Evaluation of a Dynamic Spectrum Access Scheme using the Properties of GSM Networks

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I. Motivation

Cognitive radio networks (CRNs) are an effective solution to alleviate the increasing demand for radio spectrum. In CRNs the transmission channel is licensed to the primary users (PUs), while secondary users (SUs) only access the channel in an opportunistic way when the PUs are inactive, i.e., when the PUs do not use the channel. CR technology promises significant improvement in spectrum efficiency by enabling unlicensed users (SUs) to opportunistically exploit the licensed frequency bands which are not used by licensed users (PUs).

A SU needs to detect a vacant channel for transmission, and vacates it when a PU starts to use the channel. A SU should operate transparently to the PUs and avoid causing interference to PUs acting as receivers. A SU transmission must be halted whenever a PU becomes active. The service interruption of SUs due to PUs may significantly degrade its performance. Thus effective models for evaluation of dynamic spectrum access schemes in CRNs are needed.

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). 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. Because of the popularity and the significance of GSM, [1] has investigated the dynamic spectrum access issue in CR networks under GSM-based primary networks.

II. Literature Survey

One of our primary concerns was as regards to how spectrum sensing was carried out by the Secondary User(SU). Throughout the paper, [1] assumes that the SU is able to accurately estimate whether or not some portion of the licensed spectrum is being utilized by another user, who could be primary or secondary. In [2], they outline a detailed practical implementation to carry out spectrum sensing in a GSM network. Their experimental setup consisted of an Universal Software Radio Peripheral (USRP) model B100, and a Linux-based laptop running GNURadio .The SDR equipment was tuned to the downlink GSM channel 94. They focused on the most active period of spectrum utilization by the primary users, to highlight the spectrum opportunities in the worst case scenario. The detection of the presence or absence of activity in the GSM channel (caused by the operation of the GSM system) was implemented through an Energy-based (EB) detector. They then carry out hypothesis testing to determine whether or not the spectrum is being utilized, thus validating the spectrum sensing abilities assumed in [1].

We were also interested in seeing the impact of the number of PU's on the available throughput to SU's, i.e. we wanted to see how drastically a change in the number of PU's would impact each SU's throughput. [3] reports that the average channel capacity is rather insensitive to secondary cell locations, while a significant capacity gain can be achieved when PU channel occupancy drops from 50% to 10%. This justifies the approach taken by [1] to plot the average SU throughput. Moreover, our simulation results also reveal that an initial increase in the number of PU's from 5 to 10 causes a much larger drop in SU throughput, than it does from 10 to 15, as shown in Figure 4.

In [4], they have looked into a dynamic spectrum sharing problem in CRNs under a contention-based scheme. They have derived an analytical model to compute throughputs for both primary users and secondary users. In the derivation of their analyical model they claim that the accessibility of the channel for secondary users is a bernouli trial. We use this to derive the TDMA time slots available for SUs.

The focus of [1] is on a novel dynamic spectrum access scheme which utilizes the TDMA and FDD features of GSM based primary networks to access the hidden available spectrum in CR networks.

III. Paper's contributions

The main contributions of [1] to designing a spectrum access algorithm in CR networks under GSM-based primary networks are:

1) A novel dynamic spectrum access scheme is proposed to enhance the spectrum access performance by utilizing the FDD and TDMA features in GSM-based primary networks. Four different dynamic spectrum access scenarios have been considered by incorporating the location information of SUs and PUs.

2) The performance of the CR networks under the GSM-based primary networks is mathematically modeled and analyzed. A queuing model is proposed to analyze PU transmissions in the GSM-based primary network.

3) The channel idleness duration for SU transmissions in the TDMA frame is derived using the designed queuing model. The derived channel idleness duration is used by SUs to optimize the network performance.

It is the first paper that simultaneously utilizes the TDMA and FDD features to enhance the spectrum access performance in CR networks under GSM-based primary networks.

IV. System Model

The paper assumes a GSM-based primary network following a $M/M/m/m$ queuing model with the arrival rate of λ. 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 for being served. In this paper, they 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, they do not consider the scenario where the number of PUs is more than the total system capacity.

