Energy-Aware Waiting-Line Based Resource Allocation in Cellular Network with M2M/H2H Co-existence

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***Abstract*—Since Machine-to-Machine (M2M) communications is going to be realized in advanced cellular networks, the resource allocation scheme should be re-examined to satisfy both traditional Human-to-Human (H2H) communications (e.g., voice calls) and M2M communications. Because most M2M applications are delay-tolerant and uplink-dominated, we propose a waiting-line based uplink resource allocation framework in the M2M/H2H co-existence scenario. The proposed scheme guarantees resources for H2H communications while meeting the needs of M2M communications on a first-come first-served basis. In addition, the scheme ensures the existence and uniqueness of the Bayesian Nash equilibrium and the truth-telling property. Results show that M2M devices with lower energy opportunity cost are more willing to participate in the waiting-line based scheme, and the delay in the connected mode varies according to the H2H traffic load and the total number of competitors. However, M2M devices with higher energy opportunity cost may not join this time bid resource allocation scheme. This work contributes insights into the types of resource allocation schemes, bidding with time or bidding with money, for M2M devices with different levels of energy awareness.**

I. Introduction

M2M communications allows a huge amount of autonomous devices to communicate wirelessly with each other or with a gateway, without human intervention. The applications of M2M communications differ from those of traditional H2H communications. One feature of M2M is the diversity of services and applications, such as water/gas metering systems, aquatic environmental monitoring, healthcare, and emergency alerts. M2M traffic is mostly delay-tolerant, whereas voice traffic and web browsing in H2H communications are comparatively delay-sensitive. Due to the increasing diversity of applications of M2M communications, a new M2M-oriented Quality-of-Service (QoS) categorization with eight classes in the cellular network is proposed in [1] to cover both traditional H2H services and varied M2M services in terms of real-time, accuracy, and priority. Another consideration is that the traffic types of M2M communications are predominantly uplink-oriented, whereas those of H2H communications are asymmetrically downlink.

One of the ways M2M devices connect to the core network is by being equipped with cellular capability, called *Cellular M2M* [2]. For example, the 3^{rd} Generation Partnership Project (3GPP) has devoted efforts to standardizing LTE-A (Long Term Evolution-Advanced) to realize M2M communications, a.k.a. Machine-Type communications (MTC), through infrastructure-based access networks [3]. Since the majority of M2M traffic is uplink-based, the procedure to perform uplink transmission in cellular networks should be re-examined. In general, the devices stay in the idle mode to conserve energy if there is no queued uplink traffic. Once the uplink traffic arrives, the devices execute the network entry procedure in the control plane to acquire dedicate uplink resources. Therefore, the devices enter the connected mode and uplink data to the eNB without collision in the user plane. The well-known network entry procedure in LTE-A is the RACH (Random Access Channel) procedure. The four-message exchange steps in the RACH procedure are *Preamble Transmission*, *Random Access Response*, *Connection Request*, and *Connection Resolution*. Collision may occur in the *Preamble Transmission* step due to heavy M2M uplink traffic. Overload congestion control in the network entry procedure for M2M communications is investigated in [4]. Whether the RACH procedure is appropriate for M2M communications is comprehensively discussed in [2]. Most of the existing literature explores the suitability and modification of the network entry procedure to satisfy M2M features only, such as huge device number, frequent uplink random access, and delay-tolerant services.

The exhaustive investigation of cellular networks with M2M/H2H co-existence has attracted attention recently, especially the network entry procedure [5] [6]. The concept of the preamble resource pool partition in the network entry procedure for LTE network is proposed in [5]. One method is to split the preamble resource pool into two disjoint subsets for H2H and M2M preamble transmissions separately. The other method is to have a small subset of the overall preamble resource pool for both H2H and M2M preamble transmissions, and the remaining preamble resource pool is for H2H preamble transmissions only. Considering preamble transmission throughput as the performance metric, it is observed that the former method, with disjoint resource pool subsets, is preferred when the random access load is higher than a boundary threshold. Another preamble resource pool partition scheme is proposed in [6], wherein the complete resource pool is divided into three disjoint small pools: one for H2H only, another for M2M only, and the other for hybrid H2H/M2M usage. This scheme is formulated as a non-cooperative game wherein the Nash equilibrium represents the RACH contention resolution.

