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Research article

An efficient radio-frequency spectrum utilization technique for cognitive radio networks

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ABSTRACT

Cognitive radio (CR) is a rising technology that unlocks the doors for radio spectrum scarcity problem, which is of great concern nowadays among the researchers at various levels. CR enables to unlicensed users or secondary users (SUs) to access the primary channels when licenced users or primary users (PUs) are not using these channels. Two fundamental access methods namely overlay and underlay are very popular in utilizing the free available channels or the white spaces. Various hybrid access methods have been proposed and recommended by many researchers to further enhance the radio spectrum utilization. Of course hybrid access methods are the better ways to deal this spectrum scarcity problem, but a comprehensive and directed effort is required to optimize the modality of these methods. This work proposes a Markov chain based hybrid access method named as *Hybrid Spectrum Utilization Technique* (HSUT), which tries to maximize the radio spectrum utilization by enhancing the PU's detection probability. This work also analyzes the performance of the HSUT and results obtained through OMNeT++ simulator are very encouraging. At last, this work also compares the performance of the HSUT with the overlay, underlay, Hybrid-P1 (Dhurandher et al., 2021), and the Hybrid-P2 (Dhurandher et al., 2021) access methods.

1. Introduction

The right and easy availability of the Radio-Frequency (RF) spectrum is like the oxygen for all kinds of mobile and wireless services. Over the past few years, world has witnessed an exponential growth in the number and types of wireless devices along with the services provided by these devices. Modern research in integrated technologies enabled the development of variety of tiny and thin communicating devices like laptops, tablets, mobile phones, and smart watches etc. All this has resulted an easy and economically viable access of these modern communicating devices to the masses. The demand for radio-frequency spectrum has also increased dramatically to support the variety of wireless applications [1]. Fig. 1 shows the global digitalization status for the year 2021. In a nutshell, there is a huge demand of radio-frequency spectrum to support those large number of users as shown in Fig. 1. At the same time, it is also predicted that this demand will be continuously growing in the future as well. A key point is that, "more than 90 percent internet users use mobile devices to access the internet most of the time". As per the study done in [2] the global internet users spend on an average 7 h per day.

Despite of the huge demand for radio spectrum in current time and also predicted for future, many studies done in the recent past still reveal that the utilization of the radio-frequency spectrum is really very low. This poor utilization of radio spectrum has

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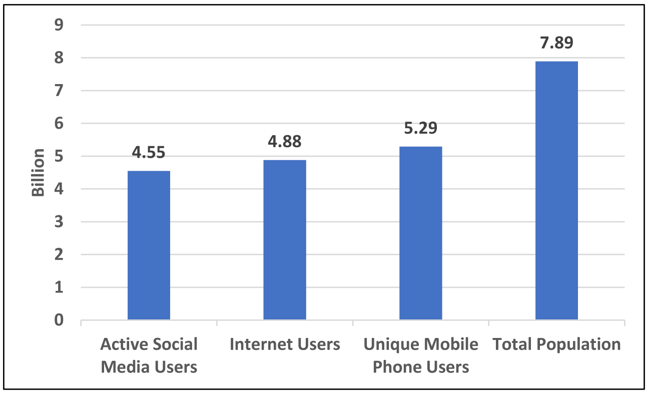

Fig. 1. Digitalization around the World in the Year 2021 [2].

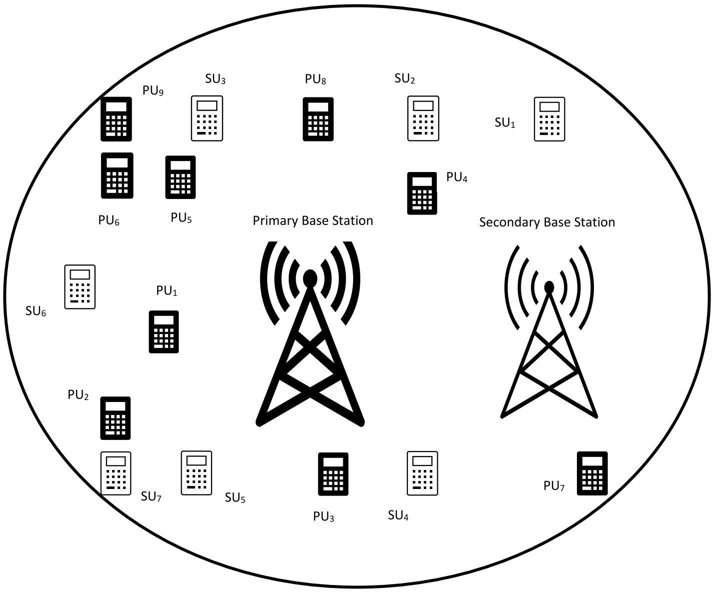

Fig. 2. Structure of a cognitive radio network.

resulted in the temporal and geographical holes [3,4]. "International Telecommunication Union (ITU)", "European Conference of Postal and Telecommunications Administrations (CEPT)", and "European Telecommunications Standards Institute (ETSI)" are the forums which are responsible for the allocation of radio bands internationally. Out of the many possible approaches for enhancing the spectrum utilization, one of the approach is to share the spectrum among different users like primary and secondary users [5–7]. Radio spectrum is the natural resource and it is always going to be finite. So improvement in spectrum utilization policies and technological development must go in parallel to take the full advantage of this scarce resource.

1.1. Cognitive radio networks

Cognitive radio enables the sharing of the radio spectrum bands. "Cognitive radio (CR) has been considered as a way forward to further improve the radio spectrum utilization in the cognitive radio networks (CRNs). Cognitive radio is built upon the principle of software defined radio (SDR) and it allows the dynamic access of the radio spectrum bands. As per the concept of cognitive radio, secondary users are allowed to use the free spectrum bands without disturbing the communication of primary users [8,9]". Haykin in [10] emphasized on the learning ability of a cognitive radio that can continuously keep learning from its environment about the different transmission parameters like frequency, modulation, and transmitting power etc. The learning ability of a cognitive radio comes through the different phases of a cognitive cycle namely spectrum sensing, spectrum analysis, and spectrum adaptability.

