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NS-2 Based Simulation Framework for Cognitive Radio Sensor Networks

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Abstract In this paper, we propose a simulation model for cognitive radio sensor networks (CRSNs) which is an attempt to combine the useful properties of wireless sensor networks and cognitive radio networks. The existing simulation models for cognitive radios cannot be extended for this purpose as they do not consider the strict energy constraint in wireless sensor networks. Our proposed model considers the limited energy available for wireless sensor nodes that constrain the spectrum sensing process - an unavoidable operation in cognitive radios. Our model has been thoroughly tested by performing experiments in different scenarios of CRSNs. The results generated by the model have been found accurate which can be considered for realization of CRSNs.

Keywords Cognitive radio · dynamic spectrum access · wireless sensor networks · cognitive radio sensor networks · simulation model.

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1 Introduction

Wireless sensor networks (WSNs) are battery powered devices that can sense, transmit and relay data continuously to the other information-seeking nodes. Due to their battery-powered nature, the sensors are designed for low-power low-range transmissions, and the network operates in a multi-hop fashion where information is relayed through multiple intermediate nodes. WSNs have been traditionally designed with fixed channel coding schemes, and therefore work in a fixed range of frequencies. As a consequence, the available spectrum quickly gets occupied as the density of sensor nodes increases. However, although occupied, the channel is still under-utilized as wireless sensors are designed to cap-

Simulator patch	Goal	Platform	WSN	CRSN	MC	PR activity	EM
NS-2 [1]	A discrete event network simulator	C++	✓	✗	✗	✗	✓
J-Sim [2]	A simulation framework for WSNs	Java	✓	✗	✗	✗	✓
Mannasim[3]	A simulation environment for WSNs	NS-2	✓	✗	✗	✗	✓
MiXiM[4]	A framework for fixed and mobile wireless networks	OMNeT++	✓	✗	✗	✗	✓
NRL Sensorsim [5]	A project to facilitate sensor network simulations	NS-2	✓	✗	✗	✗	✓
JiST / SWANS [6]	A high performance discrete event simulation engine	Java	✗	✗	✗	✗	✓
S3 [7]	A simulation tool for security problems in WSNs	C++	✓	✗	✗	✗	✓

Table 1: Simulation models and their goals to simulate the networks in literature

ture periodic (or sporadic) events that generally transmit short bursts of traffic and remain silent rest of the time [8]. This issue has fueled a new concept of adding cognitive radio capabilities in WSNs, usually termed as cognitive radio sensor networks (CRSNs). CRSNs are the opportunistic sensor networks wherein nodes have the ability to sense vacant channels (called *spectrum sensing*) and change their transmission parameters accordingly (called *spectrum decision*). CRSNs are comprised of two kinds of nodes: primary radio (PR) nodes and the cognitive radio (CR) sensor nodes [9]. The CR capable node can be configured to use both the licensed and unlicensed bands. Like traditional WSNs, the CRSN nodes are also energy-constrained devices and therefore the issue of minimum power consumption is equally important in both types of networks. In fact, it becomes even more challenging in CRSNs due to an additional task of spectrum sensing. CRSNs have gained so much importance in real world scenarios that in near future, all the sensor based applications will require CRSNs. Some real world applications of CRSNs are battle-field surveillance, food items security, health monitoring, railway track selection and smart grids etc. [10]. Efficient CRSNs deployment requires dynamic protocols that can perform accurate channel sensing along with energy conservation. This channel sensing will also contain channel selection among all multiple channels present in the network. PR activity also plays an important role in the channel selection process therefore the impact of PR activity also needs to be considered. For this purpose, CRSN simulation models are required which should be able to utilize the channels which are free from PR traffic and can disseminate the data in multi-hop scenario.

Extensive simulations are being required for any network before deployment to optimize the deployment procedure as well as to achieve required goals from the network. Simulations for WSNs can be done in various simulators such as NS-2 and OMNET++. NS-2 has been generally considered to be the suitable platform for WSN simulations. To the best of our knowledge, there exists no simulator model for CRSNs in NS-2 which is the primary motivation behind this work. We provide an environment where CRSN nodes can be modeled in the presence of several multiple channels wherein various types of PR activities may occur. CR nodes can use these channels whenever they are free from PR activity and send their data to other nodes

Simulator patch	Goal	Platform	CRN	CRSN	MC	PR activity	EM
CogNS [11]	A simulation framework for CRNs	NS-2	✓	✗	✓	✗	✗
Cr simulator [12]	A discrete simulation model for CRAHNs	OMNeT++	✓	✗	✓	✗	✗
CRNRM [13]	A routing model for CRNs	NS-2	✗	✗	✓	✗	✗
TFRC-CR [14]	A transport layer protocol for CRNs	NS-2	✓	✗	✗	✗	✗
CRAHN [15]	Modelling of end-to-end protocol for CRAHNs	NS-2	✓	✗	✗	✓	✗
CRCN [16]	A patch for simulating CRN based networks	NS-2	✗	✗	✗	✗	✗
[17]	The consideration of energy model for WSNs	NS-2	✗	✗	✗	✗	✓
[18]	An event triggered node energy model for WSNs	OPNET	✗	✗	✗	✗	✓

Table 2: Simulation models for CRNs and their objectives

in a multi-hop fashion. As all the nodes in CRSNs are considered as wireless nodes, therefore power consumption of nodes has been carefully observed in our proposed model. A user can simulate different topologies for CRSN environment including the number and density of nodes, available number of channels, noise, and other possible network parameters.

The proposed simulation model has been tested in different scenarios like changing the PR activities, topologies, density of nodes and number of available channels. The simulation results generated by the model have been thoroughly tested and validated for the generated scenarios. The remaining paper is organized as below: section 2 discusses the related work on traditional networks simulators; CRSN simulator requirements have been discussed in section 3; section 4 then provides CRSN simulator model; Simulation details have been given in section 5 and the topic concludes in section 6.

2 Related Work

Wireless network simulators are usually software tools or scripts that are developed/written to gain insight into the behavior of a given wireless network under a given scenario. Some simulators have been implemented as hardware or hybrid systems but they are not widely used for research due to their high costs. In a simulator, the wireless network can be described as a set of parameters, for example, number of nodes, density of nodes, network topology, mobility model, traffic generation model, signal power, waveform type, channel coding method, and contention schemes etc. The environment can also be described in a similar way, for example, terrain map, interference patterns, and type and intensity of noise etc. The purpose of simulation vary from experiment to experiment, however, most of these experiments measure network performance in terms of bit error rate (BER), packet error rate (PER), throughput, goodput, and latency. This is not the exhaustive list as there exist several other measures, and some of which may have greater significance in their specific domain of applications. For example, WSNs consist of battery powered wireless sensor nodes, therefore the overall power consumption and transmission range of these nodes must be investigated when simulating these networks. Similarly, in case of CRNs, the activities of CR nodes should not affect communication among primary nodes; therefore PR-CR interference becomes a highly important metric that must be minimized in

Ref.	Year	Description	Simulator Used or Not	Platform	MC	PR Activity	EM
[19]	2014	A packet size adaptation scheme to conserve the node energy	Not Used	-	-	-	-
[20]	2012	The exploration of transport protocols for delay sensitive transport in CRSNs	Used	NS-3	✗	✗	✗
[21]	2013	A power control scheme to address the communication requirements of CR based industrial WSN	Not Used	-	-	-	-
[22]	2011	To minimize the total power consumption of CRSN node	Not Used	-	-	-	-
[23]	2014	A scheme to preserve node power for enlarging network life time for CR based VANETs	Not Used	-	-	-	-
[24]	2007	An adaptive modulation scheme to maximize the network life time	Not Used	-	-	-	-
[25]	2008	A distributive power allocation algorithm to minimize the energy consumption	Not Used	-	-	-	-
[26]	2010	A scheme for selection of CR nodes with best detection performance	Not Used	-	-	-	-
[27]	2011	An architecture to model and implement a cognitive sensor network	Used	Custom	✗	✗	✗
[28]	2011	A framework to analyze the performance of CRSN	Not Used	-	-	-	-
[29]	2011	A channel management scheme to enhance energy efficiency of CRSN	Not Used	-	-	-	-
[30]	2011	An investigation of channel assigent problem for CRSN	Not Used	-	-	-	-
[31]	2011	A dynamic scheme to increase the delivery ratio and throughput of CRSN	Not Used	-	-	-	-
[32]	2012	A scheme to select optimal packet size to improve energy utilization	Not Used	-	-	-	-
[33]	2012	A channel assignment scheme for CRSNs	Not Used	-	-	-	-
[34]	2012	A scheme to select optimal transmit power for CRSNs	Not Used	-	-	-	-
[35]	2012	A user selection scheme to minimize overhead energy consumed by CRSNs	Not Used	-	-	-	-
[36]	2013	A cluster based co-operative architecture for CRSNs	Not Used	-	-	-	-
[37]	2014	A spectrum-aware cluster-based energy-efficient routing protocol for CRSNs	Not Used	-	-	-	-
[38]	2014	A spectrum-aware clustering scheme for CRSNs	Not Used	-	-	-	-

Table 3: Overview of simulations work for CRSNs

these networks. Network simulators are very useful tool to perform sensitivity and trend analysis. They have the ability to generate those scenarios that are not easily achievable in practice due to high cost involved in empirical methods. However, it is important to realize that the simulation is not a real experiment, and therefore, great care must be taken at understanding the model, its limitations, and its results.