With the device number information estimated and broadcast by the eNB, all devices make decisions on the preamble transmission probability of each disjoint resource pool in a distributed manner so as to achieve the Nash equilibrium. So far, research on M2M/H2H co-existence has focused on the network entry procedure. Few researchers have investigated the impact of M2M/H2H co-existence on the user plane for dedicate data transmission.

Another important factor to consider in M2M communications is energy efficiency. M2M devices are expected to operate on their own for years because their deployment locations might be hard to access (e.g., desolate plains or deserts). As a result, the issues of battery lifetime extension and energy efficiency are particularly significant. Regarding uplink resource allocation with M2M/H2H co-existence in LTE networks, the energy efficiency is formulated as the bit-per-joule capacity maximization problem under statistical QoS guarantees in [7]. Due to intractability, the problem is transformed into a mixed integer programming problem and solved by an invasive weed optimization algorithm to find a near optimal solution. Different from [7], we model the cellular uplink transmission procedure via a waiting-line based resource allocation framework and study the M2M devices' energy-awareness property.

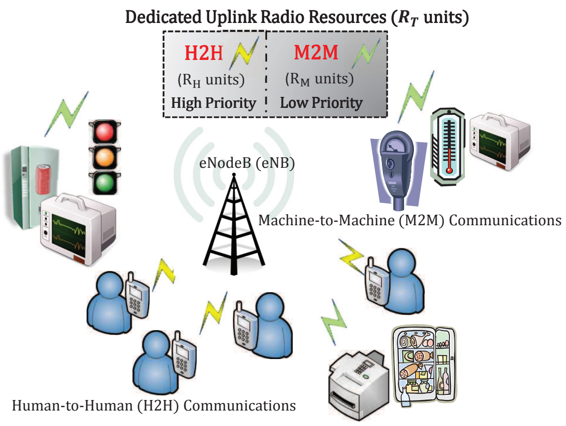

Fig. 1. Uplink cellular system with M2M/H2H co-existence scenario

In our work, we aim to explore the energy-awareness property of M2M devices when they use the same dedicated uplink resource pool as traditional H2H traffic in the cellular network, as shown in Fig. 1. We propose a waiting-line auction-based resource allocation framework to model the LTE uplink procedure from network entry to uplink data transmission. Unlike in most auctions, where players bid with money for scarce resources, a waiting-line auction allows players to bid with time [8]. This mechanism is adopted for dynamic spectrum allocation in cognitive radio networks [9], allowing users with poorer cognitive ability to access the spectrum with higher probability. The WiFi pricing system in [10] also adopts this mechanism to enhance WiFi throughput under certain conditions. With the waiting-line auction based framework, we contribute insights on the relationship among the energy opportunity cost, probability of resource accessibility, and delay for M2M devices. The energy opportunity cost is defined as the degree of importance that an M2M device attaches to the cost per energy unit. For an M2M device, a higher energy opportunity means that it must pay more attention to the cost per energy unit. We exploit the way that the energy awareness of M2M devices plays a key role in the M2M/H2H co-existence system, thereby impacting the system performance.

The rest of this paper is organized as follows. In Section II, we describe the system model. The equilibrium based on the waiting-line auction approach and its properties are derived in Section III. Evaluation results for the system characteristics are presented in Section IV. Section V concludes this work and proposes the future work.

II. System Model

We consider two types of wireless communication apparatuses, H2H devices and n M2M devices, sharing the total R_T units of dedicated uplink radio resources in the cellular network. H2H devices (e.g., smartphones), mainly intended for human-to-human activities such as real-time voice calls, are guaranteed higher priority to access the radio resources. Based on the scheduling requests made by H2H devices, the eNB allocates R_H units of resources to H2H communications first, and then distributes the remaining R_M units of resources to the M2M communications. Since the H2H traffic is mostly for real-time delay sensitive voice calls, R_H is modeled based on the arrival of voice calls, following $Poisson(\lambda)$. Due to the uncertainty about the remaining limited resources and the large number of M2M devices, it is necessary to design a resource allocation scheme for determining the winners among numerous competitors.