Fig. 2 shows the structure of a cognitive radio network (CRN). A CRN consist of the primary network(s) and the secondary network(s). Basically a primary network is a collection of PUs and a secondary network is a collection of SUs. As shown in this figure, "a cognitive radio network consists of the number of primary users, secondary users, a primary base station, and a secondary

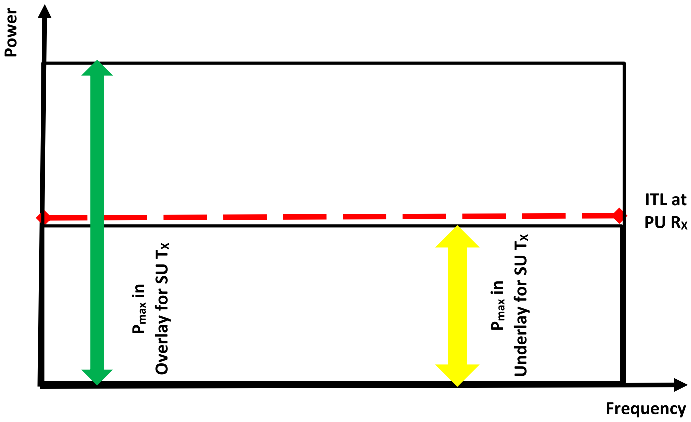

Fig. 3. Radio spectrum access illustration.

base station. Primary users are the licenced users and have the higher priority than secondary users (unlicensed users or cognitive users)" inside the network. Cognitive radio enables the sharing of the radio spectrum bands. Secondary users always look for the free spectrum bands by making use of the cognitive capability of the cognitive radio. All secondary users must protect the communication of primary users during the process of their access (may be for free channel detection or data transmission) to the primary channels.

1.2. Radio spectrum access

As shown in Fig. 2, radio spectrum bands can be used or accessed by the primary and secondary users as per their transmission requirements. The way secondary users have access to the primary channels is entirely different from the way, primary users have access to the primary channels. This difference is because of the nature of these users. Primary users are the licenced users and they have all the rights to use these channels. On the other hand, secondary users are not the licenced users and legitimately do not have any right to access these primary channels. As already mentioned, that primary users are not capable to fully utilize the available spectrum bands. Secondary users may use the freely available spectrum bands for enhancing the spectral efficiency by protecting the communication among primary users. Fig. 3 illustrates the different spectrum access mechanism by showing the frequency of a channel on the x-axis and transmitting power on the y-axis.

Overlay and Underlay are the two fundamental spectrum access methods and both of them have their own pros and cons. As shown in Fig. 3, in overlay a secondary user is allowed to transmit with its maximum transmitting power if it found a free channel. In overlay access method, it is mandatory for a secondary user to detect a free (idle) channel before the transmission otherwise it must wait for a channel to become idle. Channel sensing is of vital importance in this access method. Generally there are two types of channel sensing, "one is in-band sensing and other is out of band sensing". Sensing errors are also bound to happen in the wireless scenario and require equal attention. Channel sensing errors like "false alarm and miss detection" are need to be addressed properly to protect the communication of primary users. It is clear that parallel transmission of primary and secondary users is not allowed in case of the overlay method. Once a secondary user found any channel in idle state, then only it can use its maximum transmission power to take the full advantage of the free available channel. In this way, a secondary user may increase its spectral utilization and also can maximize its own transmission capacity. Only drawback of this method is that, secondary users can only use the channel when it is not being used by the primary users. On the other side, underlay access method allows the parallel transmission of primary and secondary users. But this parallelism comes with a very hard and stringent constraint of honouring the "Interference Threshold Limit (ITL)" as shown in Fig. 3. ITL is a predefined temperature threshold limit for a primary receiver inside a cognitive radio network. As according to this method secondary users can transmit even in the presence of the primary users, but at the same time they all need to control their transmission powers. This must result in a "minimum generated interference (well below the ITL) at the primary receiver all the time". Interference mitigation is really a daunting task in case of the underlay access method. Interference mitigation requires the continuous feedback Channel State Information (CSI) by a secondary user to decide its transmission power level. The process of receiving the correct feedback up to the secondary transmitter regarding the generated interference at the primary receiver, may be interrupted by the many different channel errors including the sensing errors. If ITL related issues are not properly managed, then it may hamper the performance of the primary users as well as of the secondary users. The good side of this method is that, secondary users need not to wait for a channel to become idle.

Many studies in the past have proved that neither "underlay and nor overlay" is good enough to makes the full utilization of the freely available radio spectrum bands. In fact both the access methods have their own transmission limitations inside the cognitive radio networks. Many researchers suggested the use of the hybrid access methods to further maximize the spectral usage. As already discussed that the utilization of radio spectrum is not only very low but it also suffer from the imbalance usage. The "Industrial, Scientific, and Medical (ISM) frequency bands" and cellular bands are experiencing overburden, while on the other hand TV transmission bands are very much underutilized especially in the rural areas and during the night times. In principle, any hybrid access method allow the change in the transmission mode at run time depending upon the status of a primary user inside a channel. This run time switching from overlay to underlay and vice-versa has been proven worthy especially in the lightly loaded radio spectrum bands. It has contributed positively in the performance enhancement for the cognitive radio networks.

A very critical question in all the hybrid access methods is that, when to switch the transmission mode and when not to switch. This work tries to answer one such question by proposing a Markovian based hybrid spectrum access technique for the cognitive radio networks. The rest of the article is structured as follows. Section 2 gives a summary of the related work. Section 3 presents the system model. Section 4 presents and discusses the achieved simulation results by making use of the OMNeT++ simulator [11]. Section 5 presents the conclusion and challenges along with the future scope for this work.

1.3. Contribution

This work proposed a Markov chain-based hybrid access method named as Hybrid Spectrum Utilization Technique (HSUT), which tries to maximize the radio spectrum utilization by enhancing the PU's detection probability. It models the primary user channel as a three state channel using the discrete time Markov chains. The concept of transition probability matrix and the fundamental matrix were used to correctly predict the behaviour of the PUs. Further, it analyzes the performance of the HSUT and results obtained through OMNeT++ simulator are very encouraging. At last, this work also compares the performance of the HSUT with the overlay, underlay, Hybrid-P1 [12], and the Hybrid-P2 [12] access methods.