By far, the most widely used simulation tools for wireless networks are NS-2 [1] and OMNET++ [39]. WSNs include wireless nodes which sense and transmit the required parameters upon occurrence of specific event. Table. 1 provides the list of some widely used simulation models available for WSNs. In literature, there is a wide variety of simulators available for WSNs which cannot be included here due to limited space. There are many platforms which support simulation of WSNs such as NS-2, OMNeT++, Java and C++ etc. Among these platforms, NS-2 and OMNeT++ are the most commonly used simulators in the network community. Since NS-3 is currently in developing phase and it will take few more years for NS-3 to become credible, thus, we have chosen NS-2 for our simulation model. Moreover there is another simulation patch i.e., CogNS, however, it does not supports PR activity.

These days most of the wireless equipment are using Industrial, Scientific and Medical (ISM) radio band for communication. Due to humungous increase of the Wi-Fi and Bluetooth enabled devices, the ISM band of 2.4 GHz has started becoming overly saturated. As a consequence, unlicensed traffic has been allowed to also operate in the TV broadcast range. The spectrum dedicated for TV broadcasts can be used for data communication in a cognitive way [40]. This concept emerged the technology of CRNs where CR nodes can opportunistically access the licensed spectrum without creating any harmful interference to PR nodes.

For a practical approach, a simulation model should provide all the blocks which are required for CRNs and CRSNs. Three main blocks which are MC (multiple channels), PR activity and EM (energy model) are required for CRSN simulation have been discussed and implemented in the proposed technique due to which the proposed simulation model is a complete and practical approach towards simulation of CRSNs. The issue of energy consumption has been elaborated in more detail in [18] and an event triggered based node energy model has been presented. As traditional WSNs do not consider multiple channels and cognitive radio capabilities so these features are missing in above mentioned work.

Many CR based models have been proposed in literature (see table. 2) that can be used to simulate CR networks. However, some important features like PR user activity and multiple channels support are missing in these models. Moreover, traditional CR based networks are assumed to have no constraints on energy consumption, and therefore, energy model must be introduced for wireless nodes containing limited power.

The CR based issues are mostly related to physical layer where transmitting parameters need to be changed according to availability of free channels, but the importance of media access layer (MAC) and network layer cannot be neglected. In CRSNs, data dissemination is usually achieved using multi-hop scenario and a particular channel can be selected on the basis of PR occupancy and the number of CR nodes sharing the channel. Reliable data dissemination becomes a complex task in multi-hop CRSN where no central entity is present for coordination among CR nodes. If a CR node selects a channel randomly, it is highly unlikely that the neighbor receivers will also tune to the same channel. In such scenarios, decisions should better be taken at network layer since a complete picture of the whole network can be obtained at network layer [41].

In [42], authors have performed a detailed review of simulation tools for intelligent vehicular networks. The issues of wireless communication between the nodes have been elaborated for researchers. Modeling of wireless links and wireless signal propagation and simulation models available for these networks have been discussed. The authors have also pointed out the importance of simulator tools for authentication of generated results which highlights the necessity of this step while performing simulations. The importance of application scenario while performing a simulation has been elaborated in [43] in which authors simulated various applications for mobile opportunistic networks and concluded that performance of simulation model varies with types of application under consideration. A number of famous and reliable simulation platforms including NS-2, NS-3 [44] and OMNet++ are available for simulating WSNs and CRNs but none of these platforms provide CRSNs based simulation model. As summarized in Table. 2, we can analyze that no simulation model at present is providing support for combined features of WSNs and CRNs. It has been also demonstrated in Table. 3 that mostly researchers are using analytical methods to understand the behavior of CRSNs. Those researches which are being performed using NS-3 or custom designed simulators are not assuming the required metrics for CRSNs. Hence, to simulate a CRSN, it is required that all the issues of WSNs and CRNs should be considered in multiple channel and multi-hop scenario for realization of CRSNs.

2.1 WSNs in NS-2

NS-2 is a platform which provides user to simulate wireless networks scenarios and many contributions have been made to add advanced functionalities in the simulator. Various analytical models and performance analysis techniques for ad hoc networks have been discussed in [45]. Specifically, the simulation environment for WSNs is available in NS-2 but CRNs simulations cannot be performed without adding the CR based functionalities. A CRN based tool has been developed for NS-2 in [16], and is available online, but this work has not been adopted widely by the researchers. The possible reasons can be the lack of multiple channels support at MAC layer and that the PR activity has not been supported for cognitive radio environment. The issue of accuracy and credibility has also been raised for these simulation models [46]. The authors in [14] have presented an equation based transport layer protocol while simulating for CRNs. They have first performed spectrum management to utilize the available channels in an opportunistic manner and simulations are done in NS-2. Another transport layer end-to-end protocol for cognitive radio network tool is provided by authors in [15]. This tool has also been developed for NS-2 and it provides PR activity analysis and routing based on this activity but multiple channel support is also missing in this work. The authors in [13] have proposed a routing layer model for CR based networks in NS-2. Their focus is to enhance throughput by performing efficient routing but existence of multiple channels effects throughput hence channel selection becomes also crucial to achieve high throughput.

2.2 CRNs in NS-2

A comprehensive evaluation of CR based network in the presence of multiple channels has been performed in [11]. The authors have given a brief study of impact of multiple channels on packet drop probability, TCP end-to-end packet delay, TCP throughput and average packet size to satisfy QoS using NS-2. [47] has used NS-2 for flooding packets in the network using sensor networks and estimated the accuracy of generated results. Another CR based simulation model for cognitive radio ad-hoc networks has been presented in [12] for OMNeT++ simulator. The authors have designed their tool for only two data channels which is very limited when considering the CR based network and also no PR activity has been assumed. There are bundle of application areas where no simulation or estimation can be performed without considering PR activity over the data channels. [48] discussed the concept of smart grids and estimation of electricity requirement for all home appliances through ZigBee but as ZigBee operates in Industrial, Scientific and Medical (ISM) band so there is high probability of interference among appliances with in a home. The only promising solution rests with CR based appliances connected with smart meter which communicates with the grid. The home area networks (HAN), neighbor area network (NAN) and wide area network (WAN) of smart grid applications can be simulated using NS-2 simulator keeping in

Activity Type	Purpose	Pattern
Long PR activity	Utilize spectrum for special call packages	Long ON and long OFF periods
High PR activity	Utilize spectrum in congested areas or during rush hours	Long ON and short OFF periods
Low PR activity	Utilize spectrum in rural areas or during less peak hours	Short ON and long OFF periods
Intermittent PR activity	Utilize spectrum for short duration of time	Short ON and short OFF periods
Mixed PR activity	To have an un predictable pattern over the spectrum	Mixture of multiple activities

Table 4: PR activity patterns

view the complexity of NS-2 as network grows [49]. To summarize the discussion, there is a need of the time for such a simulation model which should be capable of considering all the parameters of cognitive radio sensor networks and generate the results which should be acceptable for research community. [50] emphasizes on the need of such simulator because to make the best use of scarce spectrum CR based technologies are growing tremendously but the challenge is to co-exist with PR nodes with avoiding interference. In this context, a CRSN simulator is presented in this work which collectively takes all the parameters of WSNs and CRNs to ensure the accuracy of CRSN simulation model. This model is not only easy to integrate but is also scalable for any further additions in the network. NS-2 [51] has been chosen as simulation platform due to its vast application and acceptability of results by research community.

3 CRSN Simulator Requirement

There are some specific requirements for implementation of CRSNs so they need to be discussed before going into the details of CRSN simulator. Upon fulfilling these requirements, the CRSN simulator will become general and can be applied to any sort of wireless environment with variable length of multiple channels and various kinds of PR activities.

3.1 Multiple Channels

In the literature, as discussed in related work section, a very little work has been done by assuming multiple channels when simulating CR based networks. However cognitive radio environment cannot be simulated in its true spirit in the absence of multiple channels. Among multiple channels present in the network, the suitable channel is selected and transmission parameters are adjusted dynamically according to the channel requirement. The number of multiple channels impacts throughput and packets drop probability [11]. It is due to the fact that the larger is the size of available channel set, harder is the decision of selecting same set of channels between source to destination. This is a basic concern of CR based network that there should be multiple channels in the network so that when these channels are not utilized by PR nodes, they become available for CR nodes. Also the functionality of multiple channels should be scalable so that number of multiple channels can be increased/decreased according to specific application requirements. The broadcasting of hello packets over multiple channels in NS-2 has been demonstrated by [52]. Once hello packet has been transmitted in the whole network successfully, the data packets can be sent in the same fashion on the channels from where acknowledgement of hello has been received. According to some special requirements of nodes, channels can be assigned to some nodes on fixed basis too or otherwise routing layer makes decision about the selection of channels.

