Accessing the Hidden Available Spectrum in Cognitive Radio Networks under GSM-based Primary Networks

Antara Hom Chowdhury, Yi Song, and Chengzong Pang
Department of Electrical Engineering and Computer Science
Wichita State University
Email: axchowdhury@shockers.wichita.edu, {yi.song, chengzong.pang}@wichita.edu

Abstract—The Global System for Mobile Communications (GSM) system is generally considered to be one of the most successful cellular standards. However, in the cognitive radio (CR) research community, the GSM system is rarely considered as the primary network. Because of the popularity and the significance of GSM, in this paper, we investigate the spectrum access issue in CR networks under GSM-based primary networks. One unique novelty of this paper is that the special features of the GSM system (i.e., frequency division duplex (FDD) and time division multiple access (TDMA)) are simultaneously considered and utilized to further enhance the spectrum access performance of CR networks. By incorporating the location information, a novel dynamic spectrum access scheme is proposed to access the available spectrum vacancies which are usually hidden by traditional schemes. In addition, a queuing model is designed to analyze the network performance as well as to optimize system parameters. Extensive simulation results show that the proposed dynamic spectrum access scheme outperforms the traditional scheme in terms of higher throughput. To the best of our knowledge, this is the first paper that simultaneously utilizes the TDMA and FDD features to enhance the spectrum access performance in CR networks.

I. INTRODUCTION

Recently, cognitive radio (CR) technology has attracted considerable attention in the research community due to its capability to alleviate the spectrum scarcity problem caused by the rapid increase in the wireless spectrum demand and the inefficiency of current fixed spectrum allocation policies [1] [2]. CR technology promises significant improvement in spectrum efficiency by enabling unlicensed users (or, secondary users) to opportunistically exploit the licensed frequency bands which are not used by licensed users (or, primary users) [3].

The Global System for Mobile Communications (GSM) system is generally considered to be one of the most successful cellular standards. Although new technologies (e.g., long term evolution (LTE)) have emerged to provide other services (e.g., data traffic), statistics show that GSM still shares 42% of the total cellular subscriptions worldwide in 2016 (the highest market share among all cellular technologies) [4]. In addition, due to its low cost and good coverage, GSM is also a popular option for machine-to-machine wireless communications used to link various hosts such as vehicles, alarms, and vending machines [5]. Because of the popularity and the significance of GSM, in this paper, we investigate the dynamic spectrum access issue in CR networks under GSM-based primary networks. By utilizing the unique features of the GSM system, secondary users (SUs) can access some hidden available spectrum vacancies which are not explored by traditional approaches. Thus, the spectrum access performance of SUs is greatly enhanced.

In this paper, two main unique features of the GSM system are utilized to further enhance the spectrum access performance of CR networks: frequency division duplex (FDD) and time division multiple access (TDMA). First of all, in a GSM-based primary network, the frequency channels for the communications between the primary users (PUs) and the GSM base station (BS) are divided into downlink channels (i.e., channels used for communications from the GSM BS to PUs) and uplink channels (i.e., channels used for communications from PUs to the GSM BS). Therefore, if the channel used by a PU transmission in one direction (e.g., the uplink) is occupied, then the channel of the same transmission in the other direction (e.g., downlink) could be idle since the traffic intensity of the two link directions is generally asymmetric [6]. Thus, by differentiating the transmission directions of PU transmissions in the GSM system, SUs can access the available spectrum vacancies. These spectrum vacancies have not been explored by traditional schemes thus they are named the hidden available spectrum.

Secondly, in the GSM system, different users could access the same frequency channel in a TDMA manner. That is, the time frame is divided into multiple time slots (e.g., usually 8 slots). Each mobile terminal (MT)
is assigned with a designated time slot to communicate with the BS. In addition, the MT can only communicate with the BS during its own time slot in a frame. Thus, in a GSM-based primary network, when the time slot assigned for a particular PU is determined, the PU cannot transmit in other time slots of the same frame. This means that the PU reserves a particular time slot to complete its transmission. By using this consistency of the PUs in the time domain, the length of idleness of the channel in the following frames can be predicted after observing one or several frames of the channel. Since this channel idleness has not been explored before, we also name them the hidden available spectrum.

