Application-Aware Game Theoretic Pricing Algorithm for Cellular Machine-to-Machine Communications

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***Abstract*—Machine-to-machine (M2M) communications has emerged as a key enabler of the internet of things (IoT) paradigm. One of the key objectives of 5G is to provide improved support for M2M or IoT applications with diverse service and traffic characteristics. In this paper, we present an application aware game theoretic resource allocation algorithm to solve the capacity maximization problem in the uplink of a two-tier OFDMA based network with coexisting machine type communications devices (MTCDs) and conventional human type communications user equipments (HTC UEs). To mitigate the interference caused on the macro tier by the MTCDs deployed in the femtocells, we introduce an application aware pricing scheme based on the traffic characteristics of the M2M applications which discourages the exhibition of selfish or greedy behaviour. Finally, the simulation results showed that the proposed algorithm outperforms the existing algorithms in terms of overall achievable capacity, fairness and convergence speed as more users are added to the network.**

Keywords machine-to-machine communications, non-cooperative game theory, pricing

I. Introduction

The demand for mobile data traffic continues to increase exponentially due to the proliferation of connected mobile devices and data hungry mobile applications [1]. Cisco's Visual Networking Index (VNI) [2] predicted that the global mobile traffic will experience a sevenfold increase from 2016 to 2021 and that 3.3 billion machine-to-machine (M2M) connections will account for 34% of this explosive growth. One of the revolutionary feature of the Internet of Things (IoT) is the ability to connect smart devices endowed with certain sensing, automation and computing capabilities. M2M communication or machine type communication (MTC) is regarded as one of the IoT enabling technologies [3]. MTCs involves the enabling of ubiquitous connectivity and interaction over the telecommunication networks amongst MTC devices (MTCDs) without or with limited assistance from humans [4], [5]. MTC is characterised by uplink centric traffic, low powered and periodically generated transmissions of small data packet size. The application of M2M technology is noticeable in the provision of cutting-edge solutions in diverse areas such as smart metering, smart cities, e-health, security, manufacturing, transportation and consumer goods [6], [7].

Traditional cellular architectures are designed to support human type communication user equipments (HTC UEs), hence the diverse requirements of MTC poses a lot of challenges such as data rate, energy consumption, quality of service (QoS), traffic congestion, security and privacy on the network [3], [8]. MTC is mostly deployed in an indoor environment where small cells such as femtocells have been widely used to provide improved coverage and capacity. The dense deployment of MTCDs will cause uplink interference in an HTC coexistence network when all the devices are active simultaneously. Ensuring that scarce radio resources are fairly distributed to the network entities (MTCDs and HTC UEs) is another problem to be addressed in resource allocation. Fairness is a measure of evaluating the allocation of resources so that the network entity receives adequate portion of the available radio resources.

A lot of scholarly work has been done on interference mitigation and power control in cellular networks [9]–[14]. In [5], a non-orthogonal optimal power allocation algorithm was proposed to minimize the energy consumption in delay-constraint MTC enabled cellular network, but the authors did not consider the cross tier interference and power constraints on the devices in solving their convex optimization problem. Authors in [9] proposed a distributed power allocation algorithm with differentiated pricing but the use case for heterogeneous M2M applications with diverse QoS and traffic characteristics was not considered. While in [10], an energy efficient resource allocation algorithm was proposed for non-orthogonal multiple access (NOMA) and time division multiple access (TDMA) schemes. The authors however did not consider fairness among users and the constraint for fixed number of devices associated to an MTC gateway. Authors in [15] proposed a Stackelberg pricing game theoretic model to jointly maximize the capacity of the macrocell and femtocell users but the pricing is modelled solely on the interference caused by each user.

In this paper, we investigate the uplink resource allocation in an OFDMA-based two-tier heterogeneous cellular network with coexisting M2M/H2M communications. A non-cooperative game theory based approach was formulated to maximize the overall capacity of all the MTCDs while ensuring optimal use of allocated radio resources.