3.2 PR activity

As CR based networks are opportunistic networks, so only those frequency slots can be utilized by CR nodes which are free from PR traffic. Hence impact of PR activity is very important on the performance of CR nodes. A detailed survey on the types of PR activities and their implementation depending on network type has been given in [53]. PR activity models give the information about behavior and spectrum utilization by PR users. By using this information, CR users can predict the future states of PR users and can utilize best available spectrum bands for their communication. In literature various PR activity models have been proposed for implementation in different network scenarios. We can classify them in four major classes such as Markov process, queuing theory, time series and ON/OFF periods. Markov process has been widely used by researchers to estimate the PR user activity in CR based networks [54–58, 41, 59–62]. This class has been also widely implemented for developing spectrum sharing mechanisms in medium access control (MAC) for CRNs, dynamic spectrum sharing and CRSNs. Queuing theory has been used for modeling PR activity where PR user medium access delay and average packet delay can be used to calculate PR user queue length [63–66]. Time series modeling is used to estimate spectrum occupancy in GSM based networks [67, 63] and ON/OFF periods are used to model PR activity. The presence of PR user is represented by ON period and when there is no PR activity over the channel, OFF period is represented by Fig. 1. This model has been also used by other models like two-state markov model where BUSY state is represented by ON period and IDLE state is represented by OFF period. ON/OFF periods are also widely used in super WiFi concept. Super WiFi is WiFi like internet service which takes opportunistic access of spectrum holes in the network [68–72].

The PR activity i.e. the presence or absence of PR signal can be modeled as continuous-time, alternating ON/OFF Markov Renewal Process (MRP) [73]. The effect of PR activity on network performance by channel selection has been evaluated by [57]. Five kinds of PR nodes activity patterns have been considered in this simulator are elaborated in Table. 4.

3.3 Energy Model

As inherited from WSNs, CRSNs are energy constrained networks in which node energy determines the network lifetime. The ability of node to use cognitive capabilities and dynamic selection of best channel requires intelligent protocols at network and mac layer level. These intelligent protocols are more complex and consume more power which reduces the node life. While simulating CRSNs, it is necessary to consider the relation between required QoS parameters and node's energy. To optimize this, the energy model for WSN can be used by

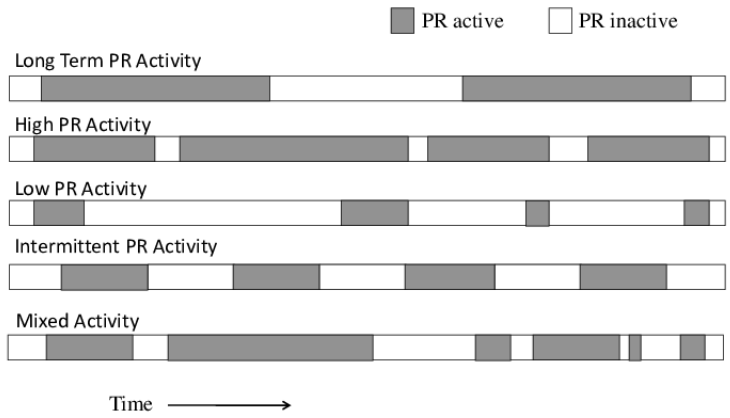


Fig. 1: Types of PR activities

considering cognitive capabilities and its effects on energy.

4 The Proposed CRSN Simulation Model

The complex system of computer network is facilitated by the concept of layering. Using the layering structure, the functionalities of communication networks can be handled. This layering structure makes smooth progress of peer-to-peer relationship between corresponding layers in two communicating nodes. In the layering stack, each layer represents a well defined function and provides its services to the immediate upper layer. The accessibility between two layers is made possible through interfaces and the function of each layer is called its protocol. It is worth mentioning here that each layer in the stack is independent in its operation. It means whatever protocol a layer implements does not effects the functionality of its upper layers [51]. NS-2 has also become available on web by [74] providing integrated environment for remote simulation and analysis of simple wired as well as wireless networks. Beginners who do not want to go into the details of NS-2 installation can utilize this web-based application. The selection of platform for any simulation based model is very important. Custom designed simulators do not simulate and evaluate all the design parameters and results generated by them cannot be considered accurate. In contrast, choosing a standard framework increases the reliability of evaluation process and results. There should also be an understanding of validation of results which reflects the effectiveness of techniques [75, 76]. Along with tool selection, the assumptions made regarding wireless environment have their impact on the results. For authentic results, it is required that realistic assumptions should be made[77]. Various simulators for IEEE 802.11 and IEEE 802.15.4 have been compared in [78] and the need for more advanced and trustworthy simulators has been highlighted. The CRSN simulator model is developed for NS-2 platform. It is due to the reason that NS-2 is an open source event-driven simulator specifically designed for research in communication networks. The selection of NS-2 makes the design architecture of

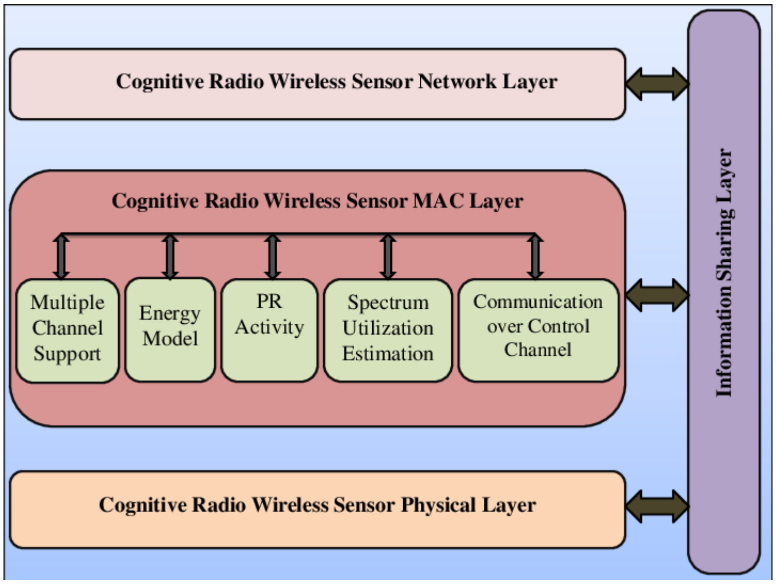


Fig. 2: CRSN simulator architecture

this model very simple. It is due to the reason that NS-2 already supports WSN and CRN simulation platforms.

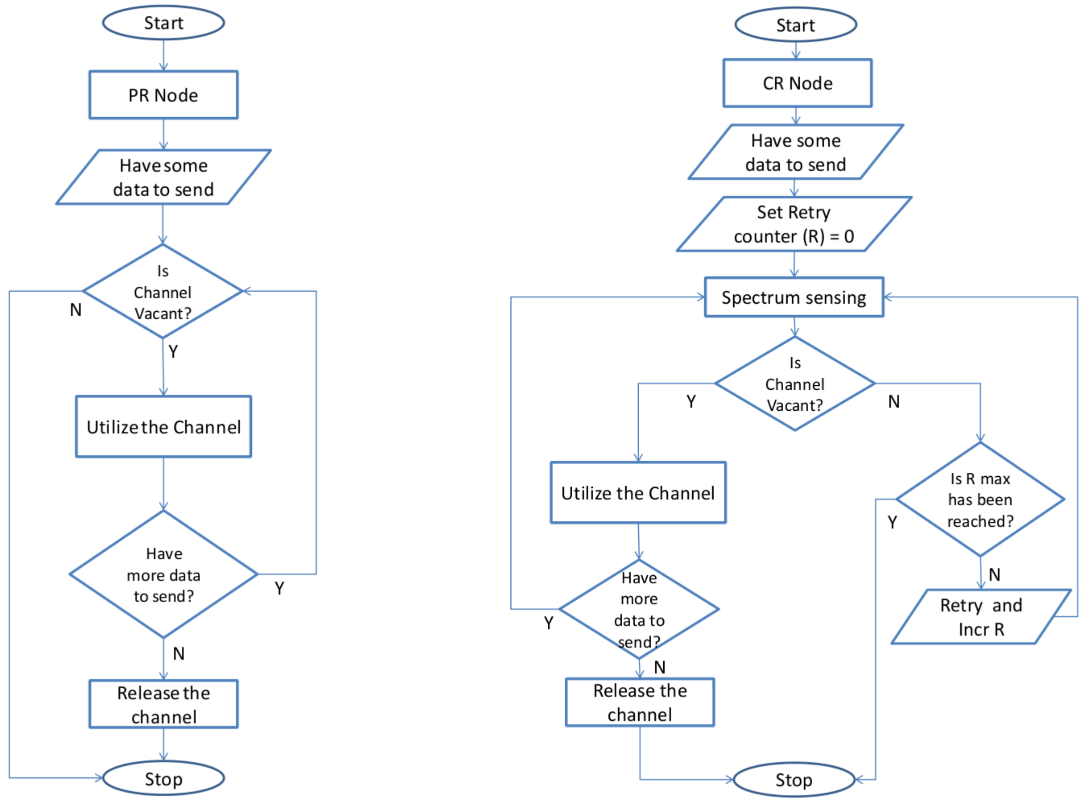
Some functionalities of CRN were missing such as multiple channel support and PR activity support which has been added in this proposed simulator. Another aspect of selecting NS-2 is the wide acceptability of this simulator in network research community. The results generated by this platform are accurate and give a real insight of issues of the network.

4.1 Architecture

In this section, the architecture of CRSN simulator will be discussed. The graphical representation of CRSN simulator architecture is shown in Fig. 2. In [79], authors have discussed that researchers should avoid using default parameters available in the simulators rather these parameters should be modified according to changes in the network. In our proposed simulator, simulation parameters like number of channels, PR activity over these channels, energy model have been modified and the following subsections will cover the details of those layers which have been modified in NS-2 for simulation of CRSN environment. These modifications have been made due to the requirements specific to CRSN and these can be changed according to implementation of CRSN in any particular scenario.