2. Related work

Overlay access method and underlay access method are the two prominent access methods in the area of cognitive radio networks. Both of them have their own inherent limitations in the process of maximizing the radio spectrum utilization. Hybrid access methods have been found quite handy in the aforementioned process of spectrum utilization. Many hybrid access methods have been proposed by different researchers at various levels. This section also presents a brief overview of the already work done in the direction of spectrum access methods. In [13], Zhang et al. proposed a Markov based hybrid spectrum access method for the cognitive radio networks. At the beginning of each time slot, the proposed method dynamically decides the transmission mode between the overlay and underlay access methods. Finally, this paper find out the "trade-off between the throughput and energy consumption". In [14], Shih et al. proposed a MAC protocol named as DH-MAC to enhance the spectral efficiency in the cognitive radio networks. This protocol allows a secondary user to switch its channel operations according to the activities of a primary user. Authors also claimed that the proposed protocol provides the better throughput for secondary users and more protection to the primary users. In [15], Chu et al. studied a Markov based hybrid and cooperative spectrum access scheme for cognitive radio networks. This scheme provides the flexibility to the secondary users of switching between the interweave and underlay mode based on the activities of the primary users. Further, this work also analysed the performance of a cooperative cognitive radio network "on the different parameters namely, symbol error rate, outage probability, and outage capacity".

In [16], Xu et al. emphasized on minimizing the level of "signal-to-interference-plus-noise ratio (SINR)" at the primary receiver for obtaining the good performance out of a cognitive radio network. Authors also proposed the two different solutions for minimizing the SINR for small scale and large scale networks separately. In [17], Huang et al. presented a comprehensive survey of the energy efficient spectrum sensing and spectrum sharing techniques for the cognitive radio networks. Authors also discussed the possible challenges in the designing of a energy aware cognitive radio network. In [18], Wang et al. developed a hybrid spectrum access mode for the cognitive radio networks which can switch its operation between underlay and overlay mode. Furthermore, authors also developed an optimal transmission strategy to guarantee a minimum quality of services for the secondary users traffic. The aforementioned transmission strategy also improves the throughput of the cognitive radio networks. In [19], Mehmeti et al. compare the performance of underlay and interweave spectrum access methods in a cognitive radio network. This paper provides an analytical study based on queueing theory to find out which method performs better as compared to the other. Average delay was considered as the performance metric for the comparison of both the methods. Finally, authors proposed a hybrid spectrum access technique that allows dynamic switching to further improve the performance of secondary users. In [20], Xu et al. presented an analytical study to calculate the optimal bandwidth for the secondary users to maximize their long term throughput in a cognitive radio network. Then authors also presented the suboptimal solution to maximize the short term throughput for the secondary users. Finally, this work presents a channel reconfiguration scheme to improve the overall performance of a cognitive radio network.

In [21], Mehmeti et al. provides the analytical comparison between the two dominant radio spectrum access methods in the cognitive radio networks namely, underlay and interweave. The comparison was done mainly on two network parameters namely, throughput and delay. Further, authors also presented a hybrid access method which allows to the secondary users to change the transmission mode from underlay to interweave and vice-versa depending upon the network conditions. In [22], Jasbi et al. introduced a hybrid communication system for improving the spectrum access in the cognitive radio networks. The introduced system exploits both the dominating spectrum access methods of cognitive radio networks namely, underlay and overlay. This system uses the underlay method to minimize the interference for the primary users and also uses the overlay method to maximize the data transfer rate for the secondary users. In [23], Gmira et al. presented a game theoretic based hybrid transmission system for improving the spectrum efficiency in the cognitive radio networks. The presented system is constrained with the SINR constraint at the primary receiver. The presented system also claimed to optimize the sensing time and energy consumption. In [24], Tragos et al. provided a detailed survey of the different spectrum allocation schemes in the cognitive radio networks. The presented work emphasized on the concept of "white spaces or spectrum holes" and also highlighted the role of cognitive radio technology in this context. Finally, this paper presented a detailed analysis of the different spectrum allocation schemes.

In [25], Senthuran et al. presented a detailed mathematical analysis of the spectrum access techniques in the cognitive radio networks. This paper proposed a Markov based hybrid transmission system to further enhance the throughput for the secondary users. Hybrid strategy provides the flexibility for secondary users to switch their transmission mode from overlay mode to the underlay mode and vice-versa. Finally, simulation results proved the analytical results and found very encouraging as far as the throughput improvement of the secondary users is concerned. In [26], Liang et al. optimized the sensing duration to correctly detect a primary user for maximizing the throughput of the secondary users in a cognitive radio network. This work also formulated a "tradeoff between the sensing duration and the achievable throughput for the secondary users". Furthermore, authors also discussed the impact of cooperative spectrum sensing and distributed spectrum sensing on the performance of a cognitive radio network. In [27], Kumar et al. presented "a comprehensive survey of the spectrum access methods namely overlay and underlay in the cognitive radio networks. This paper also compares the overlay and underlay methods on many different network parameters and finally it also analysed the performance of both the access methods" using the OMNeT++ simulator.

In [28], Le et al. proposed a channel transmission model for improving the throughput of the secondary users in the cognitive radio networks. Authors also introduced an overlapped channel assignment technique and compare it with the "non-overlapped technique and also claimed that the overlapped technique" performs better in terms of throughput. In [29], Htike et al. proposed a MAC protocol based on the concept of "Common Control Channel (CCC)" for exchanging the control information among the secondary users in a cognitive radio network. This work also presented a hybrid approach to improve the efficiency of secondary users and further proved, that the hybrid approach provides the better results. In [30], Gupta et al. presented the basic concepts for the cognitive radio networks in detail. Furthermore, authors also introduced a game theoretic based channel assignment model for further improving the performance of a cognitive radio network. In [31], Dhurandher et al. "presented a spectrum access model based on the contract theory for further improving the performance of a TDMA cognitive radio network". In [32], Touati et al. proposed an optimal and suboptimal routing protocols for the cognitive radio networks. This paper also proposed a K-hops routing protocol that allows a good compromise between the complexity and the performance of a cognitive radio network. In [33], Tong et al. "proposed a new power strategy and channel-allocation optimization for secondary users (SUs) in an orthogonal frequency-division multiplexing (OFDM)-based cognitive radio (CR) network where the coverage area of the secondary network is divided into an overlay region and a hybrid region. Simulation results validate the effectiveness of the proposed method in terms of energy efficiency".