Currently, there is no research effort on studying the FDD feature of primary networks in CR networks. In addition, there are only a limited number of papers that investigate the TDMA feature in CR networks [7]–[9]. However, these existing proposals either focus on how to establish a common control channel [7] or simply use TDMA as a medium access control (MAC) scheme for SUs [8] [9]. None of the existing work considers utilizing the unassigned time slots by PUs in a TDMA-based primary network.

In this paper, a novel dynamic spectrum access scheme utilizing the TDMA and FDD features of GSM-based primary networks is proposed to access the hidden available spectrum in CR networks. In addition, an analytical model is proposed to analyze the performance of the proposed protocol. To sum up, in this paper, a dynamic spectrum access framework of CR networks under GSM-based primary networks is formed by K PU nodes in a centralized manner and they adopt the TDMA scheme to access a PU BS 1. In the TDMA scheduling scheme, each channel is divided into repeated frame structure. Each of these frame consists of several time slots with equal length. Each PU node is allocated in a time slot. Here, there are M channels and N SUs in the network. We consider an environment where SU coexists with PUs but they are independent with each other. Each SU has its own circular transmission range with a radius of $r_s$.

The distance between one PU node and a SU node is denoted as $d_{sp}$ and the distance between the BS and the SU node is $d_{sb}$. Fig. 1 shows the network model of the GSM-based primary network co-existing with SUs [10]. The dashed circle represents the transmission range of the SU.

The rest of the paper is organized as follows: the proposed dynamic spectrum access scheme is presented in Section II. Then, the proposed mathematical model to analyze the network performance is given in Section III. In addition, performance results are shown in Section IV, followed by the conclusions in Section V.

II. THE PROPOSED DYNAMIC SPECTRUM ACCESS SCHEME UNDER GSM-BASED PRIMARY NETWORKS

In this section, we first describe the considered network model in this paper. Then, we present the details of our proposed dynamic spectrum access scheme under GSM-based primary networks.

A. Network Model

In this paper we assume that a GSM-based primary network is formed by $K$ PU nodes in a centralized manner and they adopt the TDMA scheme to access a PU BS 1. In the TDMA scheduling scheme, each channel is divided into repeated frame structure. Each of these frame consists of several time slots with equal length. Each PU node is allocated in a time slot. Here, there are $M$ channels and $N$ SUs in the network. We consider an environment where SU coexists with PUs but they are independent with each other. Each SU has its own circular transmission range with a radius of $r_s$.

The distance between one PU node and a SU node is denoted as $d_{sp}$ and the distance between the BS and the SU node is $d_{sb}$. Fig. 1 shows the network model of the GSM-based primary network co-existing with SUs [10]. The dashed circle represents the transmission range of the SU.

Fig. 1: The network model of the GSM-based primary network co-existing with SUs where SUs can access both the uplink and downlink of the primary network.

In addition, we assume that the GSM-based primary network follows $M/M/m/m$ queuing model with the arrival rate of $\lambda$ [11]. The arrival process of PUs follows the Poisson distribution. Here, the system capacity and the number of server are equal which is given by $m = MS$, where $S$ is the number of time slots per channel in the GSM system. Primary users do not have to wait

1 In the rest of the paper, the term PU node specifically refers to the primary mobile user, not the primary BS.
for being served. In this paper, we only consider that the number of PUs is less than or equal to the number of total system capacity which means that $k \leq MS$. That is, we do not consider the scenario where the number of PUs is more than the total system capacity.

B. Details of the Proposed Dynamic Spectrum Access Scheme

Next, we present our proposed dynamic spectrum access scheme for CR networks in GSM-based primary networks. The goal of the proposed scheme is to utilize the FDD and the TDMA features of the GSM-based primary network to access the licensed spectrum band for SUs without interfering the PUs.