4.1.1 CRSN Network Layer

The network layer implementation allows user to select the suitable routing protocol. This routing protocol is responsible for transmission of packets from source to destination in multi-hop scenario choosing the best route. AODV is known as an efficient routing algorithm for wireless ad-hoc networks. [80] gives the comparison of multiple routing algorithms in NS-2 and AODV has performed well among all the multi-hop routing algorithms. In this simulator, AODV has been used as routing protocol of CRSNs and the functionality of multi-hop data dissemination has been added. In addition,



(a) (b)

Fig. 3: (a) Channel Occupancy by PR nodes. (b) Channel Occupancy by CR nodes.

network layer is also used to collect statistics of the network e.g. average delivery ratio, hop count, average delay between source to destination, harmful interference ratio, number of receivers etc. By keeping this data, network layer helps to improve the energy utilization of nodes. The nodes become aware of shortest path to the destination with minimum interference to PR nodes. The interference reduction results into less number of re-transmissions which saves energy.

4.1.2 CRSN MAC Layer

Medium access control in CR based WSN should be intelligent enough to provide the dynamic behavior of spectrum selection without creating any harmful interference to PR node activity. The MAC protocol must be able to sense the channel and selects the suitable one for CR node. It should be monitoring PR activity continuously and if there is any PR activity found on any selected channel, it should stop the CR traffic and release the channel for PR node. For this purpose CSMA is used to ensure channel utilization by both PR and CR nodes. To utilize the cognitive capabilities, multiple channels are added so that among these channels, the suitable channel for CR node can be selected to transmit the data. Once multiple channels are added in the simulator then PR activity is introduced on each channel as discussed in previous section. Here it is worth mentioning that activity pattern of PR traffic can be different on each channel hence it is functionality of CRSN MAC layer to select those channels which have low PR activity or the channels which can be available for CR nodes for a considerable amount of time. Along with PR traffic, MAC protocol for CRSN selects the suitable path on the basis of energy of nodes. The energy model provides information about the total energy, remaining life time and required energy to fulfill certain transmission. A channel can be either vacant or occupied. When vacant, it can be utilized by either PR or CR node. Fig. 3(a) represents that how a PR node utilizes a channel for its communication. If it has some data to be sent, it senses the channel and utilizes it accordingly. When its transmission has been completed, it releases the channel to be used by CR nodes. If a CR node needs a channel to transmit the data, it performs spectrum sensing to avoid any PR-CR interference as shown in Fig. 3(b). When it successfully transmits its data, it releases the channel for other nodes. If CR node detects that the channel is busy, it retries to access the channel with a limit assigned to number of retries. As we increase the number of channels, the CR nodes can sense the PR activity and can utilize the free channel. A large set of channels may result into increased sensing time but with decreased PR interference probability.

Cognitive Radio Cognitive Network (CRCN) patch provided by [16] has been used as base of our simulator model. This patch can be installed on NS-2 version 2.31 and provides CSMA based maccon protocol for channel sensing and selection. There are certain shortcomings in the CRCN patch which have been removed to become practical for application of CRSN based network. Channel sensing and selection is necessary due to presence of PR activity over the same set of channels but unfortunately no PR activity model is present in CRCN patch. To overcome this, PR activity block is added in the simulator and all the activities as discussed in section 3.2 have been implemented on the channels. Here one more thing is important to discuss that maccon protocol supports a single channel for packets transmission where as multiple channels are required for a CR based network so the suitable channel among a set of channels can be selected. To obtain this objective, multiple data channels are added in our simulator and all these channels have PR activities on them. The amount of time for which a channel is being utilized by a PR node is represented by a percentage called utilization factor. A high utilization factor tells that a channel is more busy and not suitable for a CR node to utilize it, whereas a low utilization factor shows a low PR traffic pattern over the channel which makes a channel suitable to be used by CR node. PR activity block which is added in our simulation model is a generalized block. For our simulations, ON/OFF PR activity has been used however other PR activities available in literature like Markov Process, Queuing Theory, Time series etc can also be implemented.

CRCN patch also lacks the implementation of energy model. As in CRSN scenario, energy is an important parameter to estimate the lifetime of sensor mote. Our simulation model is equipped with energy model which gives the energy status about all the wireless sensor nodes in the network. The route selection by network layer is done in connection with energy of all the nodes included in the route so that once selected,

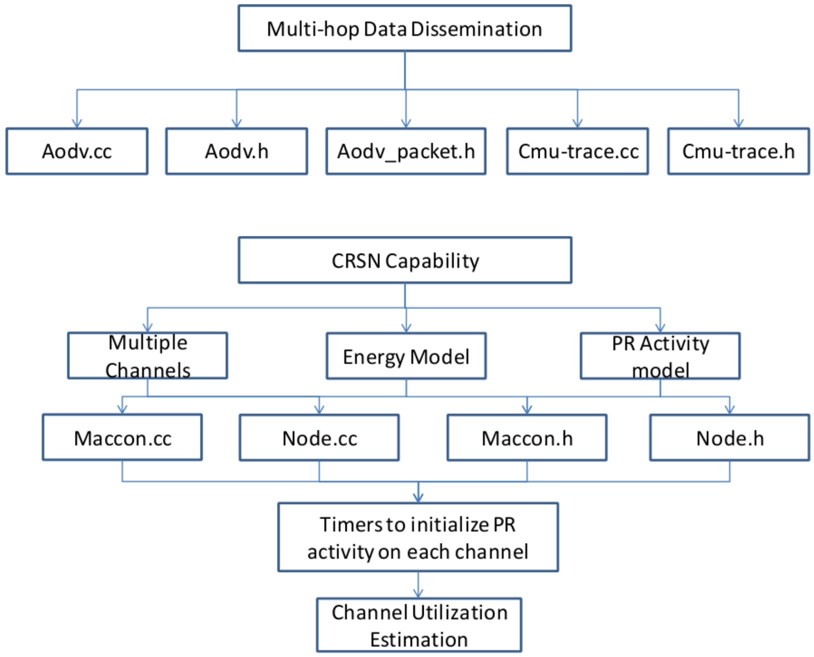


Fig. 4: Major files modified

all the nodes in the route should be able to complete the transmission of packet.

4.1.3 CRSN Physical Layer

Physical layer modeling effects the performance of higher level layers and hence the overall behavior of simulation model [81]. In [82], the author has also emphasized the need of such physical layer having cognitive capabilities where transmission radii can be selected at this layer dynamically and higher layers utilize this information for intelligent decision making. Physical layer for CRSN provide nodes the adaptability to the channel's condition. By using multiple physical interfaces, sensor nodes can operate at multiple frequencies by selecting one frequency channel at a time. The information regarding selection of frequency channel is given to this layer by MAC protocol of upper layer. The task of physical layer is to adapt the transmission parameters to communicate with the suitable channel.

5 Evaluation of Proposed CRSN Model

This section covers the details of simulation steps which are performed to implement CRSN simulator. After installing CRCN patch in NS-2.31, the first step is to enhance the functionality of AODV protocol to multi-hop data dissemination. For this purpose, we turn off all the functions of AODV and transmit only hello packets and get the acknowledgement from all the nodes in the network. Due to topological changes, sometimes it is quite possible that a node is sending a packet but cannot receive the incoming packets. To ensure the transmission and reception capabilities of all the nodes in the network, we select a random node every time for transmission and check that other nodes are receiving

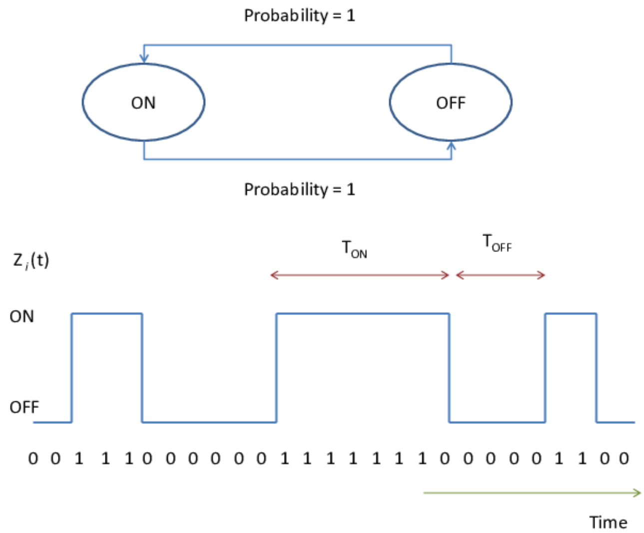


Fig. 5: Alternating Markov Renewal Process for PR activity

the packet or not. We control the selection of transmitting node and the time when transmission starts through a simple tcl script and generate traces. To perform these changes, we need to modify aodv.cc, aodv.h, aodv_packet.h, cmu-trace.cc and cmu-trace.h as shown in Fig. 4. All these files can be found in AODV and trace folders located at the base directory of NS-2.31. We have added customized packet to be transmitted using AODV routing protocol. For adding this packet, we need to make modifications in aodv.cc and aodv.h. The packets class in AODV is dependent on aodv_packet.h so it also needs to modify. The traces of packets are generated through cmu-trace.cc and cmu-trace.h. We have also modified these accordingly to show the traces of packet while transmission through multi-hops.

