Spectrum Sharing and Power Allocation Analysis in Machine to Machine Network

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Abstract
This paper addresses the problem of spectrum sharing and power allocation in M2M network, in which a licensee and multiple unlicensed M2M devices coexist and operate in the licensed channel in a local area. We develop a connectivity establishment mechanism in M2M network based on the cognitive radio technology, and derive the overall average probabilities of detection and false alarm by taking the location of M2M devices into account and employing the energy detection as the underlying detection scheme. Furthermore, we also propose an optimal power allocation scheme in the M2M network which holds the characteristics of achieving the maximum system utility and satisfying the QoS requirement of M2M devices and interference constrains of PU. The simulation results show that the proposed schemes achieve better performance.

Keywords: Machine to Machine, Cognitive Radio, Spectrum Sensing

1. Introduction

It is envisioned that machine-to-machine (M2M) communications are rapidly developing based on the large diversity of machine type terminals, including sensors, mobile phones, consumer electronics, utility metering, vending machines, and so on. With the dramatic penetration of embedded devices, M2M communications will become a dominant communication paradigm in the communication network, which currently concentrates on machine-to-human or human-to-human information production, exchange, and processing. M2M communications is characterized by low power, low cost, and low human intervention [1].

M2M communications is typically composed of billions of wireless identifiable infrastructure sensors which will be developed and deployed over the coming years. The capabilities of sensors are generally limited which puts several constraints in M2M communications, including communication spectrum, energy, computation, storage. These constraints pose a number of unique challenges in the design of network architecture and spectrum usage to achieve a highly connected, efficient, and reliable M2M communication.

The first challenge in M2M communication is the spectrum scarcity. Massive M2M terminals accessing wireless network require lots of spectrum resources, but the exploitable spectrum is becoming scarce resource. Thus, there should be a mechanism to solve the problem of imbalance between the M2M spectrum requirement and the spectrum scarcity.

Another main issue challenges the M2M communication is ever more intensive interference with more radio systems in M2M communication, including unlicensed systems operating in the industrial, scientific, and medical (ISM) frequency band, electronic equipments, and domestic appliances. The performance of M2M communications may be seriously degraded due to such self-existence/coexistence interference [2].

In this paper, we propose a cognitive radio (CR) based communication scheme to solve the spectrum scarcity and severe interference problems within M2M communication. The CR is original from the fact that most of the licensed frequency bands are severely underutilized across time and space in the sense that each licensee is granted an exclusive license to operate in a certain frequency band. The CR, which was first proposed by Mitola [3], is a promising approach to solve the problem of imbalance between the spectrum scarcity and low utilization. The main idea contained in CR technology is that the secondary user (SU) can sense and exploit temporarily and local available licensed spectrum and
adapt its radio parameter to opportunistically communicate over the spectrum of interest without harmfully interfering with the ongoing primary user (PU). As the first step enabling the SUs sharing the spectrum with the PU, the spectrum sensing component needs to reliably and autonomously identify unused frequency bands. In general, spectrum sensing approaches can be classified into three categories; energy detection, matched filter coherent detection, and cyclostationary feature detection [4].

There are several previous works addressing the M2M spectrum scarcity problem by the help of the CR. For example, in [5], a spectrum sensing model based on Markov chain was proposed to predict the spectrum hole for CR in M2M network, and the theoretical analysis and simulation results were evaluated that a Markov model with two state or four state works well enough in wireless Internet of Things (IoT) whereas a model with more states was not necessary. In [6], the authors proposed a new IoT network management architecture based on cognitive network management technology and service oriented architecture to provide effective and efficient network management of IoT.

The organization of this paper is summarized as follows. We will put our contribution into context by giving a brief description of the system model and formulating the problems in the section 2. Section 3 depicts the details of spectrum sensing scheme. Section 4 presents the spectrum sensing performance analysis. Section 5 constructs the power allocation scheme. Our simulation results are given in Section 6. Finally, we conclude this paper in Section 7.

2. Cognitive Based M2M Network

The cognitive based M2M network we considered here is shown in Figure 1. The proposed M2M network is composed of a number of machine-type devices, a licensed user (PU), and a dedicated cognitive M2M gateway. We model a situation where the M2M network operates in a local circular region with a PU, and the radius is denoted by \( R_a \). The PU with omnidirectional antenna is assumed to be the center of the region. We assume that both the M2M gateway and the devices satisfy uniform distribution in the circular region. In the M2M network, the gateway is responsible for managing the whole network, and the network related functionalities are implemented in the gateway, including connectivity establishment, access control, QoS management. In particular, the M2M gateway provides the connectivity to the devices, and the connection between the M2M network and other network, and the devices within the M2M network could directly communicate with the gateway based on the established connectivity to upload information.
In the proposed architecture, the communication within the proposed M2M network typically consists of four phases: connectivity establishment, data collection, data transmission, data processing. The connectivity establishment phase refers to the procedure used to exploit the temporarily and locally available licensed spectrum, and then establish the communication link between the device and the gateway based on the available spectrum. The data collection phase is the process executed by the devices to obtain the physical data. The data transmission phase includes the communication between the M2M gateway and devices, the M2M gateway and an external entity, respectively. The data processing phase is the process of dealing with and analyzing the data.