As mentioned earlier, in the GSM system, two distinct frequency bands are used to maintain the two-way communications between the BS and PU nodes. The uplink (UL) band is used to transmit data from PU nodes to its BS while the downlink (DL) band is used to transmit data from BS to the PU nodes. In this paper, we focus on both UL and DL channel available slots for SUs.

On the other hand, in the TDMA scheme in a GSM system, multiple PUs can share the same frequency channel by dividing the UL and DL channel into different time slots. Each PU is assigned in one fixed time slot by its BS in one frame and it continues its transmission using the same time slot in following frames until the whole message is transmitted. This means that the PU reserves a particular time slot to complete its transmission. By using this consistency of the PU transmission in the time domain, we can predict the length of idleness in the following frames in both UL and DL bands after observing the traffic activities in one or several frames of the channel.

Furthermore, by incorporating the location information, there are different dynamic spectrum access scenarios for SUs to access the hidden available spectrum depending on the distance between the SU and the PU node as well as the BS. When the PU node locates within the transmission range of a SU, then the SU will cause interference when it starts its transmission. On the other hand, when the PU locates outside the transmission range of SU, then transmission of SU will not affect the PU node. Therefore, we consider four possible scenarios according to this situation in our proposed dynamic spectrum access scheme.

1) Scenario 1: First of all, as shown in Fig. 2, both the PU node and the BS are outside of the SU transmission range. Therefore, the transmission of the SU will not cause any harmful interference to the PU node. Thus, any SU who wants to transmit data can utilize the DL channel at any time. That is, it does not need to consider whether the DL channel is busy or idle. Similarly, if the PU BS is also outside of the transmission range of the SU, the transmission of the SU will not affect the transmission of the PU BS. Then, the SU can utilize the UL channel at any time regardless of the channel availability. By combining these two cases, when both the PU node and the PU BS are outside of the SU transmission range, the SU can transmit by using both UL and DL channels whenever they are idle or busy. This is the most straightforward scenario.

2) Scenario 2: Secondly, we assume that only the PU node is located outside of the SU transmission range while the BS is within that transmission range, as shown in Fig. 3. As mentioned earlier, the SU can use the DL channel whenever it is idle or busy. However, since the PU BS locates within the transmission range of the SU, the SU may cause harmful interference when it starts its transmissions. Therefore, the SU can utilize the UL channel only when it is not being used by any PU node. By combining these two cases, we can conclude that when the PU node is outside of the SU transmission range and the PU BS is within the SU transmission range, the SU can use the DL channel whenever it is idle or busy and the UL channel only when it is idle. In Section III, the optimal idle duration of the UL channel is derived so that the SU can utilize that idle period.

3) Scenario 3: Thirdly, as shown in Fig. 4, the PU node is within the SU transmission range while the PU BS is located outside of that range. Similar from the discussion in Scenario 2, we can conclude that in this scenario, the SU can use the UL channel whenever it is idle or busy and it can use the DL channel only when it is idle. The idle duration of the DL channel is also derived in Section III.
4) Scenario 4: Finally, as shown in Fig. 5, both
the PU node and the PU BS are located within the
SU transmission range. Their transmissions could
be potentially be affected by the data transmissions of the
SU. Thus, the SU can only utilize the DL and UL
channels when they are idle. Otherwise, the SU will
cause interference to PU transmissions which is not
acceptable. The optimal transmission durations of the
DL and UL channels are calculated in Section III.

III. THE PROPOSED MATHEMATICAL MODEL TO
DERIVE THE TDMA CHANNEL IDLENESS DURATION
FOR SU TRANSMISSIONS

In this section, we present the mathematical model
to analyze the performance of the proposed dynamic
spectrum access protocol. Our goal is to derive the
TDMA channel idleness duration for SU transmissions.
The TDMA channel idleness duration is defined as the
duration when a channel is idle within one TDMA
frame.