Here we propose an intuitive first-come first-served waiting-line approach for distributing the remaining deficient resources to numerous rational M2M devices. To perform uplink transmission, M2M devices in the cellular network should wake up from the idle mode and establish network connections via network entry procedures. Then, they wait in the connected mode until the eNB grants the uplink radio resources. That is, the eNB distributes resources according to the time that devices have spent waiting in the connected mode. For M2M devices, lining up early increases their probability of winning the resources. Though the first-come first-served waiting-line principle seems to guarantee fairness among M2M devices, the waiting time might increase their energy consumption.

Energy awareness is significantly important for M2M devices to perform energy related actions, such as whether to line up in the connected mode. Energy consumption is higher in the connected mode than in the idle mode. However, due to device heterogeneity, the degrees to which M2M devices prioritize energy can differ from device to device, and even from time to time. We model this property as energy opportunity cost w_i for device i, defined as the opportunity cost in terms of energy. A higher w_i value indicates that the device weights its energy condition more heavily in decision-making process. We assume that w_i follows Gaussian distribution with mean μ and variance s^2, $w_i \sim \mathcal{N}(\mu, s^2)$. Though this distribution is public information known to all M2M devices, the exact w_i value of each device is private information known only to device i itself.

We assume the network entry time of each device to be constant k units of time ($k > 0$) for simplicity because this work focuses on the probability of resource accessibility in M2M communications based on differences in energy opportunity cost and waiting time in the connected mode. Then the device i waits for t_i units of time ($t_i \geq 0$) in the connected mode until the eNB allocates the resources, which is the reward time. The reward time, determined by the eNB, is the information common to the cellular network. The utility function of obtaining one unit of resources, $v(w_i)$, is assumed to be a function of energy opportunity cost, continuously differentiable and positively valued. Considering M2M devices with similar applications, this function is equal and well known to all M2M devices. The waiting-line based resource allocation system is depicted in Fig. 2.

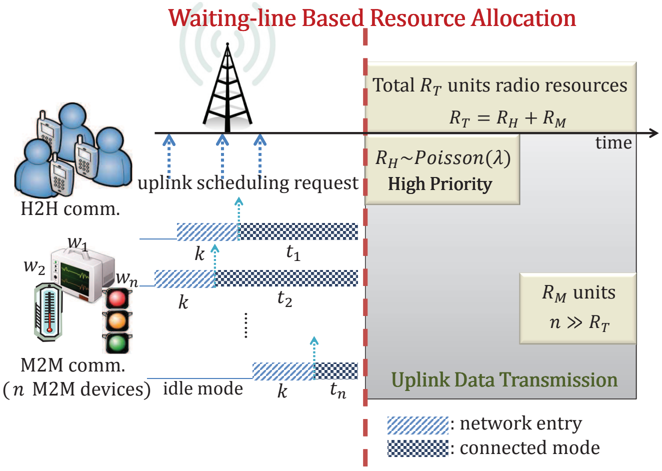

Fig. 2. A waiting-line based resource allocation framework

M2M devices can decide whether to participate in the waiting-line based resource allocation framework according to the queued uplink traffic and energy condition. If one decides not to participate, its payoff is assumed to be zero. If device i decides to participate in uplink data transmission, it has a probability of obtaining resources (i.e., resource accessibility probability P_i^w). The winner's payoff is $v(w_i) - w_i t_i - w_i k$, where $w_i t_i$ is the cost of staying in the connected mode and $w_i k$ is the cost of executing the network entry procedure. However, the device may also lose the auction with probability P_i^l due to limited resources and a high number of competitors ($n \gg R_T$). In this case, the loser's payoff is $-w_i t_i - w_i k$. From the perspective of a device i, it is best to choose the optimal waiting time in the connected mode (t_i) to maximize the expected payoff $E_i(t_i, t_{-i})$.

$$E_i(t_i, t_{-i}) = \big[v(w_i) - w_i t_i - w_i k\big] P_i^w + \big[-w_i t_i - w_i k\big] P_i^l$$

$$\begin{aligned} \underset{t_i}{\text{maximize}} \quad & E_i(t_i, t_{-i}) \\ \text{subject to} \quad & R_T = R_H + R_M, \text{where } R_H \sim Poisson(\lambda) \\ & t_i \geq 0, k > 0, n \geq R_M, i = 1, 2, 3, ...n \end{aligned}$$

The earlier the device begins waiting in the connected mode, the higher its probability of resource accessibility, albeit with the sacrifice of higher cost. The cost depends on both how long the device waits and how much importance the device attaches to its energy. The probability of resource accessibility also relies on the number of available resources and the number of competitors. We are interested in how the energy opportunity cost (i.e., degree of energy awareness) influences on this system.

