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Resource Allocation for M2M Communication in Heterogeneous Network: Coalitional Game Theory Approach

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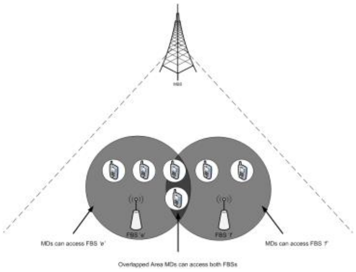
Graphical abstract



Abstract

The heterogeneous cellular network (HCN) is a promising technology to handle the rising number of devices due to their universal presence. This rising popularity HCN based Machine-to-Machine (M2M) communications is opening new opportunities and also bringing forth new system design issues. However, the main challenge of M2M communication is the possibility of huge traffic and significant difference in the nature of M2M traffic than the current commercial traffic for which current cellular network is designed and optimized. In this article, we investigate the uplink resource allocation problem of M2M devices (MDs) in the multiple Femto base station's coverage. We first model the uplink power and sub-carrier allocation in femtocells independently; Based on the cooperative game resource allocation among MDs is analyzed through non-transferable utility game to enhance the data rate performance with minimum utilization of power. Simulation results show that the resource allocation model based on cooperative game is able to provide a fair distribution of data rate compared with non-cooperative and greedy type of MDs.

Keywords: Heterogeneous cellular network; machine-to-machine communications; cooperative game; uplink resource allocation

Abstrak

Heterogen rangkaian selular (HCN) adalah teknologi yang menjanjikan untuk menangani peningkatan bilangan peranti kerana kehadiran sejagat mereka. Ini meningkat populariti HCN berasaskan Mesin-ke-Mesin (M2M) komunikasi membuka peluang-peluang baru dan juga membawa sebagainya isu-isu reka bentuk sistem baru. Walau bagaimanapun, cabaran utama komunikasi M2M adalah kemungkinan lalu lintas yang besar dan perbezaan ketara dalam trafik M2M daripada trafik komersil yang yang mana rangkaian selular semasa direka dan dioptimumkan. Dalam artikel ini, kita menyiasat masalah peruntukan sumber uplink peranti M2M (MDS) dalam liputan stesen pangkalan Femto berganda itu. Kami pertama model kuasa perhubungan naik dan peruntukan sub- pembawa dalam femtosel bebas; Berdasarkan peruntukan sumber permainan koperasi di kalangan MDS dianalisis melalui permainan utiliti tidak boleh dipindah milik untuk meningkatkan prestasi kadar data dengan penggunaan minimum kuasa. Keputusan simulasi menunjukkan bahawa sumber peruntukan model tersebut berdasarkan kepada permainan kerjasama dapat memberikan pengagihan saksama kadar data berbanding dengan jenis bukan koperasi dan tamak MDS.

Kata kunci: Rangkaian heterogen; mesin-ke-mesin (M2M) komunikasi; permainan koperasi; peruntukan sumber

■1.0 INTRODUCTION

The automated exchange of information between end devices such as sensors, vehicles or a central control center without human intervention in the field of communication is called Machine-to-Machine (M2M) communication [1]. The communication between these M2M devices (MDs) is done through wired or wireless communication link [2]. Recently in the wireless communication i.e. LTE started to consider the in-corporation among different MDs, to interact with a remote server or device directly or indirectly [2, 3]. This interaction of MDs is unique in its own way that lead to the internet of things (IoT) [4]. Large coverage of a wireless cellular network gives the opportunity to communicate with machines. The expected growth of MDs are expected to be around some billions which will connect to the cellular network in the coming future [3, 5]. Their bandwidth requirement for M2M is very small and may demand usually real or non-real time [2].

Recently, standardization activities on M2M over cellular networks have been launched by the 3GPP group in order to integrate different network technologies that can widely support a huge number of MDs [6]. However, as cellular networks are optimized for human to human (H2H) communications, there are several problems concerning MDs accessing cellular networks. Increase in numbers of MDs which poses different M2M services and might be diverse in their nature is allowing industry to think about proper resource allocation and scheduling schemes to improve the network performance, which is normally not designed for M2M communication.

In heterogeneous cellular network, all received or transmitted base stations (BSs) are different in their performance i.e. received/transmitted power, data rate, deployment density and coverage etc. [7-9]. The devices which are located under the coverage of multiple BSs then it is most suitable to connect with a strongest or nearest BS [10]. M2M machines which are using wireless uplink to communicate with BS, resource allocation e.g. power is difficult to manage due to distributed power constraints of machines instead of centralized downlink communication [11], if all the machines are battery operated then total transmission power constraint is also an important issue.