The main contributions of this paper can be summarized as follows: (i) utilize non-cooperative game to analyze the uplink power allocation with dynamic pricing in a femtocell deployed heterogeneous network with coexisting M2M/H2H communication (ii) propose a novel pricing algorithm based on the traffic demand and characteristics of the MTC devices.

- We investigate the uplink resource allocation in an OFDMA-based two-tier heterogeneous cellular network with coexisting M2M/H2M communications
- We formulated the capacity maximization problem as a joint application characteristics and interference based pricing game.

The remainder of the paper is outlined as follows: section II describes the system model and problem formulation. In Section III, a QoS-aware heuristic algorithm is proposed. In section IV, simulation results are presented to evaluate the performance of the proposed algorithm. Lastly, the conclusion is presented in Section V.

II. System Model and Problem Formulation

A. System Model

In LTE-A networks, the minimum scheduling unit of radio resources is referred to as the resource blocks (RBs). It is made up of 12 consecutive subchannels (each having a bandwidth of 15 kHz) in the frequency domain over the transmission time interval (TTI) made up of two slots with a slot duration of 0.5 ms [5].

Consider an uplink femtocell enabled OFDMA network with coexisting M2M and H2H users as shown in Fig. 1. We denote the set of underlying femto access points (FAPs), HTC UEs and MTCDs by $\mathcal{F} \triangleq \{1,\cdots f \cdots, F\}$, $\mathcal{H} \triangleq \{1,\cdots h \cdots, H\}$ and $\mathcal{M} \triangleq \{1,\cdots m \cdots, M\}$ respectively. We assume that the FAPs are deployed to support M2M services and there are M MTCDs associated to each FAP. The macro-users are the traditional HTC UEs associated to the macrocell or macro base station (MBS) and the set of available orthogonal (RBs) is denoted by $\mathcal{R} \triangleq \{1,\cdots r \cdots, R\}$.

The following assumptions have been adopted for the sake of simplicity:

1) The FAPs and all users in the network (HTC UEs and MTCDs) are randomly located within the coverage areas of the MBS and FAPs respectively.
2) The location of all network entities (MBS, FAPs, HTC UEs and MTCDs) are known.
3) The MTCDs run different applications, hence their payloads and characteristics are different.
4) The same number of MTCDs are associated per FAP.
5) Since the FAPs are independently deployed by the network users, a fully distributed resource allocation is considered due to the high cost of hardware and complexity involved in the deployment of a central FAP controller.

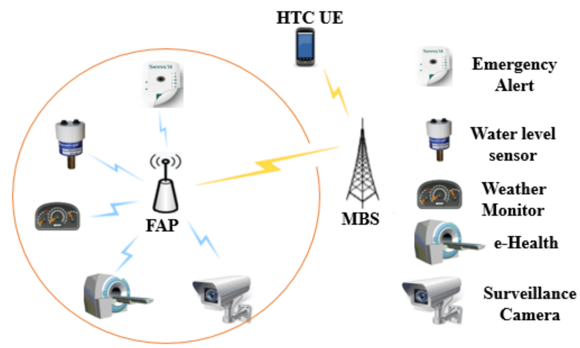

Fig. 1. System model

We denote $g^r_{m,f}$ and $g^r_{h,0}$ as the channel gain from MTCD m to the FAP f and the channel gain from HTC UE h to the MBS respectively. $P^r_{m,f}$ and and $P^r_{h,0}$ are the transmission powers of MTCD m over RB r in FAP f and HTC UE h associated to the MBS. The received signal to interference plus noise ratio (SINR) for any arbitrary MTCD $m \in M$ on the rth subchannel of the fth FAP is given by

$$\gamma^r_{m,f} = \frac{P^r_{m,f} g^r_{m,f}}{I^r_{m',f'} + I^r_{h,0} + \sigma^2} \tag{1}$$

where $I^r_{m',f'} = \sum\limits_{(m,f)\neq(m',f')}^{(M,F)} P^r_{m',f'} g^r_{m',f'}$ is the interference caused by other co-tier FAPs; $I^r_{h,0} = P^r_{h,0} g^r_{h,0}$ is the cross-tier interference caused by the macrocell and $\sigma^2 = N_o B_{RB}$ is the variance of the additive white gaussian noise power.