A. TDMA Channel Idleness Duration When SUs Are
Near the BS

First, we calculate the TDMA channel idleness
duration for SU transmissions when SUs are near the BS.
Since SUs are near the BS, we need to consider the
transmission from the BS to all PUs in the network.
From Section II, we know that there are K PUs and
M channels in the GSM network. In addition, the
time is divided into S time slots for the time division
multiple access. That is, each channel can support up to
S PUs simultaneously. Furthermore, we know that the
PU packet arrivals follow the Poisson distribution with
the average arrival rate of \( \lambda \) packet/second and the PU
packet service time follows the exponential distribution
with the average service rate of \( \mu \) packet/second.

Therefore, we model the GSM primary network as
a finite-state Markov chain where the states can be
represented as \( \{ J_0, J_1, \cdots, J_{MS} \} \). The definition of
state \( J_i \) is that there are \( i \) PUs currently active (i.e.,
transmitting date with the base station) in the system.
Since the total number of PUs that can be supported in
this GSM network is \( MS \), then the PU packet arrival rate
and the service rate of state \( J_i \) can be written as

\[
\lambda_i = \begin{cases} 
\lambda & \text{if } i < MS \\
0 & \text{if } i \geq MS 
\end{cases} 
\]

\[
\mu_i = i\mu, i = 1, 2, \cdots, MS. 
\]

Denote \( \rho = \lambda/\mu \) as the utilization factor of the primary
network. Thus, based on [11] and mathematical ma-
nipulations, the steady-state probability of the proposed
Markov chain, \( p_i \), is

\[
p_i = \frac{\rho^i}{\Gamma(MS+1)\Gamma(a)} - 1, 
\]

where \( \Gamma(x) \) is the gamma function and \( \Gamma(a, x) \) is the
incomplete gamma function [12] [13]. In addition, we
can easily obtain that \( \Gamma'(x) = x! \) and \( \Gamma(a, x) = 
\int_x^\infty t^{a-1}e^{-t}dt \) [14].
Since \( p_i \) is the probability that there are \( i \) active PUs in the entire network, then the average number of active PUs in the network is
\[
N_p = \sum_{i=0}^{W} i p_i = W \frac{i \rho^i}{\Gamma(MS+1, \rho) e^{\rho} - 1} i!
\]
where \( W = \min(K, MS) \). Using mathematical manipulations, the closed form of \( N_p \) can be expressed in (7). Therefore, the average number of active PUs on each channel is \( N_c = N_p / M \). Thus, the probability that a time slot is busy can be written as
\[
q_i = \frac{N_c}{S}.
\]
Finally, the available time duration for SU transmissions when SUs are near the BS is
\[
T = \sum_{j=0}^{\infty} j (1 - q_i) j! q_i.
\]

### B. TDMA Channel Idleness Duration When SUs Are Near the PU

Next, we derive the TDMA channel idleness duration for SU transmissions when SUs are near the PU. In this case, we only need to consider the active PUs within the transmission range of the SU. Denote the transmission range of a SU as \( A \) (i.e., \( A = \pi r_s^2 \)). Thus, we need to calculate the number of channels that are not used by any active PU within \( A \). The size of the total network area is denoted as \( A_L \). Since the locations of PUs are subject to the 2-dimensional Poisson distribution, the probability that \( p \) PUs are within \( A \) is
\[
P_a(p) = e^{-\Lambda |A|} \frac{(|A| A)^p}{p!},
\]
where \( \Lambda = \frac{K}{A_L} \) represents the PU node density in \( A_L \).