A. Proposed Dynamic Spectrum Scheme

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 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. 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. 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. The paper considers 4 scenarios:

- *Scenario 1:*
  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, or the PU BS. Thus, any SU who wants to transmit data can utilize the DL or UL channel at any time.
- *Scenario 2:*
  The PU BS locates within the transmission range of the SU, hence the SU may can 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.Since the PU nodes locate out of the SU transmission range, the SU can use the DL channel whenever it is idle or busy.
- *Scenario 3:*
  The PU node is within the SU transmission range while the PU BS is located outside of that range. 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.
- *Scenario 4:*
  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.

The four scenarios are summarised in the flowchart shown in Figure 1.

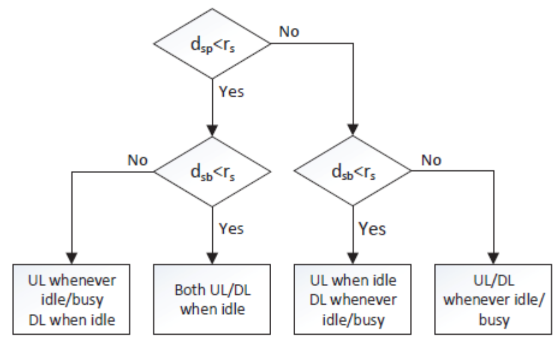

Fig. 1. The flow chart of the proposed dynamic spectrum access scheme in CR networks under GSM-based primary networks from [1].

V. Proposed Mathematical model to derive the channel idleness duration for SU transmission

The 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

Since SUs are near the BS, we need to consider the transmission from the BS to all PUs in the network. There are K PUs, L SUs and M channels in the GSM network. In addition, the time is divided into S time slots for TDMA. 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 λ packet/second and the PU packet service time follows the exponential distribution with the average service rate of μ packet/second.Therefore, we model the GSM primary network as a finite-state Markov chain where the states can be represented as $\{J_0, J_1, , J_K\}$. The definition of state J_i is that there are i PUs currently active (i.e., transmitting data with the base station) in the system. The PU packet arrival rate and the service rate of state J_i can be written as

$$\lambda_i = \begin{cases} \lambda & if \ i < K \\ 0 & if \ i \geq K \end{cases} \quad (1)$$

$$\mu_i = i\mu, i = 1, 2, ..., K \quad (2)$$

Denote $\rho = \frac{\lambda}{\mu}$. Then the steady-state probability of the proposed Markov chain, p_i, is

$$p_i = \frac{\rho^i}{\left[\frac{\Gamma(W+1,\rho)e^\rho}{\Gamma(W+1)} - 1\right] i!} \quad (3)$$

where W = min(K, MS), Γ(x) is the gamma function and Γ(a,x) is the incomplete gamma function.

The average number of active PUs in the network is

$$N_p = \sum_{i=0}^{W} \frac{i\rho^i}{\left[\frac{\Gamma(W+1,\rho)e^\rho}{\Gamma(W+1)} - 1\right] i!} \quad (4)$$

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

$$q_i = \frac{N_c}{S} \quad (5)$$

Finally, the available time duration for SU transmissions when SUs are near the BS is

$$T = 8(1 - q_i) \quad (6)$$

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

In this case, only the active PUs within the transmission range of the SU needs to be considered. Denote the transmission range of a SU as A (i.e., A $= \pi r_s^2$). We then 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

$$P_a(p) = e^{-\Lambda|A|} \frac{(\Lambda|A|)^p}{p!} \quad (7)$$

where $\Lambda = \frac{K}{A_L}$ represents the PU node density in A$_L$. Therefore, the average number of active PUs within A can be written as

$$\begin{aligned} N_p^{'} &= \sum_{i=0}^{W} i\left(\sum_{k=i}^{W} p_k\right) P_a(i) \\ &= \sum_{i=0}^{W} i\left(\sum_{k=i}^{W} \frac{\rho^k}{\left[\frac{\Gamma(W+1,\rho)e^\rho}{\Gamma(W+1)} - 1\right] k!}\right) e^{-\Lambda|A|} \frac{(\Lambda|A|)^p}{p!} \end{aligned} \quad (8)$$

Thus, the probability that a time slot is busy within the transmission range of a SU is $q_i = \frac{N_p^{'}}{MS}$. Finally, the available time duration for SU transmissions when SUs are near the PU is

$$T^{'} = 8(1 - q_i^{'}) \quad (9)$$

VI. Simulation Results

The results of the proposed mathematical model are simulated and the results are shown in the following figures. The simulation parameters used are same as that in [1].