In [34], Amer et al. proposed the concept of cooperative spectrum access mode in the cognitive radio networks. Authors also proposed a hybrid spectrum access technique, that allows to make a choice between underlay access mode and cooperative access mode depending upon the channel condition. The proposed hybrid technique was claimed to increase the performance of secondary users in terms of the achieved throughput and same was proved in the paper with the help of simulation results. In [35], Joykutty et al. discussed the role of spectrum sensing in the performance of a cognitive radio network. This paper presented the recent advances in the domain of radio spectrum sensing for correctly detecting the status of primary users in a particular channel(s). Furthermore, authors also discussed the importance of security and also the issues related to security in the area of CRNs. In [36], Ma et al. presented a Markov chain based hybrid channel transmission system for the cognitive radio networks. In this work, authors concluded that the transmission capacity of secondary users is significantly enhanced in the hybrid spectrum access mode. In [37], Usman et al. proposed an energy efficient hybrid system for the cognitive radio networks. Authors modelled the proposed communication system using the partially observable Markov decision framework. This work also presented a very innovative way of harvesting the energy for the secondary users. Finally, this work compare the proposed hybrid access method with the overlay access method and concluded that the hybrid method provides better throughput and also prolonged the lifetime of secondary users in the network. In [38], Sivagurunathan et al. presented the different types of spectrum sensing techniques along with the challenges and issues in the implementation of these techniques in the area of CRNs. In [39], Do et al. examined the network connectivity in a CRN, where a secondary user may use either overlay or underlay access method. In [40], Anjitha et al. discussed a switching system that allows secondary users to control their transmitting power which is further resulted as the improved throughput in a CRN. In [41], Zhao et al. presented an energy efficient protocol that makes a trade-off between the power transmitted and the amount of information transferred. Simulation results showed a significant improvement in the network throughput. In [42], Latif et al. presented a biological based evolutionary algorithm for channel allocation problem in the CRNs. Extensive simulation results justified the importance of presented algorithm. In [43], Liu et al. proposed a "nonorthogonal multiple access (NOMA)" based radio spectrum allocation method in the area of "Cognitive Industrial Internet of Things (CIIoT)". To improve the spectrum access performance a cluster-based CIIoT is proposed. The simulation results proved the significance of the proposed method over the traditional access methods. In [44], Liu et al. proposed a spectrum allocation method for multibeam satellite "Industrial Internet of Things (IIoT)". The concept of "nonorthogonal multiple access (NOMA)" is applied in this method to realize the long distances quality transmission. At the end of the article, simulation results validate the utility of the proposed method. In [45], Liu et al. emphasized on the shortage of radio spectrum resources keeping in view the rapid development in the area of "Internet of Things (IoT)" and 5G Networks. This paper proposed an energy efficient 5G based IoT communication system that is capable of transmitting 5G networks and IoT data simultaneously.

3. System model

The correct identification of the primary users behaviour is a real challenge in the process of maximizing the utilization of the white spaces or spectrum holes in a cognitive radio network. This section presents a Markov based hybrid channel transmission system to maximize the radio frequency spectrum utilization in a cognitive radio network. This work models the proposed hybrid transmission system using the "Discrete Time Markov Chains".

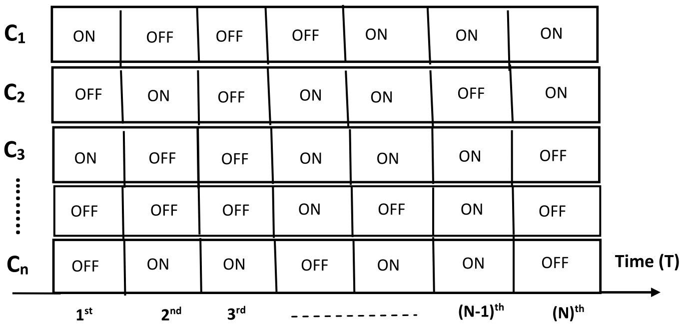

Fig. 4. Primary users channel occupancy pattern.

3.1. Markov chains

"A Markov chain may be defined as a stochastic process whose development may be treated as a series of transitions between certain states of that process. Basically Markov chains are classified into two broad categories namely as Discrete Time Markov Chains and Continuous Time Markov Chains. A Discrete Time Markov Chain allows the state transition only at the boundary of a time slot. In a Markov chain, the next state of any system depends only on the current state of the system or in other words, current state of the system depends only on the previous state of the system. The conditional probability for a transition from the nth time slot to $(n+1)th$ time slot is given by the following equation":

$$P_{ij}(n) = Prob\{X_{n+1} = j | X_n = i\} \tag{1}$$

The transition probability matrix $T(m,n)$ as shown below provides the conditional probability of transition from state i to state j.

$$T(m,n) = \begin{pmatrix} T_{00}(m,n) & T_{01}(m,n) & \dots & T_{0j}(m,n) & \dots \\ T_{10}(m,n) & T_{11}(m,n) & \dots & T_{1j}(m,n) & \dots \\ T_{20}(m,n) & T_{21}(m,n) & \dots & T_{2j}(m,n) & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ T_{i0}(m,n) & T_{i1}(m,n) & \dots & T_{ij}(m,n) & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots \end{pmatrix} \tag{2}$$

As per the definition, all the elements presented in the transition probability matrix $T(m,n)$ must satisfy the following requirements:

$$T_{ij}(m,n) \geq 0 \qquad \text{for all } i,j \tag{3}$$

$$\sum_j T_{ij}(m,n) = 1 \qquad \text{for all } i \tag{4}$$

"A Markov chain X_n is said to be a finite Markov chain with j states, if the number of possible values of the random variables X_n is finite and equal to j. The transition probabilities T_{ij} are then non-zero for only a finite number of values of i and j, and the transition probability matrix T is then a jxj matrix". This work considers that the value of variable j is 3 i.e., proposed system is having "three different states namely B (Busy), I (Idle), and S (Suspicious)".

3.2. Primary users behavioural characteristics

Fig. 4 depicts the behaviour of primary users in a particular primary channel. In this figure, x-axis shows the time slots which range from 1 to N and y-axis shows the primary channels from C_1 to C_n. Fig. 4 also illustrates the channel occupancy patterns of these channels by the many primary users.