The flow of simulation starts from tcl script. In tcl script, we specify the type of protocols applied at network and MAC layer. We also mention the radio propagation model for physical wireless channel. Other network parameters, such as, number of multiple channels, number of wireless sensor nodes and total simulation time have been also mentioned in tcl script.

Tcl script calls the network layer protocol i.e. AODV which performs neighbor discovery through our customized packet to reach the destination node. The AODV then passes its packet to the MAC layer for hop-to-hop delivery of data. MAC layer then initializes multiple channels for each node and implement PR activity. The presence or absence of PR activity is the key factor to select the channels for CR node. MAC layer selects those channels for CR node which are free from PR activity or less occupied by PR nodes.

For addition of multiple channels and PR activity, we need to modify CSMA based maccon protocol. The protocol by default supports a single-channel single-hop transmission without any PR activity over the channel. We first extend the number of channels and convert it into a generic entity so that each time user can vary the number of data channels present in the network. For each channel, there is a timer associated with it which

Parameters	Values
Number of nodes	50
Number of channels	10
Size of simulation area	1000*1000
Radio propagation model	Two-ray ground model
Network interface type	Wireless PHY
Routing protocol	AODV
MAC type	Mac/Maccon
PR activity	ON / OFF MRP
Simulation time	52 sec

Table 5: Simulation Parameters

determines the occupancy of channel. We need to modify maccon.cc and maccon.h present in the mac folder to make these changes. To extend the number of channels, NS-2 sets the maximum number of channel up to 12, we have used 10 channels but if any network requires more than 12 channels support, some modifications are required. A variable named as "Maxchannel" contains the maximum allowable multiple channels. The value of this variable should be increased and this variable can be found in three header files namely topography.h, phy.h and mobilenode.h. Increase the value of this variable at three mentioned places up to a maximum limit where multiple channels can exist.

After successful addition of multiple channels, next thing comes to the implementation of PR activity over each channel. PR activity gives the information about presence or absence of PR users over the channel. It can be modeled as continuous-time, alternating ON/OFF Markov Renewal Process (MRP) [83, 56]. This PR activity model has been widely used in the literature [56, 83–87]. The ON/OFF PR activity model approximates the spectrum utilization pattern of voice networks [88] and also very famous for public safety bands [87, 89]. Fig. 5 shows the model of a wireless channel where the ON state represents that channel is currently busy and occupied by PR node. The OFF state represents that channel is idle and unoccupied by any PR node. The time duration for which the channel i is in ON and OFF states are denoted as T^i_{ON} and T^i_{OFF} respectively. The duration which a channel takes to complete one consecutive ON and OFF period is called renewal period. Let this renewal period for a channel i at time t is denoted by $Z_i(t) = T^i_{ON} + T^i_{OFF}$ [56, 90, 91]. Both ON and OFF periods are assumed to be independent and identically distributed (i.i.d). Since each PR user arrival is independent so according to [91], each PR user arrival follows the poisson arrival process and the length of ON and OFF periods are exponentially distributed. The time duration for which a channel i is being utilized by PR user is called utilization factor of i^{th} channel and can be written as

$$u^i = \frac{E[T^i_{ON}]}{E[T^i_{ON}] + E[T^i_{OFF}]} \qquad (1)$$

where $E[T^i_{ON}]$ and $E[T^i_{OFF}]$ are the expected values of exponential distribution [90]. In this way any kind of PR activity can be added by describing the pattern as discussed in [41]. The formulations are easily implemented in maccon.cc and maccon.h and with the help of these formulations, we can estimate the number of successful attempts to access a channel, number of collisions with PR nodes which caused harmful interference etc. We control the activity of PR nodes on channels and number of channels from the same tcl script as discussed earlier so that each time user does not need to modify the code file. Similarly we have added the energy model in maccon protocol to sense the energy of CRSN node. To pass the values to the upper layer i.e.

network layer we need to modify node.cc and node.h so that network layer is aware of node's energy.

For validation of implemented modules, some results have been included for each kind of PR activity. As followed by simulation parameters shown in Table. 5, we are using 10 channels and performed simulations for all five kinds of PR activities as discussed in section 3.2 on each channel. The number of channels can be increased as per user requirement. The results shown in Fig. 6 elaborate the impact of PR activities on channel's utilization over complete simulation time. Long term PR activity (as shown in Fig. 6(a)) contains long ON and long OFF periods. This trend also reflects in the plot that channel utilization distribution is even by PR users and a long high channel utilization is followed by a long low utilization. This type of activity is found where PR users are subscribed to some special packages to utilize the channels. CR users can opportunistically use these channels because after a long ON there is high probability of long OFF period which can be useful for opportunistic spectrum access.

Fig. 6(b) gives the implementation of high PR activity which is showing that most of the time all channels are being occupied by PR nodes. If a CR user attempts to access such a channel having high PR activity, there is a high percentage that it will cause harmful interference to the PR users. As there are very short white spaces in the channel, it is recommended that only when CR nodes have very little data to transmit can use such channels.

The most suitable PR activity for any CR user has been shown in Fig. 6(c). It is clearly evident from the plot that very few numbers of channels are being occupied by PR nodes throughout the simulation time. This type of activity can be found in rural areas or less peak hours. CR users can take maximum utilization in these durations when there is low PR activity over the channel. As there are very little chances of interference with PR users, so a less sensitive (less complex) channel sensing algorithm can be used which will preserve the node energy as well. Intermittent PR activity (as shown in Fig. 6(d)) has short ON and short OFF periods and number of occupied channels are showing this behavior. This type of PR activity is found where users come for a very short duration of time. Examples of such scenario can be airports, bus terminals etc. To utilize such a channel having intermittent PR activity, it is required that CR nodes must be capable of fast channel sensing and selection and equipped with powerful battery modules.

If more than one activity type is found over the network, it is called as mixed PR activity (Fig. 6(e)). This kind of activity occur where behavior of PR users vary from time to time. For such kind of activity, it is difficult for a CR node to select a band with a probability to complete its transmission.

We can estimate the channel utilization by any PR activity using Fig. 7 where for each type of PR activity the total utilization of all channels has been represented. It is evident from Fig. 7(a) that long PR activity is appearing for almost 50 % of total simulation time and for rest of the time the channels are idle. An effect of high PR activity can be seen in Fig. 7(b) in which the utilization factor of all channels are 80%-90%. In