A. Results of the TDMA Channel Idleness Duration

Fig. 1 and 2 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 model with $MS = 20$. 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.

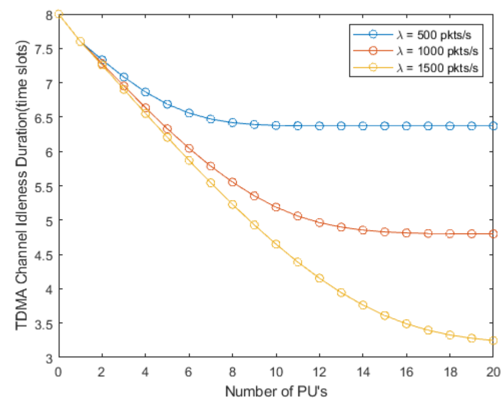

Fig. 2. TDMA channel idleness duration when SUs are near the BS

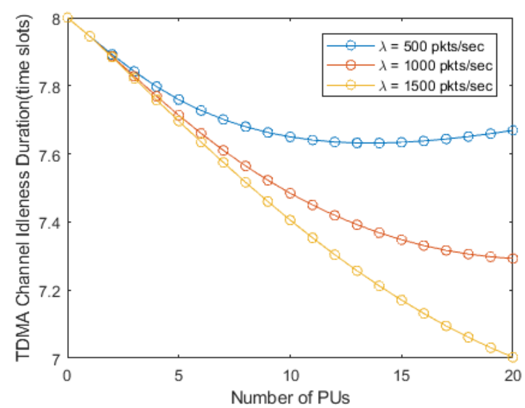

Fig. 3. TDMA channel idleness duration when SUs are near the PU.

B. Simulation result of SU throughput

Fig. 4 shows the simulation results of the SU throughput under different numbers of PUs. Depending on the physical location of SUs and PUs, and depending on the No. of active PUs within the transmission range of a SU, a SU gets a few free time slot where it transmits. This controls its throughput.

VII. Code contribution by team and Difficulties faced

All the pieces of the code for the simulation of TDMA channel idleness and SU throughput have been written by the team and nothing is taken from the internet.

The formulas given in the paper to calculate the time duration available for SUs to transmit were found to be incorrect.

- The formula of arrival rate λ_i is incorrect and should be 0 after K as there are only K users ($\leq$ MS) in the system. This would result in the change in formula for p_i, the steady state probability of the proposed Markov chain having the term $\Gamma(W+1,\rho)$ instead of $\Gamma(MS+1,\rho)$.
- If q_i is the probability of a time slot being busy, then the probability of a time slot being idle is $1-q_i$ and we can approximate the expected number of idle time slots in one GSM frame as in (6). This time is available for SUs to transmit. Figure 2 plotted using (6) matched the plot given in the paper. However the expected idle time is calculated differently in [1].
- The version of (8) given in [1] was found to be incorrect. If $P_a(i)$ is the probability that there are i PUs within A, we need to find how many of these i PUs are active, which has to lie between i and W. The corrected formula for this is 8.
- The correct formula for expected number of idle time slots for SUs in this case will be (9), whose explanation remains the same as before.

Using the corrected equations, the plots were found to match exactly that given in the paper for calculation of TDMA channel idleness duration.

The paper mentions no formal definition of what exactly they mean by SU throughput. Neither do they give any simulation procedure followed which resulted in the SU throughput graph shown in the paper. Thus we have adopted our own way for calculating SU throughput which gives the graph shown in Figure 4. Details of the SU throughput simulation procedure are explained in the next section.

VIII. Extensions Done

We have calculated, via simulation, the average SU throughput as a function of the number of PU's in the GSM network. We believe that the graph of SU throughput v/s number of PU's, given in [1], and reproduced below for convenience, is incorrect, as confirmed by our simulations. Moreover, it shows the SU throughput to be around 600 b/s even when there are no PU users. Given that the data rate of the GSM channel is 1 Mbps, and that number of SU's $< MS$, 600 b/s is certainly counter-intuitive. The procedure followed by us to calculate the SU throughput is as follows:

Step 1: Initialization

- K PU's and L SU's are placed randomly at uniform within a circle of radius equal to that of the GSM network.
- For each of the L SUs, we store the index of each PU that falls within its transmission range, and also whether the BS falls within that range.