Similarly, the received SINR of the macrouser h is given by

$$\gamma^r_{h,0} = \frac{P^r_{h,0} g^r_{h,0}}{\sum\limits_{f=1}^{F} \sum\limits_{m=1}^{M} P^r_{m,f} g^r_{m,f} + \sigma^2} \tag{2}$$

The achievable data rate over RB r for any arbitrary MTCD $m \in M$ and HTC UE is represented in (3) and (4) respectively as

$$C^r_{m,f} = B_{RB} \log_2 \left(1 + \gamma^r_{m,f}\right) \tag{3}$$

$$C^r_{h,0} = B_{RB} \log_2 \left(1 + \gamma^r_{h,0}\right) \tag{4}$$

Assuming that the payload of an MTCD is $L_{m,f}$ (measured in $bits/TTI$), we define the time duration (T) of a TTI as the time required to transmit L bits from the MTCDs to their associated FAPs. Therefore, the delay experienced by the MTCDs is given by [5]

$$T = \frac{L_{m,f}}{C^r_{m,f}} \tag{5}$$

B. Problem Formulation

Our main target is to maximize the total capacity of the MTCDs in the F FAPs while satisfying their individual delay constraints under the influence of the macrocell interference.

$$\begin{aligned} &\text{maximize} && \sum_{f=1}^{F}\sum_{m=1}^{M} \alpha_{m,f}^{r} C_{m,f}^{r}, \forall r \\ &\text{subject to} && \\ &\text{C1} && \alpha_{m,f}^{r} C_{m,f}^{r} \geq L_{m,f}/T, \forall m \\ &\text{C2} && 0 \leq P_{m,f}^{r} \leq P_{m,max}, \forall m, f \\ &\text{C3} && \sum_{m=1}^{M} \alpha_{m,f}^{r} \in \{0,1\}, \forall f, r \end{aligned} \tag{6}$$

where the constraint $C1$ represent the delay constraint of the MTCDs, and $C2$ ensures that the transmit power allocated to each MTCD is non-negative and the total transmit power of all the MTCDs in the network is not more than $P_{m,max}$, while $C3$ ensures that only one RB is allocated per MTCD.

C. Application-Aware Pricing Game Formulation

Here we proposed an application-aware pricing game (AAPG) for the two-tier network based on the interference caused on the macrocell. The pricing coefficient is expressed as a function of the priority factor of the M2M applications, so as to discourage the MTCDs from selfishly requesting for resources by prompting MTCDs with lesser priority to pay a higher price for the resource demanded. A non-cooperative AAPG is formulated as follows $G = \langle \mathcal{M}, \{\mathbf{P_m}\}, \mathbf{U_m} \rangle$ where

- Players: The set of all MTCDs $\mathcal{M}$
- Strategies: Set of MTCD's power allocation strategy $\mathbf{P_m} = \{P_{1,f}^{r}, P_{2,f}^{r}, \cdots P_{m,f}^{r} \cdots P_{M,F}^{r}\}$
- Utility: Each MTCD m maximizes its individual utility function as follows

$$U_m(P_m, \mathbf{P_{-m}}) = C_{m,f}^{r} - c_m(P_m, \mathbf{P_{-m}}) \tag{7}$$

where $\mathbf{P_{-m}}$ represent the set of transmission power of all the other MTCDs except m and the pricing function for mitigating cross-tier interference to the macro users is set as

$$c_m(P_m, \mathbf{P_{-m}}) = \frac{1}{\kappa_m} \frac{P_{m,f}^{r} g_{m,0}}{I_{m',f'}^{r} + \sigma^2} \tag{8}$$