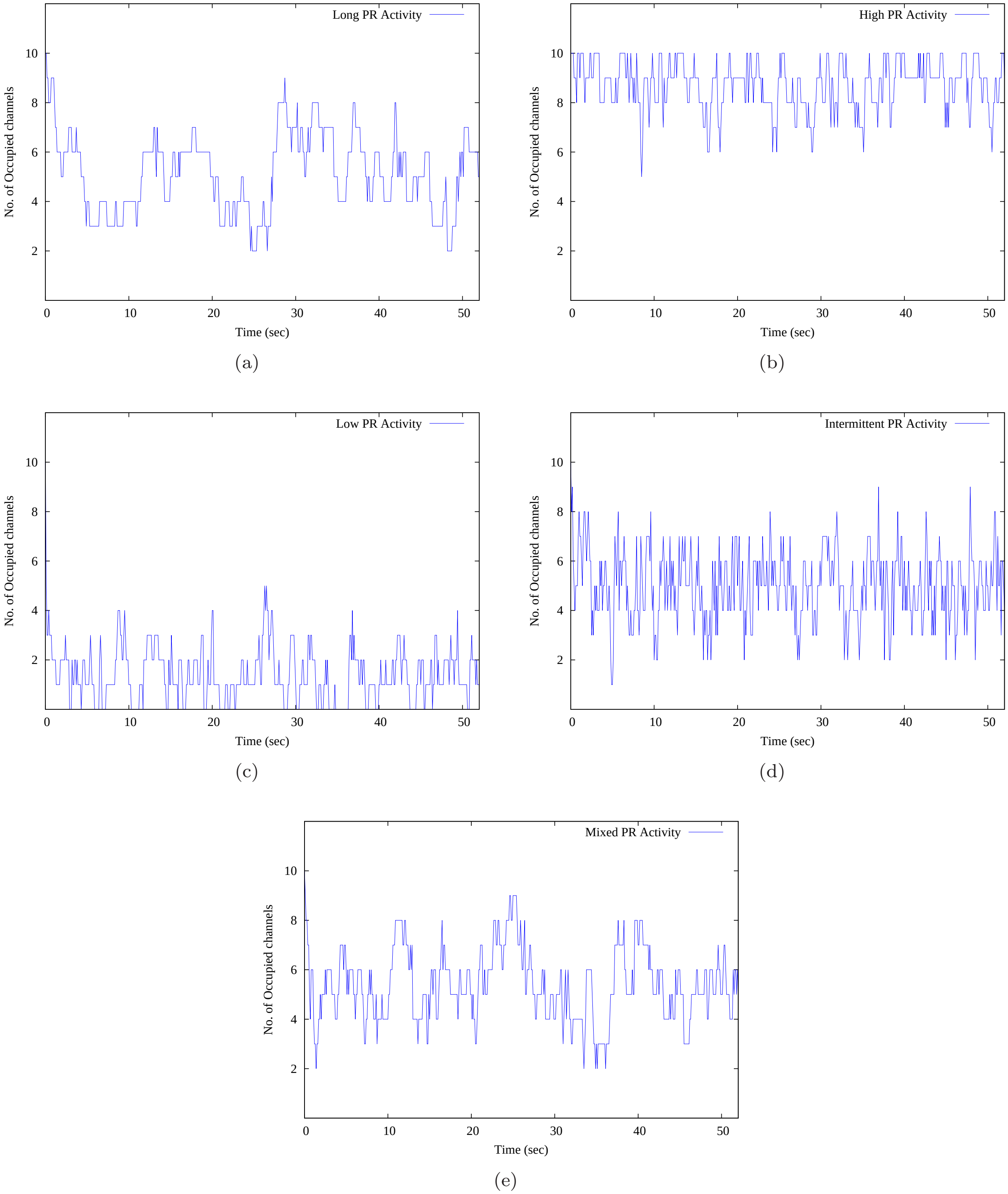


Fig. 6: Channels utilization by PR activities

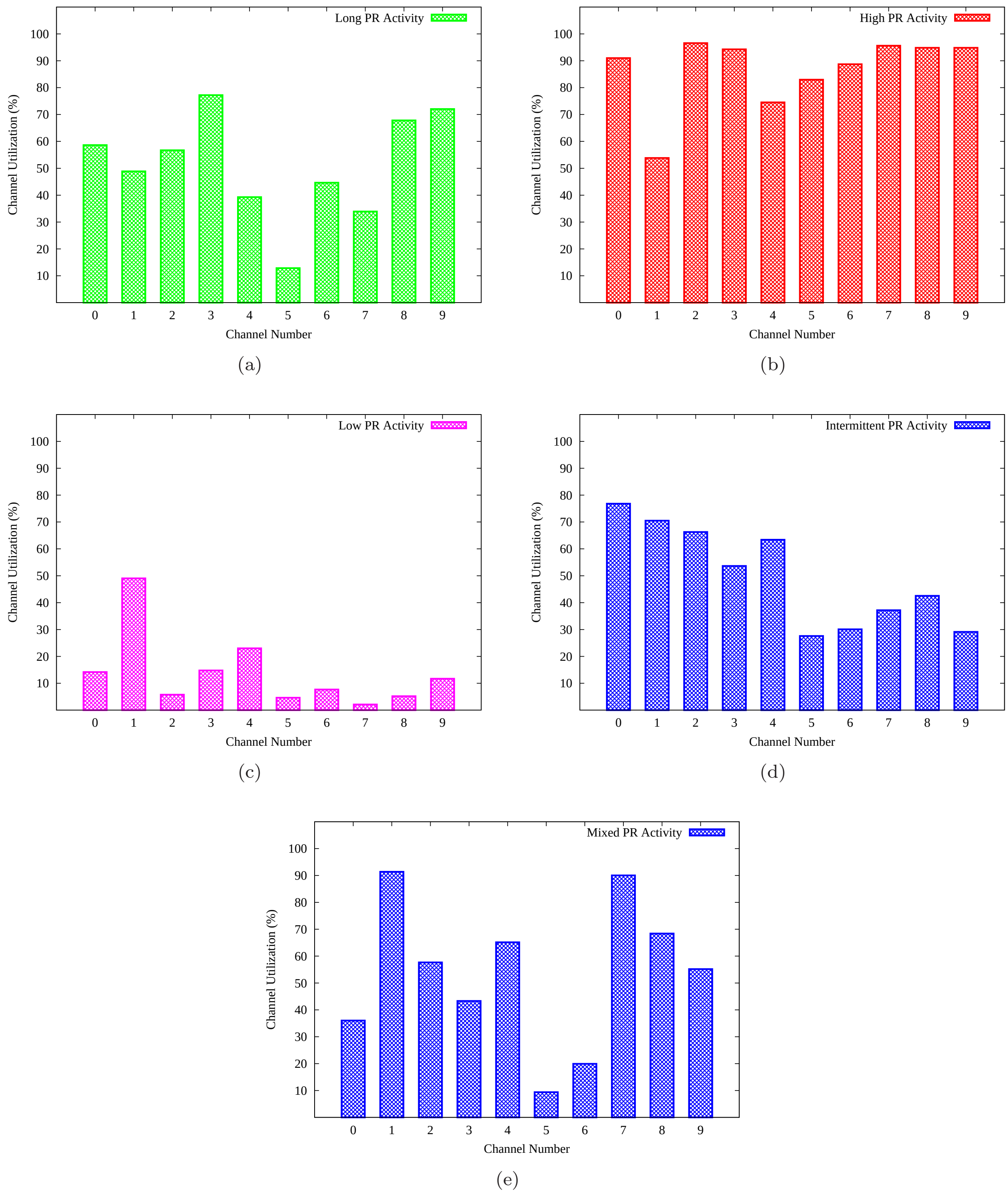


Fig. 7: All channels utilization

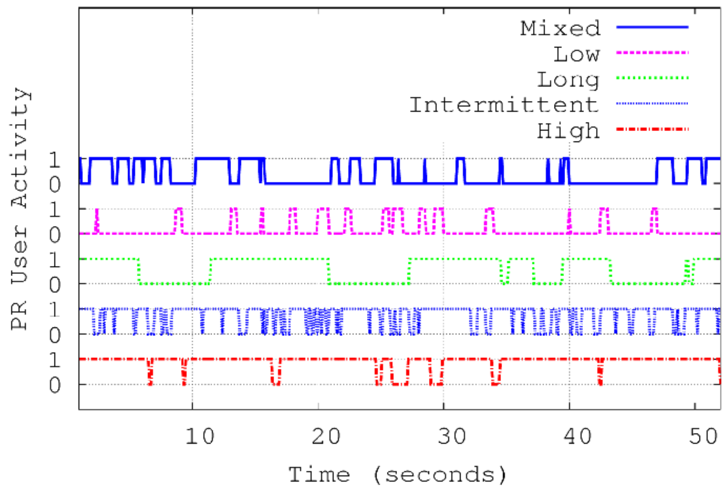


Fig. 8: All PR activities

this type of activity, all channels are busy most of the time and very little idle periods can be found. In contrast, a low PR activity is found in Fig. 7(c) and all the channels have low utilization factor. An intermittent and mixed activity can be seen in Fig. 7(d) and Fig. 7(e).

The concept of PR activities as discussed in Fig. 1 has been proved by simulations and the effect of all PR activities on all channels has been shown in Fig. 8. A “1” is showing an “ON” state whereas a “0” is used to represent an “OFF” state. It can be seen that the simulated results are exactly following the PR activities. Here the effect of long PR activity on channel utilization is more clearly visible as it is showing long “ON” and long “OFF” periods. The high PR activity is having long “ON” and short “OFF” periods where as low PR activity has short “ON” and long “OFF” states.

Another analysis of all five PR activities can be performed using Fig. 9 where the effect of each PR activity on all channels has been combined and shown as percentage of channel utilization. Lets examine the high PR activity in which all the channels are almost 90% occupied by PR users and remain idle for only 10% of the time. As intermittent PR activity has short “ON” and short “OFF” states (as shown in Fig. 8) so it is utilizing the channels for 50% of the time but the remaining 50% cannot be effectively utilized by CR nodes due to short “OFF” states and it is expected that PR user will appear again for a short period of time. This fast switching of PR nodes makes the channel unsuitable for CR nodes. The long PR activity has long “ON” and long “OFF” states due to which it is also utilizing the channels for almost 50% of the time and this activity is suitable for CR nodes because it is expected that after an “ON” state, the PR user will not appear again for a considerable amount of time. A low PR activity is attractive for CR nodes to utilize the channels as all the channels are less than 20% utilized by PR users and rest of the time remain idle. The mixed PR activity is also utilizing the channels for almost 50% of the time but a CR node cannot predict the next appearance of PR node over the channel as PR nodes do not follow any specific behavior in this type of activity.

6 Conclusion

In this paper, NS-2 based CRSN simulator model has been presented. This model supports the fundamental requirements of a CR based wireless sensor network. As the research trend is shifting towards CRSNs so it is need of the time for such a simulator so that all the future research and simulations can be based on this module. This module has been designed on NS2 so it is very flexible to extend for future enhancements and channel bonding block will be added as the extension of this work. It will provide the CR users a chunk of large bandwidth to utilize for multimedia applications. Other types of PR activities and energy models can also be integrated in this module. Another important future enhancement is to check the accuracy of our simulator in real world scenarios. It will provide a stronger base for the future researchers in this field of CRSN.