III. Waiting-Line Auction Approach

In the proposed waiting-line based resource allocation scheme with M2M/H2H co-existence, the exact number of available resources, R_M, is unknown to the M2M devices. However, its probability mass function (PMF) can be derived by $R_M = h(R_H)$, where $R_H \sim Poisson(\lambda)$ in Eq. (1).

$$P_{R_M}(R_m) = \begin{cases} \sum\limits_{k=R_T}^{\infty} \dfrac{\lambda^k e^{-\lambda}}{k!} & R_m = 0 \\ \dfrac{\lambda^{(R_T - R_m)} e^{-\lambda}}{(R_T - R_m)!} & 1 \leq R_m \leq R_T \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

Because M2M devices bid with time for scarce resources, we denote the payoff profile in time units $\pi = (\pi^W, \pi^L)$, where the winner's payoff is π^W and the loser's payoff is π^L, found by dividing the original payoff by w_i. A new attribute $a_i = \frac{v(w_i)}{w_i}$ is defined as device i's utility in time units.

$$\pi^W = a_i - t_i - k$$
$$\pi^L = -t_i - k$$

The cumulative density function (CDF) of this attribute is denoted as $G_A(a_i)$, and its probability density function (PDF) as $g_A(a_i)$. Under the assumption that w_i for all devices i follows the same Gaussian distribution, a_i among all devices has the same distribution $G_A(a_i)$ as well. Therefore, we replace $G_A(a_i)$ with $G(a)$ and $g_A(a_i)$ with $g(a)$ for the sake of simplicity. The best response of an M2M device i is to decide the waiting duration t_i based on its private information a_i with the aim of maximizing the expected payoff in time units

$$E_i^t(t_i, t_{-i}) = P_i^w \pi^W + P_i^l \pi^L. \quad (2)$$

The equilibrium strategy function can be defined as $t_i = \sigma(a_i, a_{-i})$. With higher utility on a resource, the device is expected to line up earlier. The equilibrium strategy function must be a positive-valued, strictly increasing, and differentiable function.

This waiting-line auction approach forms a Bayesian game, where n players with their own private attributes compete for uncertain amount of limited resources. The distribution of the resources and the distribution of the attributes are common knowledge to all players. The Bayesian Nash equilibrium is characterized by (i) a condition under which MTC devices decide to participate, and (ii) an equilibrium strategy function $\sigma(a_i, a_{-i})$.

First, we consider the probability of resource accessibility; i.e., the probability that a device can gain the resource if it lines up. Since M2M communications feature a great number of devices, we assume the number of bidders waiting in line is always greater than the number of available resources. Upon the moment of resource allocation, the eNB sorts all t_i in descending order, $t_{(1)} \geq t_{(2)} \geq t_{(3)} ... \geq t_{(n)}$. The devices with t_i greater than $t_{(R_M)}$ win resources. Recall that the strategy function $\sigma(a_i, a_{-i})$ is strictly increasing. Given R_M resources, the bidder wins the resource if its attribute a_i is greater than the R_M^{th}-largest attribute among other $n-1$ competitors, $a_{(R_M)}$. That is, the winning probability given R_M resources is $G_{(R_M)}(a_i)= P(a_{(R_M)} \leq a_i)$, the ${R_M}^{th}$ order statistic of the utility in time units on a resource.

$$G_{(R_M)}(a_i) = \sum_{m=0}^{R_M-1} \binom{n-1}{m} [1-G(a_i)]^m [G(a_i)]^{n-1-m}.$$

Due to the symmetry property of this auction, the resource accessibility probability should be equivalent for all devices; i.e., $P_i^w = P^w$. The derivation of P_w is shown in Eq. (3).

$$\begin{aligned} P^w &= \sum_{R_m=1}^{R_T} \text{P(win}|R_M \text{ resources)} \times \text{P}(R_M = R_m) \\ &= \sum_{R_m=1}^{R_T} G_{(R_m)}(a_i) \times P_{R_M}(R_m) \\ &= F(a_i) \end{aligned} \quad (3)$$

Eq. (3) implies that different time-valued utility on a resource results in varying probability of resource accessibility. $f(a_i)$ is the probability density function of $F(a_i)$.