Therefore, using similar analysis from the previous section, we have the average number of active PUs within \( A \) as
\[
N'_p = \sum_{i=0}^{W} i p_i P_a(i)
= \sum_{i=1}^{W} \frac{i \rho^i}{\Gamma(MS+1, \rho) e^{\rho} - 1} i! \frac{(\Lambda |A|)^i}{i!}.
\]
Thus, the probability that a time slot is busy within the transmission range of a SU is \( q'_i = N'_p / MS \). Finally, the available time duration for SU transmissions when SUs are near the PU is
\[
T' = \sum_{j=0}^{\infty} j (1 - q'_i) j! q'_i.
\]

### IV. The Performance Evaluation

In this section, we evaluate the performance of the CR networks under the proposed optimal SU packet size. First of all, we show the numerical results of the channel idleness duration using the proposed mathematical model. Then, we compare the network performance under the proposed dynamic spectrum access scheme with the scenario where the SU randomly access the spectrum [15] [16]. The default simulation parameters are summarized in Table I.

<table>
<thead>
<tr>
<th>Simulation Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>The number of channels</td>
<td>20</td>
</tr>
<tr>
<td>The number of PUs</td>
<td>20</td>
</tr>
<tr>
<td>The number of SU</td>
<td>20</td>
</tr>
<tr>
<td>The number of time slots</td>
<td>8</td>
</tr>
<tr>
<td>The radius of the GSM network</td>
<td>500 m</td>
</tr>
<tr>
<td>The radius of the SU transmission range</td>
<td>200 m</td>
</tr>
<tr>
<td>The data rate of the GSM channel</td>
<td>1 Mbps</td>
</tr>
<tr>
<td>The average length of SU packet arrival rate</td>
<td>1000 packets/s</td>
</tr>
<tr>
<td>The average length of PU packet</td>
<td>8000 bits</td>
</tr>
<tr>
<td>The time slot length</td>
<td>577 ms</td>
</tr>
</tbody>
</table>

#### A. Numerical Results of the TDMA Channel Idleness Duration

Fig. 7 and 8 show the numerical results of the TDMA channel idleness duration under different numbers of PUs and different PU packet arrival rate obtained from the proposed analytical model in Section III. As we can see, the TDMA channel idleness duration decreases as the number of PUs increases. In addition, the TDMA channel idleness duration decreases when the PU packet arrival rate increases. If the PU packet arrival rate is fixed, it is worth noting that the channel idleness duration becomes stable when the number of PUs increases.

#### B. Simulation Results of the SU Throughput

Then, we present the simulation results of the SU throughput. Since there is no exiting work on dynamic spectrum access in CR networks under GSM-based primary networks, we compare our proposed scheme
with a benchmark scheme where SUs do not access both uplink/downlink and cannot intelligently access the TDMA idle time slots. Fig. 9 shows the simulation results of the SU throughput under different numbers of PUs. It is shown that the proposed scheme outperforms the traditional scheme in terms of higher SU throughput.


\[
N_p = \frac{e^\rho \Gamma(W+1)\Gamma(W+2)\Gamma(W+1, \rho) - \Gamma(W)\{e^\rho \Gamma(W+2)\Gamma(W+1, \rho) + \Gamma(W+1)\rho W^{-1} - e^\rho (-1 + \rho - W)\Gamma(W+2, \rho)\}}{\Gamma(W)\Gamma(W+1)\Gamma(W+2)} \left[ \frac{\Gamma(MS+1, \rho) e^\rho}{\Gamma(MS+1)} - 1 \right]
\]

(7)

Fig. 8: Numerical results of the TDMA channel idleness duration when SUs are near the PU.

Fig. 9: Simulation results of the SU throughput under different numbers of PUs.

V. CONCLUSION

In this paper, the dynamic spectrum access issue in CR networks under GSM-based primary networks is investigated. The FDD and TDMA features of the GSM system are considered and utilized to enhance the spectrum access of SUs for the first time. A novel dynamic spectrum access scheme is proposed by utilizing the FDD and TDMA features in GSM-based primary networks. In addition, four different dynamic spectrum access scenarios have been considered by incorporating the location information of SUs and PUs. The channel idleness duration for SU transmissions in the TDMA frame is also derived. Simulation results show that the proposed dynamic spectrum access scheme outperforms the traditional spectrum access scheme in terms of higher throughput. More importantly, the proposed scheme will play a significant role in the CR network development to the real world.

REFERENCES