References

1. The network simulator ns-2, 1995.
2. A simulation framework for sensor networks, 2003.
3. Manna sim framework, 2002.
4. Mixim framework, 2011.
5. Nrl sensorsim, 2005.
6. Java in simulation time / scalabale wireless adhoc network simulator, 2004.
7. Sensor security simulator (s3), 2005.
8. O. B. Akan, O. B. Karli, and O. Ergul. Cognitive radio sensor networks. *IEEE Network*, Vol. 23, No. 4:34–40, 2009.
9. P. Steenkiste, D. Sicker, G. Minden, and D. Raychaudri. Future directions in cognitive radio network research. Technical Report Vol. 4, No. 1, National Science Foundation Workshop Report, 2009.
10. Syed Hashim Raza Bukhari, Mubashir Husain Rehmani, and Sajid Siraj. A survey of channel bonding for wireless networks and guidelines of channel bonding for futuristic cognitive radio sensor networks. *IEEE Communications Surveys & Tutorials*, 18(2):924–948, 2016.
11. Vahid Esmaeelzadeh, Reza Berangi, Seyyed Mohammad Sebt, Elahe Sadat Hosseini, and Moein Parsinia. Cogns: A simulation framework for cognitive radio networks. *Wireless Personal Communcations*, 2013.
12. Shah Nawaz Khan, Mohamed A. Kalil, and Andreas Mitschele-Thiel. crsimulator: A discrete simulation model for cognitive radio ad hoc networks in omnet ++. In *Wireless and Mobile Networking Conference (WMNC)*, 2013.
13. Pingnan Lee and Gengyu Wei. Ns2 model for cognitive radio networks routing. In *IEEE International Symposium on Computer Network and Multimedia Technology*, 2009.
14. Abdulla K. Al-Ali and Kaushik Chowdhury. Tfrc-cr: An equation-based transport protocol for cognitive radio networks. *Ad Hoc Networks*, 11:1836 – 1847, 2013.
15. Marco Di Felice, Kaushik Roy Chowdhury, Wooseong Kim, Andreas Kassler, and Luciano Bononi. End-to-end protocols for cognitive radio ad hoc networks: An evaluation study. *Performance Evaluation*, 68:859 – 875, 2011.
16. Cognitive radio cognitive network simulator, 2013.
17. Neha Singh, Rajeshwar Lal Dua, and Vinita Mathur. Network simulator ns2-2.35. *International Journal of Advanced Research in Computer Science and Software Engineering*, 2:224–228, 2012.

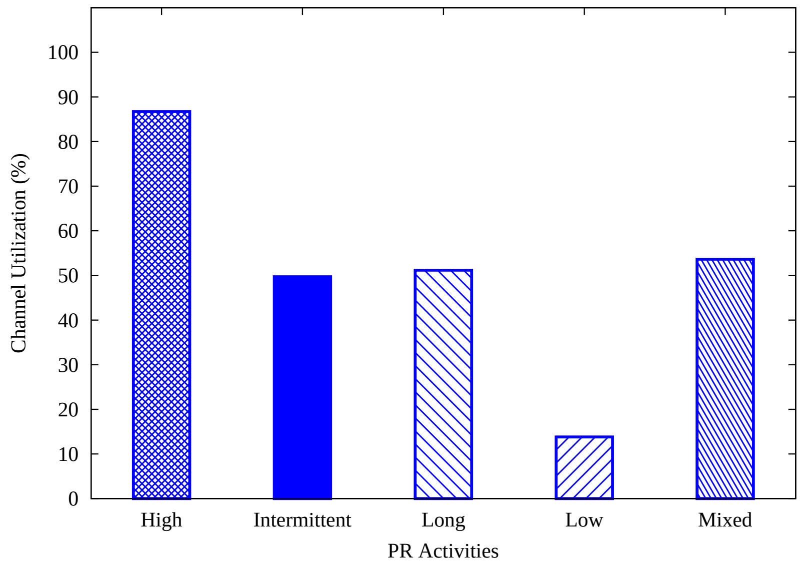


Fig. 9: Combined channel utilization

18. Hai-Ying Zhou, Dan-Yan Luo, Yan Gao, and De-Cheng Zuo. Modeling of node energy consumption for wireless sensor networks. *Wireless Sensor Network*, 3:18–23, 2011.
19. Xiaoyuan Li, Dexiang Wang, Janise McNair, and Jianmin Chen. Dynamic spectrum access with packet size adaptation and residual energy balancing for energy-constrained cognitive radio sensor networks. *Journal of Network and Computer Applications*, 41:157–166, 2014.
20. A Ozan Bicen, V Cagri Gungor, and Ozgur B Akan. Delay-sensitive and multimedia communication in cognitive radio sensor networks. *Ad Hoc Networks*, 10(5):816–830, 2012.
21. Tran Minh Phuong and Dong-Seong Kim. Robust distributed power control for cognitive radio based industrial wireless sensor networks. In *Proc. Int. Conf. Sensors*, volume 41, pages 9–12, 2013.
22. Huazi Zhang, Zhaoyang Zhang, Xiaoming Chen, and Rui Yin. Energy efficient joint source and channel sensing in cognitive radio sensor networks. In *2011 IEEE International Conference on Communications (ICC)*, pages 1–6. IEEE, 2011.
23. Mohammad Jalil Piran, Yongwoo Cho, Jihyeok Yun, Amjad Ali, and Doug Young Suh. Cognitive radio-based vehicular ad hoc and sensor networks. *International Journal of Distributed Sensor Networks*, 2014, 2014.
24. Song Gao, Lijun Qian, Dhadesugoor R Vaman, and Qi Qu. Energy efficient adaptive modulation in wireless cognitive radio sensor networks. In *2007 IEEE International Conference on Communications*, pages 3980–3986. IEEE, 2007.
25. Song Gao, Lijun Qian, and Dhadesugoor R Vaman. Distributed energy efficient spectrum access in wireless cognitive radio sensor networks. In *2008 IEEE Wireless Communications and Networking Conference*, pages 1442–1447. IEEE, 2008.
26. Zaheer Khan, Janne Lehtomaki, Kenta Umebayashi, and Johanna Vartiainen. On the selection of the best detection performance sensors for cognitive radio networks. *IEEE signal processing letters*, 17(4):359–362, 2010.
27. Chung-Hsien Kuo and Ting-Shuo Chen. Pn-wsna: an approach for reconfigurable cognitive sensor network implementations. *IEEE Sensors Journal*, 11(2):319–334, 2011.
28. Zhongliang Liang, Shan Feng, Dongmei Zhao, and Xuemin Sherman Shen. Delay performance analysis for supporting real-time traffic in a cognitive radio sensor network. *IEEE Transactions on Wireless Communications*, 10(1):325–335, 2011.

29. Jeong Ae Han, Wha Sook Jeon, and Dong Geun Jeong. Energy-efficient channel management scheme for cognitive radio sensor networks. *IEEE Transactions on Vehicular Technology*, 60(4):1905–1910, 2011.
30. Xiaoyuan Li, Dexiang Wang, Janise McNair, and Jianmin Chen. Residual energy aware channel assignment in cognitive radio sensor networks. In *2011 IEEE Wireless Communications and Networking Conference*, pages 398–403. IEEE, 2011.
31. Zemin Hu, Yongmei Sun, and Yuefeng Ji. A dynamic spectrum access strategy based on real-time usability in cognitive radio sensor networks. In *Mobile Ad-hoc and Sensor Networks (MSN), 2011 Seventh International Conference on*, pages 318–322. IEEE, 2011.
32. Mert Can Oto and Ozgur B Akan. Energy-efficient packet size optimization for cognitive radio sensor networks. *IEEE Transactions on Wireless Communications*, 11(4):1544–1553, 2012.
33. Mehdi Askari, Yousef S Kavian, Hooman Kaabi, and Habib F Rashvand. A channel assignment algorithm for cognitive radio wireless sensor networks. In *Wireless Sensor Systems (WSS 2012), IET Conference on*, pages 1–4. IET, 2012.
34. Jose Roberto Ayala Solares, Zouheir Rezki, and Mohamed-Slim Alouini. Optimal power allocation of a single transmitter-multiple receivers channel in a cognitive sensor network. In *2012 International Conference on Wireless Communications in Underground and Confined Areas, ICWCUCA 2012*, 2012.
35. N.u. Hasan, W. Ejaz, S. Lee, and H.S. Kim. Knapsack-based energy-efficient node selection scheme for cooperative spectrum sensing in cognitive radio sensor networks. *IET Communications*, Vol. 6, No. 17:2998–3005, 2012.
36. K Hareesh and Poonam Singh. An energy efficient hybrid co-operative spectrum sensing technique for crsn. In *Automation, Computing, Communication, Control and Compressed Sensing (iMac4s), 2013 International Multi-Conference on*, pages 438–442. IEEE, 2013.
37. Ghalib A Shah, Fatih Alagoz, Etimad A Fadel, and Ozgur B Akan. A spectrum-aware clustering for efficient multimedia routing in cognitive radio sensor networks. *IEEE Transactions on Vehicular Technology*, 63(7):3369–3380, 2014.
38. Huazi Zhang, Zhaoyang Zhang, Huaiyu Dai, Rui Yin, and Xiaoming Chen. Distributed spectrum-aware clustering in cognitive radio sensor networks. In *Global Telecommunications Conference (GLOBECOM 2011), 2011 IEEE*, pages 1–6. IEEE, 2011.
39. Object oriented modular discrete event network simulation framework, 2003.
40. Y. Yuan, P. Bahl, R. Chandra, and P. Chou. Knows: Cognitive radio networks over white spaces. In *International Sumposium on New Frontiers in Dynamic Spectrum Access Networks*, pages 416 – 427, 2007.
41. M. H. Rehmani, A. C. Viana, H. Khalife, and S. Fdida. SURF: A distributed channel selection strategy for data dissemination in multi-hop cognitive radio networks. *Computer Communications*, Vol. 36, No. 10:1172–1185, 2013.
42. Francisco J. Ros, Juan A. Martinez, and Pedro M. Ruiz. A survey on modeling and simulation of vehicular networks: Communications, mobility, and tools. *Computer Communications*, 2014.
43. Iain Parris, Fehmi Ben Abdesslem, and Tristan Henderson. Facebook or fakebook? the effects of simulated mobile applications on simulated mobile networks. *Ad Hoc Networks*, 12:35–49, 2014.
44. Mubashir Husain Rehmani and Yasir Saleem. *Network Simulator NS-2*, chapter 615, pages 6249 – 6258. IGI-Global, 2015.
45. Jiajia Liu, Hiroki Nishiyama, Nei Kato, Tomoaki Kumagai, and Atsishi Takahara. Toward modeling ad hoc networks: Current situation and future direction. *IEEE Wireless Communications*, 20:51–58, 2013.
46. Todd R. Andel and Alec Yasinsac. On the credibility of manet simulations. *IEEE Computer Society*, 39:48 – 54, 2006.
47. David Cavin, Yoav Sasson, and Andre Schiper. On the accuracy of manet simulators. In *Proceedings of the sec-*

ond ACM international workshop on Principles of mobile computing, 2002.