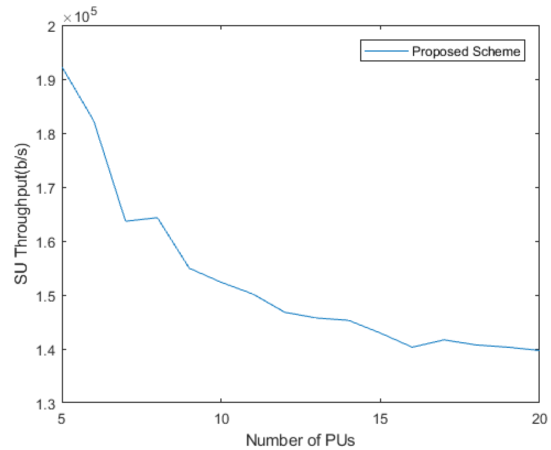

Fig. 4. SU throughput under different numbers of PUs.

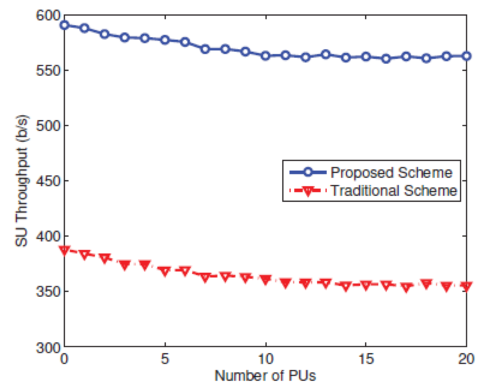

Fig. 5. SU throughput as shown in [1].

Step 2: Simulation Steps

- For each of the PU's, generate an arrival and service time drawn from an exponential distribution with parameters λ and μ respectively.
- Since $K < MS$, each PU will be allocated a time slot and a channel(called a Resource Block(RB)). This allocation is done uniformly at random, and stored.
- A similar generation of arrival and departure time's is done for the SU's. However the service time can be shortened, if an interfering PU arrives in between an SU service.
- For each SU, we now allocate it a channel and time slot randomly.
  - We then check if the channel allocated is an uplink or a downlink channel.
  - If it is an uplink channel, then we check if the PU BS lies in the transmission range of SU. If it does, then only if there is an allocation in the same RB which arrives before the SU and departs after the SU, do we try another random allocation for the SU.
  - If it is a downlink channel, then we check if there is a PU allocated the same RB. If it does, then only if

it lies in the transmission range of SU ,arrives before the SU and departs after the SU, do we try another random allocation for the SU.
   - Having allocated an RB to the SU, we now check if the interfering transmissions identified above arrive during the SU service time. In this case, the SU suffers a packet loss, else the packet is successfully transmitted.
- These steps are then repeated iteratively until the end of the simulation time.

Step 3: Average SU Throughput Calculation

The total throughput (T_{SU}) for each SU is then calculated as:

$$T_{SU} = \frac{Y_{SU} * B}{t} \tag{10}$$

where Y_{SU} is the number of successful transmissions, B is the average packet length in bits and t is the the sum of successful and unsuccessful transmission times.

We can see from Figure 4 that the SU throughput decreases as the number of PU's increases, which is to be expected. Moreover, if the SU's have the ability to do spectrum sensing accurately as assumed in the above simulation, we can see that they can achieve a reasonably high data rate, when $K << MS$, as is the case here. Our simulation results thus differ significantly from those in [1], and we believe our results to be accurate

IX. Drawbacks of Throughput Simulation Approach

There are a few corner cases that we have not accounted for, but due to the simulation parameters assumed in [1], these events are of negligible probability

- We have not accounted the case of an interfering PU arriving and departing before the SU in the same iteration. In other words, we have assumed independence between iterations.
- We have not considered the event that two PU's or two SU's are assigned the same RB, in which case there would be a packet loss for the SU and a new RB identified for the PU.

References

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