For M2M communication, the main objective is to minimize their transmitting power and maximize their data rate. M2M communication typically transmitting short session from huge numbers of machines [12]. Random access is a proposed solution in [13], in which MDs are grouped as per Quality of Service (QoS) requirements. Group based resource allocation scheme enhances cooperative machine grouping with and without controller for energy efficient M2M communication [14][15]. Furthermore, controller with cognitive feature is proposed which helps to maximize the spectral efficiency and avoid collisions. Moreover, dynamic resource allocation procedure is given in order to provide better QoS among MDs and H2H devices [16].

Resource allocation is a hot issue for the devices which are willing to connect in uplink under the coverage of multiple BSs with limited transmitting power and limited ability to take decision. Recently, there have been extensive research works that have applied game theory for the analysis of resource allocation in wireless communication networks. This is basically due to the need for distributed mobile networks where machines can take independent decision [17]. Cooperative game theory provides analytical tools to study the behavior of rational players when they cooperate make a coalition to strengthen their positions in the game[18]. Coalition game is adapted in [19] to control the accesses by mobile user to BSs and check the super-additiviity property of the network. In [20], reinforcement learning is adapted to control the accesses by MDs to avoid overload control in M2M communication.

In this paper, we modeled a new way to analyze the resource allocation problem of M2M communication in Heterogeneous cellular network by using coalitional game theory. By adapting this method machines have ability to maximize their data rate while taking care of other members of the coalition. The results are compared in terms of independent decision of machine verses coalitions effect.

The rest of the paper is divided into following sections: Section 2 gives the system model and assumptions. Section 3 gives the coalition game model, rate of coalition and strategies of the coalitions. Section 4 gives the analysis on coaltion game formation. Section 5 gives the numerical result and discussion. Section 6 concludes the paper.

2.0 SYSTEM MODEL AND ASSUMPTIONS

The basic model of HCN is shown in Figure 1. The MDs are under the coverage of multiple FBSs in which we consider L cellular links in between K MDs and FBS e and f sharing the same sub-carriers $\mathcal{N} = \{1, 2, \ldots, N\}$ which consists of N numbers of orthogonal sub channels. Let there be $\mathcal{K} = \{1, 2, \ldots, K\}$, where $K \geq 2$, uplink MDs trying to connect with any one of the given FBS and has a rate requirement R_i. We assume that all the sub-carriers have the same bandwidth of B Hz. Any machine can use any of the sub-carriers within the band to transmit its data. Furthermore, the channel power gain is denoted by $h_{ie}^{l}$and h_{if}^{l} from machines to FBS e and f on sub-channel l. The channel gain set for FBS e is $h_{ie} = \left\{h_{ie}^{(1)}, h_{ie}^{(2)}, \ldots, h_{ie}^{(N)}\right\}$ and for the further competing FBS $h_{if} = \left\{h_{if}^{(1)}, h_{if}^{(2)}, \ldots, h_{if}^{(N)}\right\}$. The channel gain may depend on distance, attenuation, random fading effect and antenna gain. Let $p_{ie}^{(l)}$ and $p_{if}^{(l)}$ denote the transmission power to transmit data from the MDs of link i while the interfering power from interfering link j is denoted by $p_{je}^{(l)}$ and $p_{je}^{(l)}$ to the FBS e and FBS f respectively. The transmit power vector of MDs is defined by, $\mathcal{P}_i \triangleq \{p_i^{(1)}, p_i^{(2)}, \ldots . p_i^{(N)}\}$.

Thus, the signal to interference ratio (SIR) at FBS e on sub-channel l is given as

$$SIR_{ie} = \frac{\sum_{i\epsilon E} h_{ie}^{(l)} p_{ie}^{(l)}}{\sum_{j\epsilon F} h_{jf}^{(l)} p_{jf}^{(l)}} \qquad (1)$$

Similarly, the SIR at FBS f on sub-channel is given as:

$$SIR_{if} = \frac{\sum_{i\epsilon F} h_{if}^{(l)} p_{if}^{(l)}}{\sum_{j\epsilon E} h_{je}^{(l)} p_{je}^{(l)}} \qquad (2)$$

where, E and F are the group of machine attached to FBS e and f and producing interference for FBS f and e respectively. Perfect channel state information (CSI) is estimated by FBS dedicated machines with static in mobility and channel quality is invariant [21].