Next, we consider the condition when a device participates in the auction. The fixed non-negative time cost spent on the network entry procedure, k, may discourage a rational device with a small value a^* from joining the auction. The time-valued utility of a resource, a^*, is so small that device i would be indifferent between being awarded with zero time spent in the connected mode ($t_i = 0$) and no participation at all.

$$a^* F(a^*) - k = 0 \quad (4)$$

The value of a^* determines whether an M2M device wakes up from the idle mode and participates in the waiting-line based resource allocation. A device i with $a_i > a^*$ is willing to participate, and one with $a_i < a^*$ is not.

The Bayesian Nash equilibrium is characterized by (i) the cutoff time-valued utility of a resource, a^*, determined in Eq. (4), and (ii) the equilibrium strategy function $\sigma(a_i, a_{-i})$. According to Eq. (9) in [8], the equilibrium strategy function should satisfy a first order differential equation, which can be expressed as Eq. (5).

$$\sigma'(a_i, a_{-i}) = \sigma'(a_i) = a_i f(a_i), \; a_i > a^* \quad (5)$$

We know that device i with private attribute a_i slightly greater than the cutoff value a^* would be willing to participate but would only wait for an extremely short time. This observation gives the initial condition for Eq. (5) as follows:

$$\lim_{a_i \to {a^*}^+} \sigma(a_i) = 0 \quad (6)$$

Thus, the specific equilibrium strategy function can be derived from Eq. (7).

$$t_i = \sigma(a_i) = \int_{a^*}^{a} \sigma'(y) dy = \int_{a^*}^{a} y f(y) dy \quad (7)$$

Next we show three properties of the waiting-line based resource allocation framework: existence, uniqueness, and truth-telling.

Proposition 1. *The Bayesian Nash equilibrium of the waiting-line based resource allocation framework exists. The equilibrium strategy function $t_i = \sigma(a_i)$ in Eq. (7) for all devices i is a Nash equilibrium.*

TABLE I. MATHEMATICAL NOTATIONS AND DEFINITION

Notation	Definition
n	Total M2M device number
R_T	Total units of dedicate uplink resources
R_H	Dedicate uplink resources allocated for H2H communications $R_H \sim Poisson(\lambda)$
R_M	Dedicate uplink resources allocated for M2M communications $R_M = h(R_H) = R_T - R_H$
w_i	Energy opportunity cost of M2M device i W follows Gaussian distribution $W \sim N(\mu, s^2)$
k	Network entry time
t_i	Waiting time in the connected mode of M2M device i
$t_{(j)}$	The j^{th}-largest waiting time among all M2M devices
$v(w_i)$	Utility function of obtaining a unit of resource
π^W	The winner's payoff in time units
π^L	The loser's payoff in time units
a_i	Time-valued utility on a unit of resource for M2M device i
$a_{(j)}$	The j^{th}-largest time-valued utility on a unit of resource among all M2M devices
$G_A(a)$	Cumulative distribution function of random variable A
$G_{(j)}(a)$	Cumulative distribution function for the order statistic of rank j among $n-1$ independent drawings from the CDF $G_A(a)$
$F(a_i)$, P_i^w	The resource accessibility probability of M2M device i
$f(a_i)$	Probability density function of $F(a_i)$
$\sigma(a_i, a_{-i})$	Equilibrium strategy function
a^*	The condition that determines an M2M device to participate in waiting-line process or not

