \( F_3 \), which has the largest true capacity, will be selected by \( U_6 \). The expected total payment is less than \( \xi \bar{C}_{1,6} = 1.13 \) because it needs to pay transfer payment to other FAPs.

Figure 3 shows the expected transfer payment of \( F_n \) with open FMD \( U_4 \) (\( n = 1, 2 \)) and closed FMD \( U_6 \).
We can see that the transfer payment of each FAP monotonically decreases because the larger the reported average subchannel capacity is, the more transfer payment should be paid to others. Therefore, FAPs will not report exaggerate information if they take the transfer payment into consideration. We also find that the transfer payment curve of $F_n$ with the largest real average subchannel capacity lies above other curves. This is because the expected payment is proportional to the real channel capacity (25) and (26). So the FAP with larger real channel capacity needs larger transfer payment to guarantee truth-telling.

Furthermore, the transfer payment can be seen as a kind of tax. When all FAPs report true information, the transfer payments of all FAPs $T$ are $T_{1,6} = 0.2765$, $T_{2,6} = 0.0148$, and $T_{3,6} = -0.2906$, respectively. We can see that $T_{1,6} + T_{2,6} + T_{3,6} = 6.5 \times 10^{-4} \approx 0$, an example of Proposition 2. Even after we consider the fluctuations in the limited simulation times, the transfer payments at the points with maximum expected transfer payments are 0.2966, 0.0081, and −0.3167, and their sum is −0.0120, which is of the order of 1% and is within a reasonable error range.

Second, we consider the performance of the JACSA scheme and OSA scheme for an open access scenario. We primarily focus on the allocation result and throughput of the network at different $K$ and $M_O$. Primarily, we set $M_O = 5$ and $N_O = 3$ and change the value of $K$ to investigate the influence of the number of subchannels. From Figure 4 we can see that when the number of subchannel ($K$) increases, the throughput of the network will increase at the same time. Because each FAP has more subchannels for allocation when $K$ increases and more FMDs get the chance to obtain more channel resource than the scenario with lower $K$, which increase the throughput of the network. Besides, as $K$ increases, the relative difference between the joint and optimal subchannel allocation is almost the same, and the JACSA scheme can give a throughput about 90% of the OSA scheme with a much lower complexity.

Then we set $N_O = 3$ and $K = 8$ and change the value of $M_O$ to investigate the influence of FMDs. Figure 5 shows the throughput of the JACSA scheme and OSA scheme under the condition of different number of FMDs. As the number of open FMDs increases, the subchannel can be used more sufficiently, and thus the throughput of the system is larger.

Third, comparing the JACSA scheme with the OSA scheme for the hybrid access scenario. We set $N_O = 2$, $M_O = 5$, $N_C = 1$, and $M_C = M_{C1} = 2$ and change the value of...
Figure 6 shows the throughput of all open and closed FAPs in JACSA and OSA scheme. Similar with the open access scenario, the total throughput does not change much with increasing of $K$. However, the throughput of all open FAPs is smaller for the OSA scheme than that for the JACSA scheme, while the throughput of all closed FAPs is larger. This means that the current JACSA scheme does not sufficiently use the closed FAPs.

Similarly, we consider the influence of the number of closed FMDs in the hybrid access scenario. Figure 7 shows the throughput of all open and closed FAPs in the JACSA and OSA schemes. Increasing of the number of closed FMDs means that both subchannels of the open and closed FAPs are used sufficiently and the throughput of both kinds of FAPs increases.

Finally, in the hybrid access scenario, due to the existence of the closed FAP, which is exclusive to closed FMDs, these closed FMDs have more access choices, and thus they probably have larger per user capacity. Compared with the situation where this FAP is open, however, there is less chance for access, thus total throughput decreases. First, we look from the perspective of the FAPs and calculate the total throughput of the system. Figure 8 shows the throughput of open and closed FAPs with $N_O = 2$ and $N_C = 1$, respectively, and a total number of FMDs $M_O + M_C = 8$ and transfers one FMD from open status to closed. In order to compare with the open access scenario, we also plot the $N_O = 3$ and $M_O = 8$ case. The horizontal axis represents the combinations of FAPs and FMDs. We can see that compared with open and hybrid access scenarios, the throughput is less in the latter, when the maximum value is equal to the throughput in the former. When there is no closed FMD in the hybrid, as there is one empty FAP which has no access, the total throughput is minimum. With the increasing of the closed FMDs, the total throughput and that for all closed FAPs increases, and the throughput for all open FAPs decreases slightly, as more FMDs may access closed FAPs. Therefore, no matter how many closed FMDs there are, total throughput is smaller in the hybrid access scenario, compared with open access.

From the perspective of FMDs, the average capacity is enjoyed by each FMD, as shown in Figure 9. When there is no closed FMD, as there are less open FAPs, the average capacity for open FMDs is smaller. If one FMD decides to join the CSG, the average capacity to be obtained is larger than that of an open FMD, and is also larger than that received by other
open FMDs. As the closed FMDs probably access the closed FAP, the open FMDs have less competition and enjoy larger average capacity. As more FMDs join the CSG, as there are more competitions for the closed FAP, the average capacity decreases for each closed FMD but is still larger than that received by open FMDs and received with an open FMD. If all FMDs become closed, the situation is the same as in the open access scenario, and the capacity of each closed FMD is minimum. This indicates that, when closed FAPs exist, by becoming a closed FMD, the average capacity each FMD enjoys grows.

6. Conclusion

In this paper, we focus on the OFDMA femtocell-based M2M network with several femtocells and MTC devices distributed randomly in open access scenario and hybrid access scenario. In order to solve the truth-telling and subchannel allocation problems under these two scenarios, we propose a joint access control and subchannel allocation scheme based on the AGV mechanism. We use the transfer payment to balance the total payment and prove that there is only one equilibrium to be reached at the point when all FAPs reported their true capacities. By comparing the JACSA scheme with the OSA scheme in the two scenarios, we show that the JACSA scheme can obtain near optimal results with lower complexity. Finally, we compare the open access scenario with hybrid access scenario in the JACSA scheme, and the simulation results show that from the view of FAPs, an open access scenario is better to get more payments, but from the view of FMDs, when there are closed FAPs, it is better to join the CSG for better services.

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