The solution of the proposed AAPG is the Nash Equilibrium (NE), which ensures that the player $m \in \mathcal{M}$ does not transmit with a power other than the allocated power. Thus, no player can unilaterally alter their allocated power to improve their utility. Thus, the condition satisfied by the NE is defined as:

$$U_m(P_m^{*}, \mathbf{P_{-m}^{*}}) \geqslant U_m(P_m, \mathbf{P_{-m}^{*}}) \tag{9}$$

where the best power allocation is represented by the NE of the player $m \in \mathcal{M}$ and is achieved by equating the derivative of (7) to zero as shown below

$$\begin{aligned} &\frac{\partial U_m}{\partial P_{m,f}^{r}} = \\ &\frac{B_{RB}}{\ln 2}\left[\frac{g_{m,f}^{r}}{P_{h,0}^{r} g_{h,0}^{r} + \sum_{f=1}^{F}\sum_{m=1}^{M} P_{m',f'}^{r} g_{m',f'}^{r} + \sigma^2 + P_{m,f}^{r} g_{m,f}^{r}}\right] \\ &- \frac{1}{\kappa_m} \frac{g_{m,0}}{\sum_{(m,f)\neq(m',f')}^{(M,F)} P_{m',f'}^{r} g_{m',f'}^{r}} \end{aligned} \tag{10}$$

By equating (10) to zero, the optimal power allocated to an MTCD $m \in \mathcal{M}$ in FAP f at RB r is expressed as

$$\begin{aligned} {P^{*}}_{m,f}^{r} = &\Bigg[\kappa_m \frac{B_{RB}}{\ln 2} \frac{\sum_{(m,f)\neq(m',f')}^{(M,F)} P_{m',f'}^{r} g_{m',f'}^{r}}{g_{m,0} g_{m,f}^{r}} \\ &- \left(\frac{P_{h,0}^{r} g_{h,0}^{r} + \sum_{f=1}^{F}\sum_{m=1}^{M} P_{m',f'}^{r} g_{m',f'}^{r} + \sigma^2}{(g_{m,f}^{r})^2}\right)\Bigg]_{0}^{P_{m,max}} \end{aligned} \tag{11}$$

The set of optimal NE transmitting power for the MTCDs is $\mathbf{P_m^{*}} = \{{P^{*}}_{1,f}^{r}, {P^{*}}_{2,f}^{r}, \cdots {P^{*}}_{m,f}^{r} \cdots {P^{*}}_{M,F}^{r}\}$. Taking the second derivative of (7), we obtain

$$\frac{\partial^2 U_m}{{\partial P_{m,f}^{r}}^2} = -\frac{B_{RB}}{\ln 2}\left[\frac{g_{m,f}^{r}}{I_{m',f'}^{r} + I_{h,0}^{r} + \sigma^2 + P_{m,f}^{r} g_{m,f}^{r}}\right]^2 \leq 0 \tag{12}$$

It can be seen that U_m is quasi-concave since (12) is negative. The existence and uniqueness of the NE for the non-cooperative pricing game has previously been proven in [9], [16].

III. Proposed Algorithm

Algorithm 1 Application-aware resource allocation algorithm

1: Initialize the set of FAPs: $f = \{1, 2, \cdots, F\}$;
Set of MTCDs: $m = \{1, 2, \cdots, M\}$;
Set of HTC UEs: $h = \{1, 2, \cdots, H\}$;
Set of RBs: $r = \{1, 2, \cdots, R\}$;
2: for each FAP, compute the SINR of each associated MTCDs $m \in M$ according to (1);
3: Each FAP computes the price to be paid by each MTCDs according to (8);
4: Compute the optimal transmission power for each MTCDs according to (11)
5: Calculate the achievable data rate for each MTCD according to (3)
6: repeat steps 3,4 and 5 until convergence
7: end

IV. Simulation Results and Analysis

In this section, we provide several simulation results to evaluate the performance of the proposed application aware pricing game algorithm, as compared with the non-cooperative

TABLE I
M2M DEVICE CONFIGURATION

MTC Application	Size of payload (Byte per TTI)	Priority (κ_m)
e-Health (ECG)	20	0.8
Emergency Alerting	32	1
Water level sensor	64	0.5
Weather Monitoring	128	0.7
Surveillance Camera	512	0.3

power allocation (NPAG) algorithm in [9]. The uplink of a two-tier OFDMA network is considered for simulation in Fig. 2. We set the number of MTCDs per FAP to 5, with each MTCD running different M2M applications as shown in Table I. The radius of the MBS and FAP is set as 500 m and 60 m respectively. Also, the maximum transmit power of HTC UEs and MTCDs is set as 20 dBm and 30 dBm respectively. The rest of the simulation parameters are given in Table II.