Proof: The time-valued expected payoff of device i in Eq. (2) by following the equilibrium strategy function is

$$\begin{aligned} E_i^t\{\pi(\sigma(a_i), a_i)\} &= F(a_i)\pi^W + (1 - F(a_i))\pi^L \\ &= a_i F(a_i) - \int_{a^*}^{a_i} y f(y) dy - k \end{aligned} \quad (8)$$

Then, we consider device i, deviating from the equilibrium strategy function, would rather wait in the connected mode with time T instead of $\sigma(a_i)$. Since $\sigma(\cdot)$ is a monotonic increasing function, there exists a unique reverse function $\sigma^{-1}(\cdot)$, which determines the fraudulent time-valued utility $a_i' = \sigma^{-1}(T)$. The time-valued expected payoff with deviation is

$$\begin{aligned} &E_i^t\{\pi(T, a_i)\} = a_i F(\sigma^{-1}(T)) - \int_{a^*}^{\sigma^{-1}(T)} y f(y) dy - k \\ &\text{, where } T = \int_{a^*}^{\sigma^{-1}(T)} y f(y) dy \end{aligned} \quad (9)$$

Comparing the difference between the expected payoff of applying the equilibrium strategy function $\sigma(a_i)$ and deviation with T in Eq. (10), we aim to explain the existence of the Bayesian Nash equilibrium.

$$\begin{aligned} &E_i^t\{\pi(\sigma(a_i), a_i)\} - E_i^t\{\pi(T, a_i)\} \\ &= \left(a_i F(a_i) - \int_{a^*}^{a_i} y f(y) dy \right) \\ &\qquad - \left(a_i F(\sigma^{-1}(T)) - \int_{a^*}^{\sigma^{-1}(T)} y f(y) dy \right) \\ &= a_i \left(\int_{\sigma^{-1}(T)}^{a_i} f(y) dy \right) - \int_{\sigma^{-1}(T)}^{a_i} y f(y) dy \\ &= a_i \left(\int_{\sigma^{-1}(T)}^{a_i} (1 - \frac{y}{a_i}) f(y) dy \right) \end{aligned} \quad (10)$$

Since the time-valued attribute a_i is always positive, we need to justify the result of Eq. (10) is always positive in two cases: (i) $T > \sigma(a_i)$ and (ii) $T < \sigma(a_i)$, so that the Bayesian Nash equilibrium exists. In case (i), $\sigma^{-1}(T) > a_i$ holds because $\sigma(\cdot)$ is a strictly increasing function. Taking the integral range into consideration, we observed that $\frac{y}{a_i} \geq 1$. The integral part can be transformed into $\int_{a_i}^{\sigma^{-1}(T)} (\frac{y}{a_i} - 1) f(y) dy$, which is always positive. Similarly, $a_i > \sigma^{-1}(T)$ and $\frac{y}{a_i} \leq 1$ hold in the case (ii) so that the integral part is always positive. Thus, we have proved Eq. (10) always to be positive, meaning deviation from the equilibrium function $\sigma(\cdot)$ will not make device i better off. The Bayesian Nash equilibrium exists, and $\sigma(\cdot)$ is a Bayesian Nash equilibrium. ■

Proposition 2. *The Bayesian Nash equilibrium of the waiting-line based resource allocation framework is unique, meaning that the equilibrium strategy function $t_i = \sigma(a_i)$ in Eq. (7) applies for all devices i.*

Proof: Assume there exists another equilibrium waiting time strategy function $\varsigma(a_i)$ better than $\sigma(a_i)$ to reach Pareto improvement. Based on the relationship between affordable waiting time and the time-valued utility on the resource, $\varsigma(a_i)$ is a positive-valued, strictly increasing and differentiable function. Since it should satisfy the boundary condition in Eq. (5) whether to participate the waiting-line auction, $\varsigma(a_i)$ must have the similar structure as Eq. (7). However, $\varsigma(a_i) < \sigma(a_i)$ results in worse expected payoff as indicated in Eq. (10). By contradiction, $\varsigma(a_i)$ should not exist so that the unique Bayesian Nash equilibrium is $\sigma(a_i)$. ■

Proposition 3. *The truth-telling property is guaranteed in the waiting-line based resource allocation framework.*