The value *OFF* for a particular time slot indicates that the channel is idle i.e., no primary user is using this channel in that particular time slot. Similarly, the value *ON* for a particular time slot indicates that the channel is busy i.e., a primary user is using this channel in that particular time slot. As seen from the figure, that the channel occupancy pattern of primary users is quite irregular or quite random. This is but obvious, as the primary users are licenced users and they have all the rights to access these channels as per their requirement. The correct identification or prediction of channel occupancy pattern for any of the primary channel has never been an easy task. Cognitive radio is capable of identifying the status of a primary user by using the sensing capability. In addition to it, the primary users behaviour may be predicted through the several mathematical techniques available like Markov

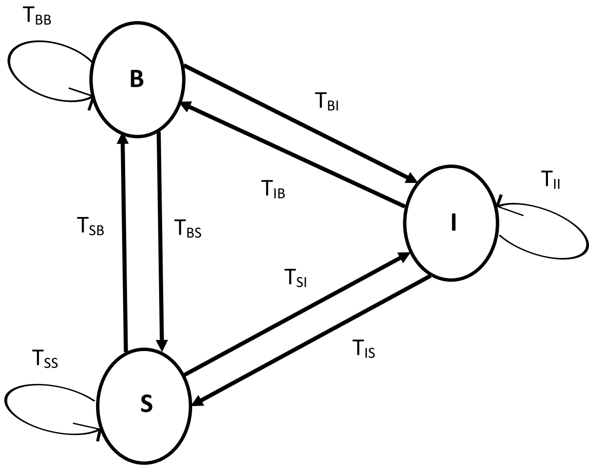

Fig. 5. Primary user channel as seen by secondary users.

Process, game theory, and queuing theory etc. This work uses the Markov chain, which is also known as a special kind of Markov process to predict the behaviour of any primary user in a particular channel. As already mentioned, secondary users are unlicensed users (also called as cognitive users) in a cognitive radio network and they have the lower channel access priority as compared to the primary users inside the network. So, correct identification or prediction of primary users status on any of the primary channel is of utmost importance. Only by doing this, free spectrum holes may be better utilized and secondary users performance may be enhanced without disturbing the transmission among the primary users. At last it would significantly enhance the performance of a cognitive radio network.

3.3. Proposed hybrid transmission method

The proposed hybrid method models a primary channel in “three different states namely B (Busy), I (Idle), and S (Suspicious)”. It means a primary channel is considered here as a three transient states Markov chain as depicted in Fig. 5, where the next state of any channel depends only on present state of that channel.

3.3.1. Markovian primary user channel

Fig. 5 characterizes a primary channel in three transient states as seen by the secondary users. Transient states mean that a primary channel may change its state from any given state to any other state at the beginning of a particular time slot. All the three states are described below:

State B (Busy): “Primary user is using the channel, and secondary user is not allowed to use this channel because contrary to it would interfere the primary user’s transmission. A secondary user may use this channel only when it is made free by the primary user.

State I (Idle): No primary user is using this channel right now and the channel is said to be free (Idle). A secondary user may use the channel at this moment with its maximum transmission capacity to fully utilize the channel. Obviously when there is no primary user in the channel at this moment, it will do no harm to any primary user.

State S (Suspicious): Although primary user is using the channel, but at the same time a secondary user is allowed to transmit its data with limited power. A secondary user can transmit by controlling its transmission power level so that the interference generated at the primary receiver is well below the predefined threshold ITL. Hence in this state the achievable transmission capacity would be low due to the lower value of the transmission power for a secondary user.

The elements of a transition probability matrix represents the transition probabilities for moving from one state to any other state. T_{C_1} matrix represents the conditional probability for a transition from any one state (out of B, I, S) to any other state (out of B, I, S) in the channel C_1. The transition probability matrix T_{C_1} may be easily computed by using the $T(m, n)$ matrix as shown in Eq. (2) above” [12].

$$T_{C_1} = \begin{pmatrix} T_{BB} & T_{BI} & T_{BS} \\ T_{IB} & T_{II} & T_{IS} \\ T_{SB} & T_{SI} & T_{SS} \end{pmatrix} \tag{5}$$

“If any secondary user wish to use a primary channel then first it needs to sense the channel based on the transition probability matrix as shown above. Also the transition probabilities must be used by the secondary user in a priority order of T_{II}, T_{SI}, and T_{BI}, where T_{II} has the highest priority and T_{BI} has the lowest priority. We are assuming here that the primary users traffic is positively correlated. For such a traffic the transition probability of returning to the same state is higher than the transition probability of moving to any other state" [12]. For example,

$$T_{II} > T_{IS} \text{ or } T_{IB} \tag{6}$$

$$T_{SS} > T_{SI} \text{ or } T_{SB} \tag{7}$$

$$T_{BB} > T_{BI} \text{ or } T_{BS} \tag{8}$$

Eqs. (6)–(8) approved the priorities order of transition probabilities as discussed above.

3.3.2. Potential and fundamental matrices of a Markov chain

As the elements of a transition probability matrix provides the transition probabilities for moving from one state to any other state. The elements of the potential matrix of a Markov chain gives the *expected number of times a particular state is visited* by the Markov chain, provided that the Markov chain starts in a given state.

$$P = \begin{pmatrix} P_{00} & P_{01} & \dots & P_{0j} & \dots \\ P_{10} & P_{11} & \dots & P_{1j} & \dots \\ P_{20} & P_{21} & \dots & P_{2j} & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ P_{i0} & P_{i1} & \dots & P_{ij} & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots \end{pmatrix} \tag{9}$$

Let P_{ij} be "the expected number of times that state j is visited given that the Markov chain starts in state i, and let P be the potential matrix whose $ijth$ element is P_{ij}". The matrix P is also expressed as:

$$P = \sum_{n=0}^{\infty} T^n \tag{10}$$

where T is the transition probability matrix as discussed above. Further, the part of potential matrix which is responsible for the *transitions from one transient state to another transient state is called the fundamental matrix*. The fundamental matrix is represented as follows:

$$F = \begin{pmatrix} F_{BB} & F_{BI} & F_{BS} \\ F_{IB} & F_{II} & F_{IS} \\ F_{SB} & F_{SI} & F_{SS} \end{pmatrix} \tag{11}$$