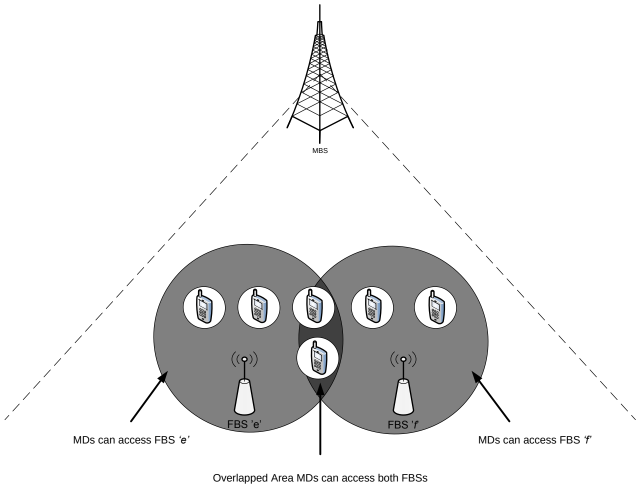


Figure 1 Two tier macro-femto network

3.0 COALITION GAME MODEL

In this section, we present a non-transferable utility (NTU) cooperative game where K machines are players. The set of MDs called coalitions of MDs are denoted by by, $(E, F) \subseteq \mathcal{K}$. These two coalitions of MDs that have admitted by FBSs e and f respectively, such that $E \cap F = \emptyset$ and $E \cup F = K$. The MDs are allowed to change their coalition to another to get better rates.

3.1 Rates of Coalitions

Let R_{ie} and R_{if} denote the rates of MD when it is in their respective coalition and attached with the FBS. We can find the rate of each MD when it is linked with FBS e or f. Since in transmission mode from MDs to FBS needs to relay packets transmitted from the MDs to the FBS and the same sub-channel is used for the transmission by the neighboring coalition for the transmission of their MDs to their respective FBS. The rate R_{ie} and R_{if} is totally dependent on the MDs within the coalition and the resources distributed among them as shown in Eq. 3 and Eq. 4.

For FBS e,

$$R_{ie} = \sum_{l=1}^{N} \frac{B}{N} \log_2(1 + SIR_e) \tag{3}$$

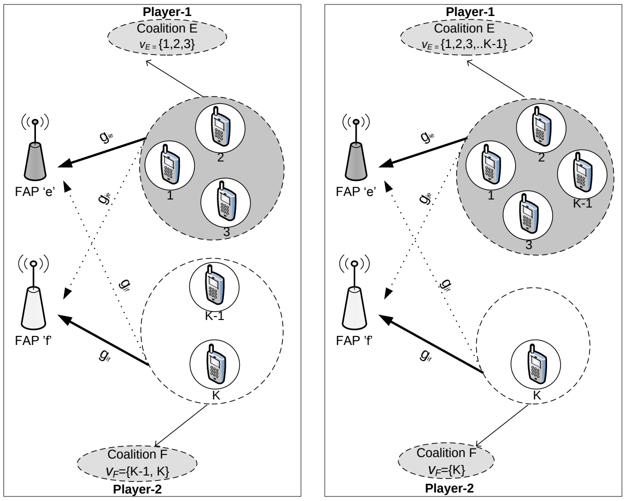
similarly, for FBS f,

$$R_{if} = \sum_{l=1}^{N} \frac{B}{N} \log_2(1 + SIR_f) \tag{4}$$

Increase in the MDs will tend to reduce the share of each MD within the coalition. MDs within a coalition do not conflict with other MDs of the same coalition which tends to reduce the interference level within the coalition. MDs of the same coalition used distinctive non-overlapped sub-carriers for transmission. However, the interference limit increases as the number of MDs increase in the neighboring coalition due to same resources being shared by the other coalition, which tends to reduce the total data rate of the other coalition.

Moreover, each sub-channel can be assigned to only one MD of the coalition and this sub-channel can be reused by the neighboring coalition. This reuse of sub-channel can create interference for the other MDs of the different coalitions.

Each MD has an ability to leave or connect with any of the FBS to maximize their own data rate. MDs in our model have only two directions either join coalition E or coalition F. MDs are allowed to dis-join their connection with any of the FBS based on their data rate requirements. Transmitters are accepted or rejected in coalition based on their rate requirement and impact of their participation in coalition on other members. If all transmitters are with same rate requirements, then resources can be distributed equally within the available resources. We assumed that rate requirement of transmitters are not same and for fair resource allocation among transmitters bankruptcy game is used.