Proof: Assume device i with the true time-valued utility on the resource a_i applies the equilibrium strategy $\sigma(a_i)$. However, if it lies the time-valued utility to be $\tilde{a}_i \neq a_i$, the waiting time will be $\tilde{t} \neq \sigma(a_i)$ by following the strictly increasing equilibrium strategy function. As shown in Eq. (10), the expected payoff will not be better off. Therefore, a rational device should apply the equilibrium strategy $\sigma(a_i)$ and honestly reveal its private time-valued utility a_i. ■

IV. Simulation Result

We implement the waiting-line based resource allocation framework on a MATLAB-based simulation platform. We not only verify the correctness of the mathematical model but also explore the properties of the system such as truth-telling, expected delay in the connected mode caused by different H2H traffic load, M2M device number, and the degree of energy awareness. The total amount of resources is assumed to be 50 units, for the total number of resource blocks in LTE with bandwidth 10 MHz is 50. We assume the M2M devices have homogeneous applications and set the utility of obtaining one unit of uplink resources $v(w_i) = 1$, indifferent to the energy opportunity cost. The energy opportunity cost follows Gaussian distribution with $\mu = 100$ and $s = 20$. The network entry time k is set to be 0.01 units.

First, we investigate the relationship between the energy awareness parameter of the M2M devices (i.e., the energy opportunity cost) and their waiting time in the Bayesian Nash equilibrium. In Fig. 3, when the number of M2M competitors increases, M2M devices with higher energy opportunity cost become less interested in the waiting-line based resource allocation scheme, whereas M2M devices with lower energy opportunity cost spend more time waiting in line to compete for the resources. Similar results can be found in Fig. 4. As the H2H traffic load increases, fewer resources remain for M2M communications. The threshold of the energy opportunity cost at which M2M devices are willing to participate decreases. This change implies that M2M devices with higher energy opportunity cost will not participate in this resource allocation scheme due to their stringent energy conditions, such as a low energy level or high difficulty of recharging energy storage devices. Both in Fig. 3 and Fig. 4, we verify the mathematical results match the simulation results well.

Then we explore the expected waiting time (delay) in the connected mode among all winners in Fig. 5. We observe that as the number of M2M devices increases, the expected waiting time in the connected mode rises given the same H2H traffic load. The reason is that the potential M2M winners with lower energy opportunity cost tends to increase their waiting time, as shown in Fig. 3, given the increasing total competitors and the same distribution of energy opportunity cost $N(\mu, s^2)$. Therefore, the expected waiting time of the fixed amount of winners tends to increase. In addition, when the H2H traffic load becomes heavy, the expected waiting time of the winners decreases due to the comparatively decreasing probability of resource accessibility and slightly longer waiting time. Furthermore, the variation of the waiting time increases

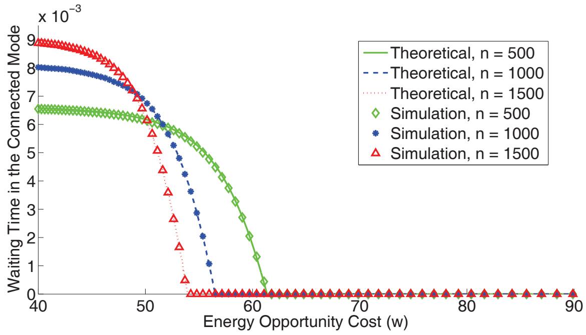

Fig. 3. Waiting time in the Bayesian Nash equilibrium vs. energy opportunity cost (w) in scenarios with different M2M device number (medium H2H traffic load $\lambda = 35$)

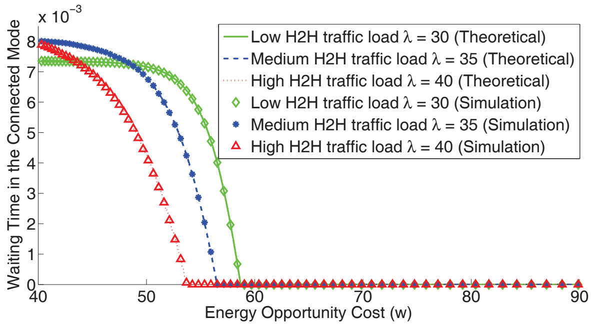

Fig. 4. Waiting time in the Bayesian Nash equilibrium vs. energy opportunity cost (w) in scenarios with different H2H traffic loads (M2M device number $n = 1000$)