It is noteworthy that the connectivity establishment between the devices and the M2M gateway is the fundamental process for the M2M network communication. In this section, we propose a cognitive based connectivity establishment scheme. In the following, we will elaborate on the connectivity establishment mechanism and the performance analysis. Moreover, the main difference between the connectivity establishment mechanism proposed in this paper and the traditional one is that our method is based on cognitive radio, which can provide more flexibility, and the end user can dynamically use the white spectrum based on the spectrum environment and the demands.

First, the fundamental feature of cognitive systems is the capability of recognizing communication environments and adaptively modifying the communication parameters, i.e., the SUs need to sense the target spectrum, and use the idle subchannel. Based on the spectrum sensing, as depicted in Figure 2, we propose a connectivity establishment mechanism which contains 5 main steps:

1. Kick-off the spectrum sensing: M2M gateway informs the devices through a predefined channel to start the spectrum sensing process.
2. Self-organization spectrum sensing: Each device implements the spectrum sensing to find the idle spectrum.
3. Collection of the available spectrum: The M2M gateway collects the available spectrum from the devices, and selects an idle sub-spectrum to establish the connectivity between the device and the gateway.
4. Spectrum confirmation: The gateway sends a notice to the device to confirm the selected idle sub-spectrum.
5. Connectivity establishment: Both of the gateway and the device configure their RF with the selected spectrum, and establish the connectivity.

Figure 2. Connectivity Establishment Mechanism

3. Spectrum Sensing Scheme

In the above connectivity establishment mechanism, one of the main challenges is the spectrum sensing, and the devices should perform the spectrum sensing by the use of a self-organization way without the gateway intervention. In this section, we consider a spectrum sensing scheme in which the
devices in M2M network are allowed to access the unused licensed spectrum without adversely interfering with the licensed user (PU). One of the central tasks in the spectrum sensing scheme is spectrum opportunity detection through sensing. Here, we assume the devices could detect the PU’s transmitted signal in the licensed channel after receiving the gateway’s kick-off information.

In this paper, we employ the energy detection as the underlying spectrum sensing scheme. An energy detector simply measures the energy received on the licensed channel during an observation interval and declares a white space if the measured energy is less than a proper threshold. The spectrum sensing problem may be modeled as a binary hypothesis problem: $H_0$: The PU is absent, $H_1$: The PU is present.

To facilitate the following discussion, we assume that the devices within M2M network could carry out the spectrum sensing with energy detectors independently. Thus, the spectrum sensing with energy detection is to decide between the following two hypotheses,

$$x(t) = \begin{cases} n(t), & H_0 \\ hs_p(t) + n(t), & H_1 \end{cases}$$  \hfill (1)

where $x(t)$ is the received signal at the devices, $s_p(t)$ is the PU’s transmitted signal, $n(t)$ is the additive white Gaussian noise (AWGN), $h$ is the channel gain. Let $P_p$ denotes the transmitted power of PU, the received instantaneous signal-to-noise ratio (SNR) at a specific device is defined as follows,

$$\gamma = \frac{P_p P(r)x}{N},$$ \hfill (2)

where $x$ is the specific device’s frequency-flat channel fading, $r$ denotes the distance between the device and the PU, $N$ is the power of AWGN. We denote by $\xi$ the collected energy which serve as decision statistic. Following by the work [7], the distribution of $\xi$ is

$$\xi = \begin{cases} \chi^2_{2m}, & H_0 \\ \chi^2_{2m}(2\gamma), & H_1 \end{cases}$$  \hfill (3)

where $\chi^2_{2m}$ and $\chi^2_{2m}(2\gamma)$ denote the central and non-central chi-square distribution, respectively, each with $2m$ degrees of freedom and a non-centrality parameter $2\gamma$ for $H_1$. Note that $m = TW$ is the time-bandwidth product, and for simplicity, it is assumed to be an integer. The average probabilities of detection and false alarm for the specific device over a fading channel are thus given by the following equations, respectively,

$$P_d = P(\xi > \tau|H_1) = \int_{\chi^2_{2m}} \frac{1}{\Gamma(m/2)} \Gamma(m, \tau/2) f_{\xi}(x)dx,$$ \hfill (4)

$$P_f = P(\xi > \tau|H_0) = \int_{\chi^2_{2m}(2\gamma)} \frac{1}{\Gamma(m/2)} \Gamma(m, \tau/2) f_{\xi}(x)dx = \frac{\Gamma(m, \tau/2)}{\Gamma(m)},$$ \hfill (5)