(a) (b)

Figure 2 Cooperative game based system model

3.2 Strategies of the Coalitions

It is discussed in the previous section that MDs have ability to leave or join any coalition to get better data rate. Each coalition has its self-value which is dependent on the members of coalition e.g MDs. Increase or decrease in the MDs changes the self-value of the coalitions. However, our model consists of a fixed number of MDs and FBSs so the self-value of a coalition is totally dependent on its own coalition members and its neighboring coalition members. An increase in the number of MDs within the coalition tends to increase the self-value of the coalition; however the self-value of other coalition decreased. The actions of first coalition is the compliment action of second coalition, which is shown in Figure 2. These two coalitions acts as a two opposite players which are competing for resources depends on the weight of the coalition. Worth of each coalition depends on the number of MDs attached. Coalition E is the compliment of coalition F and vice versa. Bankruptcy game adapted in the next section to tackle the fair resource allocation among the collated members of the coalition.

The worth of each coalition is the maximum sum of payoffs that it can achieve for its members and also the minimizing factor from the other coalition as interfering power.

For characteristic function[18][22], coalition E

$$v_E = \max_{p_i} \sum_{l=1}^{N} R_{ie}$$

$$v_E = \min_{p_j} \sum_{l=1}^{N} R_{ie}$$

$$v_E = \max_{p_i} \min_{p_j} \sum_{i \in E} R_{ie}(p_{1,\ldots} p_{K-1,} p_{K,}) \tag{5}$$

$$p_i \in E, p_j \in F$$

$$s.t.\begin{cases} \sum_{l=1}^{N} p_i^l \le p_t \\ p_i^l \ge 0, \\ \alpha_{ie} \in \{0,1\} \\ \sum_{l=1}^{N} \alpha_i R_{ie} \le R_{i,min} \end{cases}$$

$$v_E = \sum_{i=1}^{E} \sum_{l=1}^{N} \log_2(1 + SIR_{ie}) \qquad (6)$$

Similarly, coalition F

$$v_F = \max_{p_i} \sum_{l=1}^{N} R_{if}$$

$$v_F = \min_{p_j} \sum_{l=1}^{N} R_{if}$$

$$v_F = \max_{p_i} \min_{p_j} \sum_{i \epsilon F} R_{i,f}\left(p_{1,\ldots\ldots}p_{K-1,}p_{K,}\right) \qquad (7)$$

$$p_i \epsilon F, p_j \epsilon E$$

$$s.t.\begin{cases} \sum_{l=1}^{N} p_i^l \le p_t \\ p_i^l \ge 0, \\ \alpha_{ie} \in \{0,1\} \\ \sum_{l=1}^{N} \alpha_i R_{if} \le R_{i,min} \end{cases}$$

$$v_F = \sum_{i=1}^{F} \sum_{l=1}^{N} \log_2(1 + SIR_{if}) \qquad (8)$$

■4.0 COALITIONAL GAME FORMATION

The objective of this resource allocation scheme is to guarantee the rate requirement of the machines in a fair manner. Each machine has different rate requirements and sub-carriers have different conditions. Coalition among the machines helps to achieve rate requirements of each machine.

4.1 Bankruptcy Game

This game is modeled as by the pair$(\mathcal{K}, v)$, where K is the set of MDs and v is a characteristic function of the game are also called self-value of the game. The self-value (v) depends upon the resources available to be distributed among the MDs. No MD can get more than it claimed or less than the minimum rate requirement and that the total resources are divided among the MDs. The data rate of each machine in a coalition is determined by the Shapley value, which provides a fair distribution of resources among the MDs of the coalition. The MDs with different data rate requirement will get their share as per its requirement and the resources available.

4.2 Self Value (v)

In [23] and our proposed model, v is a real valued function of the game satisfying the following conditions.

i. $v(\emptyset) = 0$

ii. Super-additivity, let E and F are two different coalition $(E \cap F = \emptyset)$, then $v(E) + v(F) \le v(E \cup F)$.