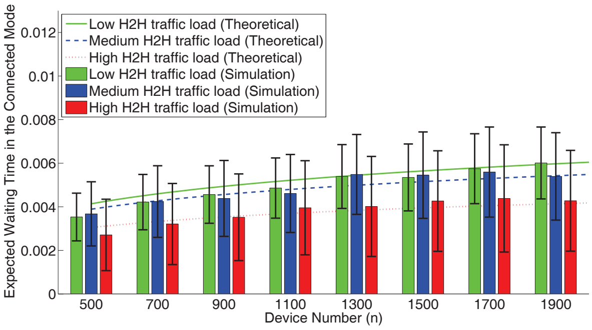

Fig. 5. Expected waiting time (delay) in the connected mode vs. M2M device number under high/medium/low H2H traffic load scenarios with $\lambda = (30, 35, 40)$ respectively

when the M2M resources become more scarcer due to the higher H2H traffic load.

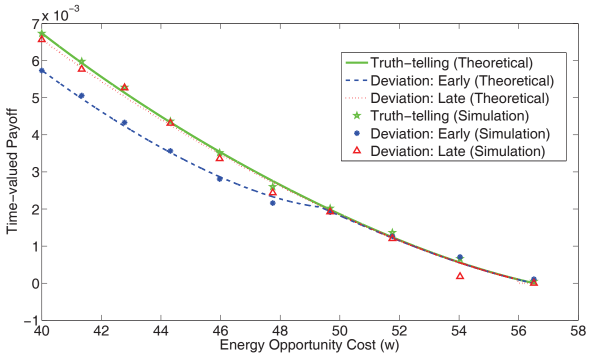

Fig. 6. Time-valued payoff vs. energy opportunity cost (w) with different strategies: truth-telling, deviation with early arrival in line, and deviation with late arrival in line (M2M device number $n = 1000$, medium H2H traffic load $\lambda = 35$)

The truth-telling property of the waiting-line based resource allocation scheme is guaranteed, as mentioned in Proposition 3. We observe that the expected payoff of deviation from the Bayesian Nash equilibrium is worse whether the M2M device arrives earlier or later in the connected mode. If it arrives earlier, the probability of resource accessibility increases with the sacrifice of the increasing waiting time cost. If it arrives later, its waiting time cost decreases with the sacrifice of the lower probability of resource accessibility, and it still devotes a fixed amount of entry cost. Therefore, truly revealing the private value is the optimal strategy in the waiting-line based resource allocation scheme.

We see from Fig. 3 and 4 that the operator can design a resource guarantee pricing scheme for M2M devices with higher energy opportunity cost. Since those devices are not willing to spend time waiting, they can directly compensate the operator financially for direct resource access. Moreover, the pricing scheme should be dynamic, considering different M2M device numbers and H2H traffic loads in the system. When the number of M2M devices rises or the H2H traffic load increases in certain situations, the range of energy opportunity cost within which M2M devices will not participate in the auction expands. Therefore, the charges to the M2M devices for direct resource access can be higher, since more M2M devices will turn to the resource allocation scheme based on money instead of the auction with time bids. We plan to extend research on the pricing scheme for M2M devices with higher energy opportunity cost in the future work.

V. Conclusion

In this work, we design a waiting-line based uplink resource allocation scheme for the M2M/H2H co-existence scenario in a cellular network. H2H communications is ensured certain resources, whereas M2M communications is served with the remaining resources in a first-come first-served manner. The existence and uniqueness of the Bayesian Nash equilibrium, and the truth-telling property are guaranteed. We observe that the willingness to participate in the waiting-line based resource allocation scheme depends on the energy awareness of the M2M devices, the H2H traffic load, and the total number of M2M devices. The scheme with time bidding is especially suitable for M2M devices with lower energy opportunity cost. In other words, we obtain insights for the operator into a pricing-based resource allocation scheme for M2M devices with higher energy opportunity cost. Furthermore, the pricing can be dynamic based on variations in H2H traffic load and the level of energy-awareness of M2M devices.

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