where $\tau$ denotes the device energy detection threshold, $\Gamma(\cdot)$ and $\Gamma(\cdot, \cdot)$ are complete and upper incomplete gamma function, respectively, $f_{\xi}(x)$ is the PDF of $\gamma$ under fading, $Q_{\alpha}(\mu, \nu)$ denotes the generalized Marcum Q-function defined as follows,

$$Q_{\alpha}(\mu, \nu) = \frac{1}{\mu^{\nu+1}} \int_{\nu}^{\infty} x^\nu \exp\left(-\frac{x^2 + \mu^2}{2}\right) I_{\nu-1}(\mu x)dx,$$  \hfill (6)
where $J_{m-1}(.)$ is the modified Bessel function of the first kind and order $m-1$. It is noteworthy that (5) is derived due to the fact that $\Gamma(m, \tau/2)/\Gamma(m)$ is independent of $\gamma$.

4. Spectrum Sensing Performance Analysis

In this section, we will analyze the spectrum sensing performance based on the proposed energy detection method in M2M network. To facilitate the following analysis, we assume that the devices in M2M network satisfy uniform distribution in the circular region and the number of devices is distributed according to a homogeneous Spatial Poisson process with density $\lambda$. Thus, the probability that there exist $m$ devices in a region of measure $R$ is given by

$$\text{Prob}(m) = \frac{e^{-\lambda R} (\lambda R)^m}{m!}. \quad (7)$$

Hence, the probability that the device is at a distance $r$ from the PU may expressed as

$$f(r) = \frac{2r}{D} \quad 0 \leq r \leq R_a \quad (8)$$

with $D = R^2_a$. Let $P_d$ and $P_f$, be $P_d^s$ and $P_f^s$ averaged over all locations of devices, respectively, and we assume that all devices use the same decision rule, i.e., devices adopt the same energy threshold $\tau$. Then, $P_d$ and $P_f$ can be calculated by

$$P_d = E(P_d), \quad (9)$$

$$P_f = E(P_f) = E\left(\frac{\Gamma(m, \tau/2)}{\Gamma(m)}\right) = \frac{\Gamma(m, \tau/2)}{\Gamma(m)}, \quad (10)$$

where $E(.)$ denotes the expectation. Furthermore, following by the work [8], (9) can be calculated by conditioning on the number of devices, i.e.,

$$E(P_d^s) = \sum_{k=0}^{\infty} \frac{e^{-(\lambda \pi D)^k}}{k!} E(P_d^s | k \text{ devices}). \quad (11)$$

By plugging (8) into (11), after some manipulation, we have

$$E(P_d^s) = \sum_{k=0}^{\infty} \frac{e^{-(\lambda \pi D)^k}}{k!} E(P_d^s | k \text{ devices})$$

$$= \sum_{k=0}^{\infty} \frac{e^{-(\lambda \pi D)^k}}{k!} E_i(P_d)^k$$

$$= e^{\lambda \pi D E_i(P_d)^{k-1}}, \quad (12)$$

where (12) is obtained due to the fact that $\sum_{i=0}^{\infty} \frac{e^{-\sigma}}{i!}(\sigma)^i = 1$, and $E_i(P_d)$ may be calculated by

$$E_i(P_d) = \int_{\frac{\sqrt{2r}}{\sqrt{\tau}}}^{\infty} f_i(x)dx = \frac{\int_{\tau}^{\infty} Q_m\left(\sqrt{2r}, \sqrt{\tau}\right)^{2r}dr}{D}. \quad (13)$$

We can investigate that both $P_d$ and $P_f$ are functions in term of $\tau$, and can be denoted by $P_d(\tau)$ and $P_f(\tau)$, respectively.
5. Power Allocation Scheme

In this section, we propose an optimal power allocation scheme in the M2M network which holds the characteristics of achieving the maximum system utility and satisfying the QoS requirement of M2M devices and interference constraints of PU. In particular, the spectrum overlay strategy does not necessarily impose transmission power restriction on the M2M devices, but rather on when and where they can occupy the licensed spectrum. The M2M devices can transmit only when the PU is inactive. The central issue of this approach is to identify the local and instantaneous unused spectrum with some detection probability.

In order to formulate the optimal power allocation problem, we further model a situation where \( K \) M2M devices coexist and operate with the PU, and the PU has a \( \rho_p \) probability to access the spectrum, and each M2M device wants to opportunistic access the spectrum without causing the unacceptable interference to the PU. In the cognitive based M2M network, there exist some basic problems that must be carefully investigated. The most important two are power allocations and interference managements of M2M devices. An ideal power allocation scheme should maximize the system utility of devices while causing acceptable interference to the PU. In this paper, we assume that the devices adopt a spread spectrum signaling format in which the transmitted power is evenly spread across the entire available spectrum.