4.3 Shapley Value

In [24] [25], Shapley proposed a solution concept, known as the Shapley value φ, to assign a unique payoff value to each MD in the n- coalitional game.

$$\varphi_i(v_E) = \sum \frac{|E|!\,(|K| - |E| - 1)!}{|N|!}[v(E \cup \{i\}) - v(E)] \qquad (9)$$

$$\varphi_i(v_F) = \sum \frac{|F|!\,(|K| - |F| - 1)!}{|N|!}[v(F \cup \{i\}) - v(F)] \qquad (10)$$

4.4 Steps of Proposed Algorithm

1: FBS Set: $\mathcal{M} = \{1,2, \ldots \mathrm{M}\}$; MDs set per FBS are $\mathcal{K} = \{1, 2, \ldots, K\}$;
2: Initially allocate the same power to each sub-channel;
3: MDs in FBS e measures h_{ie} and in FBS f measures h_{if};
4: MDs under coverage of both FBS e and FBS f will measure both h_{ie} and h_{if};
4: Link with best SIR will be selected either under FBS e or FBS f;
5: MDs under FBS e and FBS f are called coalition E and coalition F respectively;
6: Calculate the self-value (v) of coalition based on the channel gain and the available power by using non-cooperative game theory as in Eq. 6 and Eq. 8
7: After self-value of coalition calculates payoff for the machines by using the bankruptcy game.
8: Shapley value can calculate the share of resources in a fair manner among the MDs of coalition E and coalition F through Eq. 9 and Eq. 10.
9: Calculation continues as new machine enters or leaves the coalition, which will affect the self-value of each coalition.

■5.0 NUMERICAL RESULTS

The Figure 3 shows the few cases of MDs behavior on the network. In which non-cooperative behavior of the MDs and also the cooperative behavior is shown. In greedy behavior MDs tried to maximize their own data rate without looking at the other members of the network, which tends to maximize the data of only the MD which is located near to the FBS while other MDs which located at far distances from the FBS suffer from the starvation. This allows MDs with good channels on certain sub-carriers to reserve those sub-carriers with probability one, thus depriving MDs worse channel from being allocated these sub-carriers. However, different cases e.g. case-1 and case-2 are the two different coalitions such as coalition E and coalition F with different coalition members. The MDs within the coalition want to maximize their data rate but cannot get more than their share as per

Shapley value in Eq. (9) and Eq. (10). The fair distribution of resources among MDs happened with different worth of coalitions. Furthermore, case-3 is a non-cooperative game theory solution in which all MDs to get as per Nash equilibrium instead of fair distribution of resources.

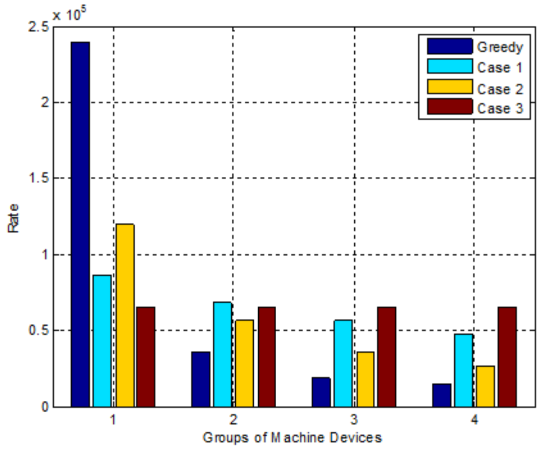


Figure 3 Rate achieved by the M2M devices under different conditions

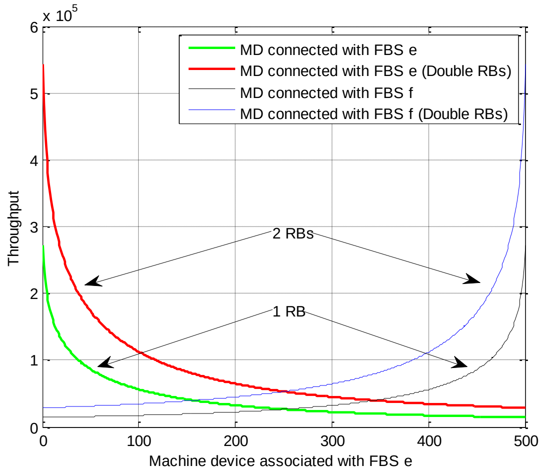


Figure 4 Performance of MDs connected under different FBSs and different RBs

In Figure 4 the performance of femto network is shown in terms of data rate and the MDs connected with the FBSs. The network performance is evaluated by increasing resource blocks and the MDs connected. It is observed that if all MDs join the same coalition under the same FBS it will eventually decrease the overall data rate which can be enhanced by introducing some new RBs. By introducing new coalition under different FBS can ease the load on the network.

■6.0 CONCLUSION AND FUTURE WORK

In this paper, we have adapted cooperative game to avoid the problem of resource allocation in M2M communication. Based on the cooperative game MDs can maximize their data rate upto to the limit allocated by coalition through Shapley value and if M2M devices still not getting as per its minimum threshold then it will defect from the connected coalition and can join the other coalition. The scheme helps to distribute the resources fairly among numbers of MDs.

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