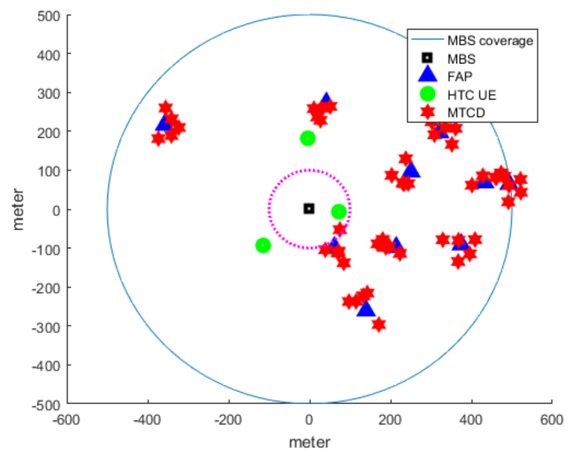

Fig. 2. Topology of the simulated network

TABLE II
SIMULATION PARAMETERS

System Parameters	Values
Subcarrier bandwidth	180 kHz
Number of MTCDS per FAP	5
Number of FAP	$1-10$
Maximum power of MTCDs	20 dBm
Maximum power of HTC UE	30 dBm
Noise spectral density	-174 dBm/Hz
Pathloss exponent	4
Pathloss (MTCD to FAP)	$127 + 30\log_{10} d$ where d is the distance in km
Pathloss (HTC UE to MBS)	$128.1 + 37.6\log_{10} d$

Fig. 3 shows the overall capacity of the FAP system of the proposed AAPG algorithm compared with existing NPAG algorithm in [9] and price based resource allocation algorithm in [15]. The application aware pricing scheme is employed to mitigate the co-tier interference as the number of FAPs is increasing. It can be observed that the proposed algorithm

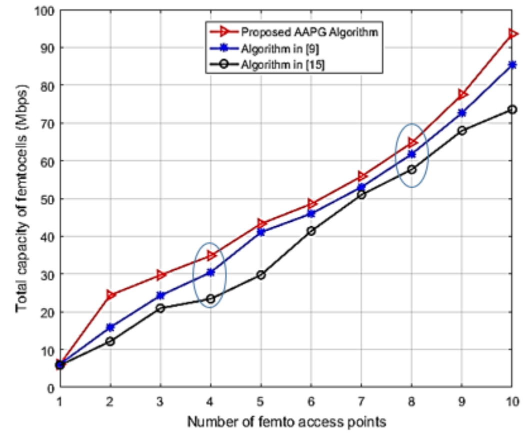

Fig. 3. Capacity of femto access points

outperform the existing algorithms leading to between $8-21\%$ in the capacity of the femtocell.

Fig. 4 shows the convergence of the proposed algorithm versus the algorithms in [9] and [15]. It can be observed that when the number of FAPs is set to 3, the proposed algorithm outperforms the other algorithms even though they all took 5 iterations to converge. As the number of FAPs is increased to 10, the proposed algorithm 8 iterations to converge, while the algorithms in [9] and [15] require 7 and 11 iterations to converge respectively.