For any M2M device \( v \), its SINR can be expressed as

\[
\eta_v = \frac{P_v G_v}{n_0 + \sum_{v \neq v} P_v G_v},
\]

where \( n_0 \) is the background noise power that is assumed to be the same for all devices, \( G_v \) is the channel direct gain between device \( v \) and gateway, \( G_{iG}(P_{iG}) \) is the channel cross gain from \( i \)th (PU) device to device \( v \), \( P_i (P_{iG}) \) is the transmitted power of \( i \)th device (PU).

In order to guarantee the device’s QoS, the proposed power allocations scheme should satisfy the following SINR constraints

\[
\eta_i \geq \beta_i, \quad i = 1, 2, \ldots, K.
\]

Here \( \beta_i \) is the required SINR corresponding to the desired value of bit error rate. In order to evaluate the performance of the \( i \)th device, we adopt the following utility function as the metric

\[
U_{si} = (1 - \rho_p) \ln(\eta_i)
\]

One of the most important goals we want to achieve is the optimal power allocation for different devices. Specifically, the power allocation scheme should coordinate the devices’ transmitted power to achieve the maximum system utility. In this subsection, we assume that the device should perfectly sense the PU’s activity, i.e., they can exactly sense the PU’s behavior. Based on the aforementioned discussion, the optimal power allocation problem can be expressed as follows

\[
\begin{align*}
\max \quad & \sum_{i=1}^{K} U_{si}, \\
\text{s.t.} \quad & 0 \leq P_j \leq P_{j,\text{max}} \quad j = 1, 2, \ldots, K, \\
& \eta_i \geq \beta_i, \quad i = 1, 2, \ldots, K,
\end{align*}
\]

where \( P_{j,\text{max}} \) is the maximum transmitted power of \( j \)th device. Note that the objective function \( \sum_{i=1}^{K} U_{si} \) is
equivalent to $\ln\prod_{i=1}^{K} (1 - \rho_i) \eta_i$ which provides the well-known proportional fair among $i^{th}$ device [8].

Moreover, if $\rho_i = 0$, i.e., the PU is inactive, the objective function can be reduced to $\prod_{i=1}^{K} \eta_i$; otherwise, if $\rho_i = 1$, i.e., the PU occupies the spectrum, the objective function can be reduced to 0. The above two extreme cases are easier solved. Thus, in this paper, we mainly consider the case $0 < \rho_i < 1$. It is easy to find that (17) is a constraint optimization problem, it can be solved by the method of generalized geometric programming [11]. For facilitating the following discussion, we formulate (17) into a standard generalized geometric programming form

$$
\min_{\delta_1, \ldots, \delta_K} \left( t_1^{(1 - \rho_1)} \right),
$$

s.t. \( (P_n^{\max})^{-1} P_j \leq 1 \) for $j = 1, 2, \ldots, K$,

$$
\frac{P_j}{\eta_i} \leq 1 \quad i = 1, 2, \ldots, K,
$$

$$
(\prod_{i=1}^{K} \eta_i)^{-1} \leq t_1,
$$

where $t_1$ is a nonnegative associated variable. We can solve (17) by solving the standard geometric programming (18) with variables $P_n$ and $t_1$.

6. Simulation Result

In this section we present the application of the formulas constructed in the previous sections through some additional numerical simulation. More specifically, we are interested in investigating the relationship between the M2M overall average probability of detection and the threshold [12].

Figure 3 shows the M2M overall average probability of detection as a function of the detection threshold for different radii of the M2M network. As expected, increasing the detection threshold would significantly reduce the average probability of detection. We also observe that increasing the radius of the network deteriorates the average detection performance. In fact, for a larger scale network the PU's signal is difficult to be detected for those kinds M2M devices located far from the PU.

In Figure 4, we show the optimal M2M network utility value under different PU's access probability and different $R$. As expected, the optimal system utility value declines when $\rho_p$ increases. When the PU's access probability is closed to 1, the optimal system utility value will be increased. In addition, we can observe that the optimal system utility value with high $R$ is larger than that with low $R$.

![Figure 3](image)

**Figure 3.** $P_d$ vs. $\tau$ for different radii of the network ($\lambda = 0.01$, $m = 10$)
7. Concluding Remarks

Spectrum sharing is viewed as a crucial component of the emerging M2M network\textsuperscript{(13)}. In this article, we study the spectrum sensing problem in M2M network in which the M2M devices and the gateway coexist with the PU. We obtain the overall average probabilities of detection and false alarm. Moreover, we propose an optimal power allocation scheme in the M2M network which holds the characteristics of achieving the maximum system utility and satisfying the QoS requirement of M2M devices and interference constrains of PU.

8. References