The $ijth$ element of a fundamental matrix gives the "expected number of times the Markov chain is in transient state j, given that it started in transient state i." Further Eq. (11) may be rewritten as:

$$F = \sum_{k=0}^{\infty} T^k \tag{12}$$

Now Eq. (13) gives the "expected number of visits to transient state j given that the Markov chain started in transient state i." The matrix F may be formulated further as:

$$F = I + T + T^2 + \cdots \tag{13}$$

where I represents the identity matrix.

$$F - I = T + T^2 + T^3 + \cdots = TF \tag{14}$$

$$F - TF = I \implies (I - T)F = I \tag{15}$$

and F also satisfies the,

$$F(I - T) = I \tag{16}$$

Because,

$$FT = TF = T + T^2 + \cdots \tag{17}$$

Now by using the Eqs. (14) & (17), following expression may be computed:

$$I = (I + T + T^2 + \cdots)(I - T) \tag{18}$$

By applying Eq. (13) and using the geometric progression formula of summation from 0 to infinity, F may also be written as:

$$F = \sum_{k=0}^{\infty} T^k = I + T + T^2 + \cdots = \frac{1}{(I - T)} \tag{19}$$

which implies that,

$$F = \sum_{k=0}^{\infty} T^k = I + T + T^2 + \cdots = (I - T)^{-1} \tag{20}$$

Finally F may be concluded as follows:

$$F = (I - T)^{-1} \tag{21}$$

The Eq. (21) suggests that the fundamental matrix F may now be very easily computed using the transition probability matrix T. As already mentioned that the elements of a fundamental matrix provides *the mean number of times* the Markov chain visits to a particular transient state, provided that the Markov chain starts in another given transient state.

3.3.3. Operational details

This section provides the operational details concerning of finding an optimum channel(s) for the secondary users and also provides the details regarding the selection of a transmission method.

"The Eq. (5) calculates T_{C_1}, similarly matrices T_{C_2}, T_{C_3}, and T_{C_n} may be computed for the channels C_2, C_3, and up to C_n respectively, assuming there are n primary channels in the cognitive radio network.

Let vector $V_t = \{T_{BI}, T_{II}, T_{SI}\}$

$$V_{tmax} = \max_{V_t} \bigcup_{i=1}^{n} T_{C_i} \tag{22}$$

As the vector V_t represents the three different transition probabilities and for all of them outgoing state is common with the state value I (Idle). So V_{tmax} provides the vector with the *maximum transition probability* that the channel state will enter into the state I (Idle).

Further by referring to the Eq. (5) and also applying the Eq. (21), matrices F_{C_1}, F_{C_2}, and F_{C_n} may be computed for the channels C_1, C_2, and up to C_n respectively.

Let vector $V_f = \{F_{BI}, F_{II}, F_{SI}\}$

$$V_{fmax} = \max_{V_f} \bigcup_{i=1}^{n} F_{C_i} \tag{23}$$

As the vector V_f represents the three different values of *mean number of times* and for all of them outgoing state is common with the state value I (Idle). So, V_{fmax} provides the vector with the *maximum mean number of times* that the channel state will enter into the state I (Idle).

Furthermore, let us consider vector V_{tfmax} as follows:

$$V_{tfmax} = V_{tmax} + V_{fmax} \tag{24}$$

Now according to the proposed hybrid access method (HSUT), a secondary user would select the channel with the maximum value of vector V_{tf} and in that way *it enhances its chances of getting an idle primary channel*. This is exactly the primary goal of any secondary user in a cognitive radio network. If a secondary user still does not find any of the channel in the idle state, then it must switch its transmission to the underlay mode for a duration of one time slot. Now If a secondary user is neither getting any of the channel in I (Idle state) nor S (Suspicious state) at the time slot t, then it must wait for one time slot. Further at the beginning of the next time slot $t+1$, it must re-examine the vector V_{tfmax} for finding the next available idle channel(s). This entire process must be repeated by a secondary user in the order as specified above, to always look for a better transmission opportunity available inside a cognitive radio network" [12]. Algorithm 1 outline the steps required for the spectrum access using the proposed hybrid access method.

3.3.4. Performance analysis

This section analyzes the performance of the proposed hybrid access method as presented above. As already discussed, Eq. (11) gives the "expected number of times the Markov chain is in a transient state j, given that it started in any given transient state i."

$$\text{So, mean number of visits to state I} = F_{BI} \tag{25}$$

considering that the Markov chain started in state B. Similarly if the Markov chain started in state S, then

$$\text{Mean number of visits to state I} = F_{SI} \tag{26}$$

Algorithm 1 :Hybrid Spectrum Utilization Technique (HSUT)

1: Initialize: Number of PUs, Number of SUs, Number of Primary Channels = n, time slot t = 0
2: begin
3: for i = 1 to n do
4: {
5: $V_t = \{T_{BI}, T_{II}, T_{SI}\}$
6: $V_f = \{F_{BI}, F_{II}, F_{SI}\}$
7: }
9: $V_{tmax} = \max_{V_t} \cup_{i=1}^{n} T_{C_i}$
10: $V_{fmax} = \max_{V_f} \cup_{i=1}^{n} F_{C_i}$
11: $V_{tfmax} = V_{tmax} + V_{fmax}$
12: if $C_i == C_{V_{tfmax}}$
13: Transmission in Overlay mode on channel C_i
14: else if $C_{V_{tfmax}}$ = = null
15: {
16: while (t ! = 1)
17: Transmission in Underlay mode
18: else
19: {
20: while (t ! = 1)
21: No transmission
22: }
23: }
24: go to step 3
25: end

Further, the mean number of time steps the Markov chain spends in transient state I is given by the following expression:

$$\text{Mean number of time steps spent in state I} = \frac{1}{(1 - T_{II})} \tag{27}$$

By using Eqs. (25), (26), and (27), the total time spent by the Markov chain in state I can be calculated as follows:

$$T_{BI} = (F_{BI}) \cdot \frac{1}{(1 - T_{II})} \tag{28}$$

and,

$$T_{SI} = (F_{SI}) \cdot \frac{1}{(1 - T_{II})} \tag{29}$$

Now, throughput (Ψ_{PH}) for the proposed access method can be expressed as follows:

$$\Psi_{PH} = R_O \cdot (T_{BI} + T_{SI}) + R_U \cdot T_S \tag{30}$$

Here R_O and R_U are the channel data rates in the overlay and underlay methods receptively for the proposed access method (HSUT). Here $(T_{BI} + T_{SI})$ represents the total time for a particular channel, that the channel is in the idle state. T_S represents the time for a particular channel, that the channel is in the suspicious state. It is quite evident that,

$$R_O \quad > \quad R_U \tag{31}$$

4. Simulation results and analysis

This section presents and discusses the simulation results carried out on the many different network parameters. OMNeT++ simulator [11] was used for the simulation purpose. OMNeT++ simulator was chosen, as it provides the framework to simulate the different types of networks including the wireless networks. GUI (graphical user interface) and animating facility is much better in OMNeT++ as compared to the other network simulators. The OMNeT++ simulator can effectively monitor and captures the physical layer details and also facilitates the higher layers protocols. This simulator also supports the simulation of the cognitive radio networks. Table 1 shows the different simulation parameters used during the simulation process.