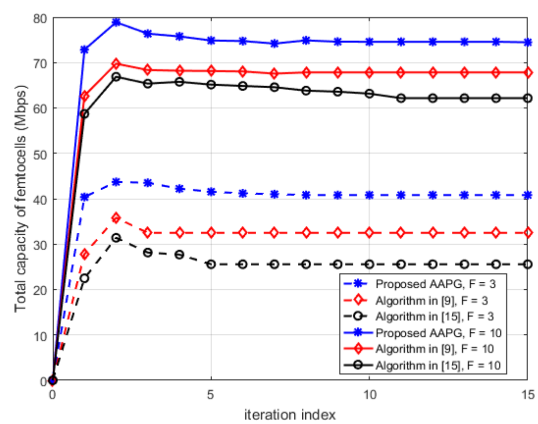

Fig. 4. Convergence of proposed algorithm

In Fig. 5, we compare the performance of the proposed AAPG and the other existing algorithms using the tiered fairness index (TFI) in [17], which evaluates the fairness between the macro and femto tiers. TFI is described as the measure of fair resource allocation between the macro and femto tiers; and it is given as

$$f_{FTI} = \frac{\left(H \sum_{h=1}^{H} C_{h,0}^{r} + F \sum_{f=1}^{F} \sum_{m=1}^{M} C_{m,f}^{r} \right)^{2}}{(H+FM)\left[\sum_{h=1}^{H} (HC_{h,0}^{r})^{2} + \sum_{f=1}^{F} \sum_{m=1}^{M} (MC_{m,f}^{r})^{2} \right]} \tag{13}$$

The results obtained for fairness ranges from 0 (worst case) to 1 (best case). We can see that as the number of FAP is increased from 1 to 10, the proposed algorithm achieves better fairness compared to the existing algorithms.

Fig. 6 show the overall data rate of each M2M applications in the network as the number of FAP is increasing. Surveillance camera application transmits 512 Byte of data per TTI and as expected, it achieves the highest data rate in the network. The overall capacity of each M2M application is a function of the size of the payload of the application.

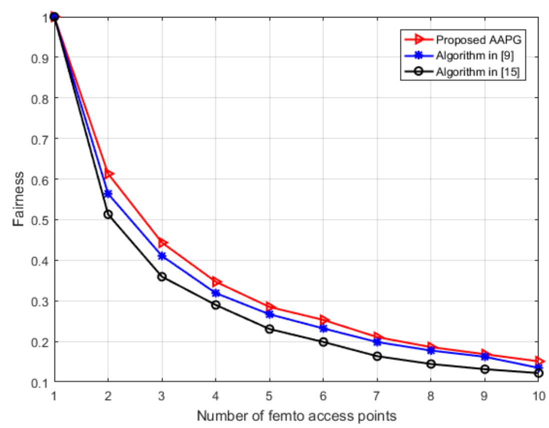

Fig. 5. Tiered fairness versus the number of femto access points

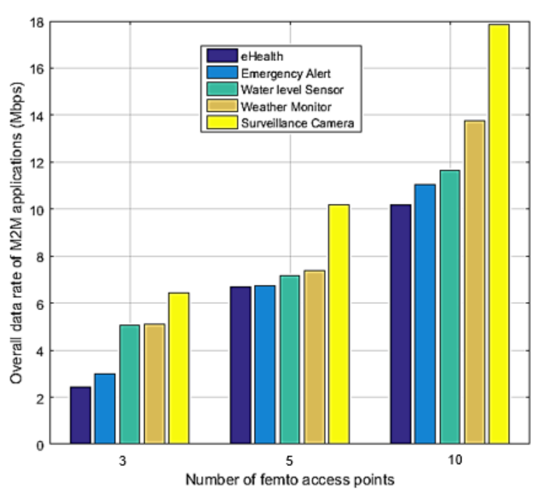

Fig. 6. Overall capacity of M2M applications in the network

V. Conclusion

In this paper, application-based resource allocation algorithm has been investigated. The capacity maximization problem was formulated as a non-cooperative game taking the transmit power and delay constraints into account. The application-aware pricing scheme mitigates the co-tier interference as more MTCDs are added to the network. The performance of the proposed algorithm against existing algorithm was compared in terms of capacity and tiered fairness. We also investigated the convergence speed of the proposed algorithm and the overall achievable data rates for each M2M applications in the network. Numerical results show that the proposed algorithm outperforms the existing algorithms in terms of the overall capacity, convergence and fairness in the allocation of the resource blocks.

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