Fig. 6 shows the flow chart for the simulation procedure. Networks in the OMNeT++ simulator are designed using the reusable simple modules. These simple modules are to be written in C++ language. Then these simple modules are to be connected to form a compound module. A wired or wireless network in OMNeT++ is a compound module itself. OMNeT++ simulator can be downloaded from [11] and can be installed as per the instructions given in OMNeT++ Installation Guide [11]. To start the simulator

Table 1
Simulation parameters.

Name of parameter	Value of parameter
Total simulation time	10 000 s
No. of iterations	500
No. of PUs	10
No. of SUs	10
No. of primary channels	8
Channel data rate	2 Mbps
SU packet length	500 Bits
Slot duration	20 ms
PU arrival probability	0–1

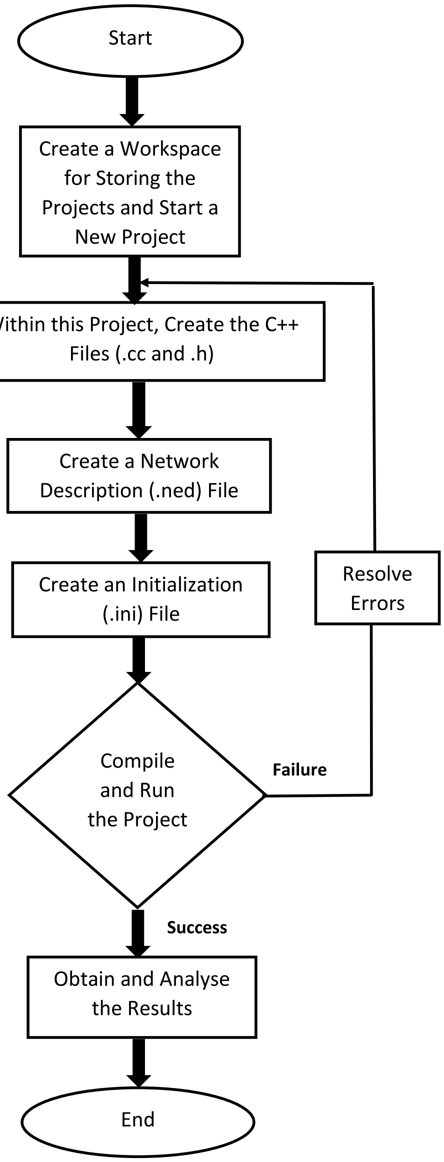

Fig. 6. Flow chart for simulation model.

you need to type the command omnetpp in terminal or directly it can be run using the short cut as created on the desktop during the installation. Now at the very first step, one need to create a workspace for storing the projects. After creating the workspace, any new project can be started in that workspace. Now within this project, one needs to create the C++ files (.cc and .h), which contain

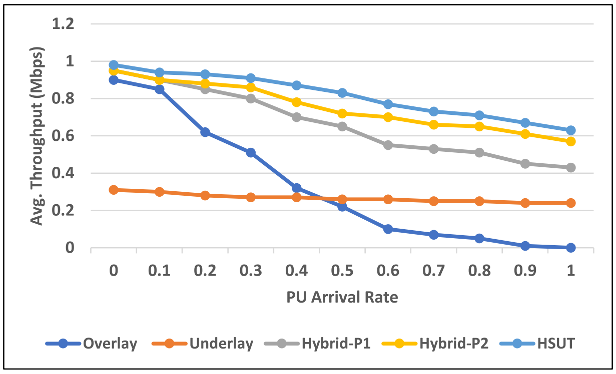

Fig. 7. SU throughput versus PU arrival rate.

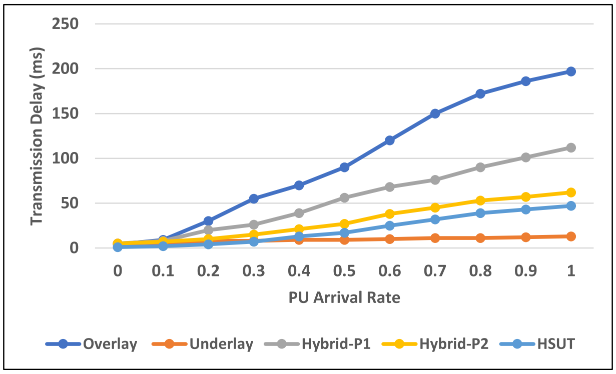

Fig. 8. Transmission delay versus PU arrival rate.

the implementation of the simple modules. Then one needs to create a Network Description (.ned) file. This file is used to create the topology of the network. Then initialization (.ini) file needs to be created and it is used for assigning values to the different network parameters. Finally for obtaining the simulation results, one needs to compile and run the project as per the instructions given in the OMNeT++ User Manual [11].

Fig. 7 shows the impact of PUs arrival rate on the SUs throughput. When the arrival rate of PUs is very low, there is not much difference among the throughputs achieved by the overlay, Hybrid-P1, Hybrid-P2, and the HSUT methods. Throughput achieved in the underlay method is very low as compared to the all other access methods. This is so because that in the underlay method, each SU has to honour the *Interference Thresholds Limit (ITL)* by controlling their transmission power. The throughput achieved by the underlay method is almost constant for all the different PUs arrival rates, reason being that SUs are allowed to transmit even in the presence of PUs. As the PU arrival rate increases, throughput of the overlay, Hybrid-P1, Hybrid-P2, and the HSUT methods starts decreasing, but it decreases very sharply for the overlay method. During this time interval, HSUT performs much better in comparison to the Hybrid-P1 and Hybrid-P2 access methods. This is so because, HSUT uses the fundamental matrix along with the transition probability matrix to find the idle channels. As a result of it, proposed method (HSUT) always provides more number of idle channels and thereby SUs have better transmission opportunities in HSUT as compared to the all other access methods considered here.

Fig. 8 shows the impact of PUs arrival rate on the transmission delay for the SUs. When the PUs arrival rate is very low, the transmission delay for all the access methods is almost negligible. But as the PU arrival rate increases, transmission delay in the overlay method increases very sharply. HSUT outperforms the Hybrid-P1 and Hybrid-P2 methods for almost all different PU arrival rates. The reason for the same is already mentioned in the description of Fig. 7. Transmission delay for the underlay method is almost constant and infact lowest for the entire duration. This is so because in case of underlay method, any SU need not to wait for the channel to become idle, as this method permits parallel transmission of SUs with PUs.

Fig. 9 shows the impact of the number of SUs on the achievable throughput by the SUs. When there are very small number of SUs, not much difference is observed among the throughputs of the overlay, Hybrid-P1, Hybrid-P2, and the HSUT access methods. At this point of time throughput achieved in the underlay method is lowest, reason being all SUs need to control their transmission power to honour the ITL. As the number of SUs increases, the throughputs for the overlay, Hybrid-P1, Hybrid-P2, and the HSUT methods decreases with the increasing value of the number of SUs. Here HSUT outperforms the overlay, Hybrid-P1, and the Hybrid-P2 access methods. The throughput achieved in the underlay method is almost same for all the cases, for the reasons as already mentioned above.

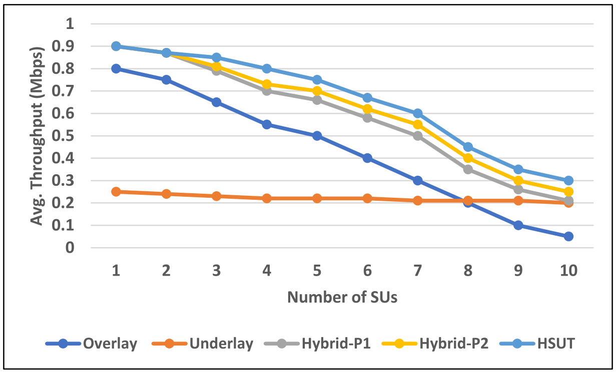

Fig. 9. Throughput versus number of SUs.

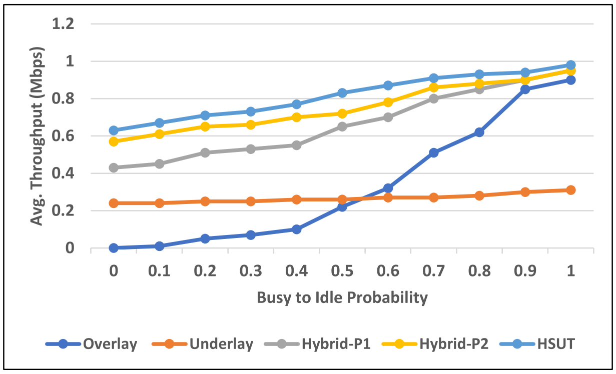

Fig. 10. Throughput versus busy to idle probability.

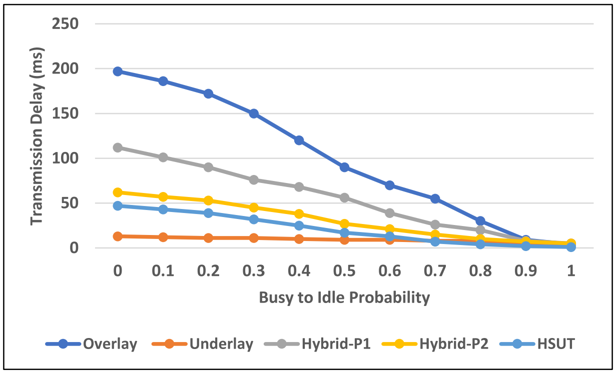

Fig. 11. Transmission delay versus busy to idle probability.

Fig. 10 shows the impact of busy to idle probability on the throughput of the SUs. It is evident from this figure that the HSUT outperforms all other access methods for the reason as already mentioned in the description of Fig. 7. When the busy to idle probability is very low, there is not much transmission opportunities available in the overlay method and that is why it achieves the lowest throughput among all other access methods. The performance of the underlay method is again almost same, as it allows the parallel transmission of PUs with SUs with the limited transmission power. As the value of busy to idle probability increases, the overly method finds the more transmission opportunities and as a result of it, the throughput gain for this method increases very sharply.

Fig. 11 shows the impact of busy to idle probability on the transmission delay of SUs. The transmission delay is highest in the overly method for the low vale of busy to idle probability. This is so because at this point of time, there is hardly any idle channel is available for SU's transmission. For this case, underlay, Hybrid-P1, Hybrid-P2, and the HSUT access methods perform well as all these methods allow SUs transmission even in the presence of the PUs obviously with the controlled transmission power. As the busy to idle probability increases, all the methods increase their chances of getting the idle channel(s) and that is why the transmission delay of all the methods decreases and almost touches 0 when the busy to idle probability is equal to 1.

5. Conclusion

Optimization of Radio-frequency spectrum utilization is of vital importance nowadays. This paper proposed a Markov based hybrid access method to further enhance the spectrum utilization in a cognitive radio network. This work analysed the performance of the proposed method by doing the mathematical modelling based on the Markov chain. Simulation was also carried out using the OMNeT++ simulator for many different network parameters. Achieved simulation results proved the significance and utility of the proposed method, especially when simulation results were compared with the overlay, underlay, Hybrid-P1, and the Hybrid-P2 access methods. The proposed method combines the advantages of overlay and underlay methods to further enhance the utilization of the unused spectrum holes. This work assumed that the primary user traffic is positively correlated and it also assumed that the channel sensing process is perfect. These may be treated as the limitations of this research work. In future work, optimization of sensing duration can also be done along with the PUs behaviour prediction for further improving the Radio-frequency spectrum utilization. Prediction of primary users' behaviour, secondary users' transmission power control, managing the ITL, and protection of primary users from secondary users' transmission are considered as the key challenges in the process of further improving the Radio-frequency spectrum utilization in the cognitive radio networks.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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