48. Rong Yu, Yan Zhang, Stein Gjessing, Chau Yuen, Shengli Xie, and Mohsen Guizani. Cognitive radio based hierarchical communications infrastructure for smart grid. *IEEE Network*, 25:6 – 14, 2011.
49. Weilin Li and Xiaobin Zhang. Simulation of the smart grid communications: Challenges, techniques, and future trends. *Computers and Electrical Engineering*, 40:270 – 288, 2014.
50. Jianfeng Wang, Monisha Ghosh, and Kiran Challapali. Emerging cognitive radio applications: A survey. *IEEE Communication Magazine*, pages 74 – 81, 2011.
51. Teerawat Issariyakul and Ekram Hossain. *Introduction to Network Simulator NS2*. Springer, 2009.
52. Zeeshan Ali Khan and Mubashir Husain Rehmani. A tutorial on broadcasting packets over multiple-channels in a multi-inferface network setting in ns-2. Technical report, LEAT, CNRS, University of Nice Sophia Antipolis, France and Lip6/Universtie Pierre et Marie Curie (UPMC) Paris, France, 2010.
53. Yasir Saleem and Mubashir Husain Rehmani. Primary radio user activity models for cognitive radio networks: A survey. *Journal of Network and Computer Applications*, Vol.43:1–16, 2014.
54. Suzan Bayhan and Fatih Alagoz. A markovian approach for best-fit channel selection in cognitive radio networks. *Ad Hoc Networks*, 12:165–177, 2014.
55. Yang Li, DongYu ning, Zhang Hui, Zhao Hai tao, ShiHai xian, and ZhaoXin-xing. Spectrum usage prediction based on high order markov model for cognitive radio networks. In *IEEE10th international conference on computer and information technology(CIT)*, 2010.
56. A.W. Min and K.G. Shin. Exploiting multi channel diversity in spectrum agile networks. In *INFOCOM*, 2008.
57. S. Bayhan and F. Alagoz. Distributed channel selection in CRAHNs: a non-selfish scheme for mitigating spectrum fragmentation. *Ad Hoc Networks*, 10:774–788, 2012.
58. M. H. Rehmani. *Opportunistic Data Dissemination in Ad-Hoc Cognitive Radio Networks*. PhD thesis, University of Pierre and Marie Curie, 2011.
59. Wang Zheng, Huat Chew Yong, and Yuen Chau. On discretizing the exponential on off primary radio activities in simulations. In *IEEE 22nd international symposium on personal indoor and mobile radio communications (PIMRC)*, 2011.
60. Wang Shanshan, Zhang Junshan, and Tong Lang. A characterization of delay performance of cognitive medium access. *IEEE Transaction on Wireless Communications*, 11:800–809, 2012.
61. Jiao Lei, Song Enbin, Pla V, and Li FY. Capacity upper bound of channel assembling in cognitive radio networks with quasistationary primary useractivities. *IEEE Transaction on Vehicular Technology*, 62:1849–1855, 2013.
62. Geirhofer Stefan, Tong Lang, and Sadler Brian M. Cognitive radios for dynamic spectrum access dynamic spectrum access in the time domain : modeling and exploiting white space. *IEEE Communication Magazine*, 45:66–72, 2007.
63. Wang Zhe and Salous Sana. Spectrum occupancy statistics and time series models for cognitive radio. *Journal of Signal Processing Systems*, Vol. 62, No. 2:145–155, 2011.
64. H. Shiang and M. Van Der Schaar. Queuing-based dynamic channel selection for heterogeneous multimedia applications over cognitive radio networks. *IEEE Transactions on Multimedia*, Vol. 10, No. 5:896–909, 2008.
65. Jonathan Gambini, Simeone Osvaldo, Bar-Ness Yeheskel, Spagnolini Umberto, and Yu Takki. Packet wise vertical handover for unlicensed multi standard spectrum access with cognitiveradios. *IEEE Transaction on Wireless Communications*, 7:5172–5176, 2008.
66. Jonathan Gambini, Simeone Osvaldo, Spagnolini Umberto, Bar-Ness Yeheskel, and Kim Yungsoo. Cognitive radio with secondary packet-by-packet vertical handover. In *IEEE international conference on communications (ICC)*, 2008.
67. Li Li, Xu Changqing, and He Jian. Resource allocation for ofdma-based cognitive radio systems with primary user activity consideration. In *IEEE international conference on communications (ICC)*, 2011.

68. Mitola Joseph Hu Nansai, Yao Yu-Dong. Most active band (mab) attack and countermeasures in a cognitive radio network. *IEEE Transaction on Wireless Communications*, 11:898–902, 2012.

69. S. Joshi, P. Pawelczak, D. Cabric, and J. Villasenor. When channel bonding is beneficial for opportunistic spectrum access networks. *IEEE Transactions on Wireless Communications*, Vol. 11, No. 11:3942–3956, 2012.

70. Brah, Felix, Dayoub, Iyad, Vandendorpe, and Luc. Constrained resource allocation for ofdma cognitive radio networks with primary users activity consideration. In *IEEE international symposium on wireless communication systems (ISWCS)*, 2012.

71. Chen Chiuan-Hsu and Wang Chin-Liang. Power allocation for ofdm-based cognitive radio systems under primary user activity. In *IEEE 71st vehicular technology conference (VTC)*, 2010.

72. Sabharwal Ashutosh Dash Debashis. Paranoid secondary:waterfilling in a cognitive interference channel with partial knowledge. *IEEE Transaction on Wireless Communications*, 11:1045–1055, 2012.

73. W. Lee and I. F. Akyildiz. Optimal spectrum sensing framework for cognitive radio networks. *IEEE Transactions on Wireless Communications*, Vol. 7, No. 10:3845–3857, 2008.

74. Barun Kumar Saha, Sudip Misra, and Mohammad S. Obaidat. A web-based iintegrated environment for simulation and analysis with ns-2. *IEEE Wireless Communications*, 20:109–115, 2013.

75. Lee Breslau, Deborah Estrin, Kevin Fall, Sally Floyd, John Heidemann, Ahmed Helmy, Polly Huang, Steven McCanne, Kannan Varadhan, Ya Xu, and Haobo Yu. Advances in network simulation. *IEEE Computer*, 33:59–67, 2000.

76. John Heidemann, Kevin Mills, and Sri Kumar. Expanding confidence in network simulations. *IEEE Network*, 15:58–63, 2001.

77. David Kotz, Calvin Newport, Robert S. Gray, Jason Liu, Yougu Yuan, and Chip Elliott. Experimental evaluation of wireless simulation assumptions. In *7th ACM international symposium on Modeling, analysis and simulation of wireless and mobile systems MSWiM*, 2004.

78. Laura Marie Feeney. Towards trustworthy simulation of wireless mac/phy layers: A comparison framework. In *15th ACM international conference on Modeling, analysis and simulation of wireless and mobile systems MSWiM*, 2012.

79. Daniel Hiranandani, Katia Obraczka, and J.J. Garcia-Lunia-Aceves. Manet protocol simulations considered harmful: The case for benchmarking. *IEEE Wireless Communications*, 20:82–90, 2013.

80. Josh Broch, David A. Maltz, David B. Johnson, Yih-Chun Hu, and Jorjeta Jetcheva. A performance comparison of multi-hopwireless ad hoc network routing protocols. In *IEEE international conference on Mobile computing and networking MobiCom*, 1998.

81. Mineo Takai, Jay Martin, and Rajive Bagrodia. Effects of wireless physical layer modeling in mobile ad hoc networks. In *2nd ACM international symposium on Mobile ad hoc networking & computing MobiHoc*, 2001.

82. Johnson Kuruvila Ivan Stojmenovic, Amiya Nayak. Design guidelines for routing protocols in ad hoc and sensor networks with a realistic physical layer. *IEEE Communication Magazine*, 43:101–106, 2005.

83. G. Yuan, R. Grammenos, Y. Yang, and W. Wang. Performance analysis of selective opportunistic spectrum access with traffic prediction. *IEEE Transactions on Vehicular Technology*, 59:1949–1959, 2010.

84. H. Kim and K. Shin. Fast discovery of spectrum opportunities in cognitive radio networks. In *IEEE DySPAN*, 2008.

85. O. Mehanna, A. Sultan, and H.E. Gamal. Cognitive mac protocols for general primary network models. Technical report, Cornell University, 2009.

86. A.S. Zahmati, X. Fernando, and A. Grami. Steady-state markov chain analysis for heterogeneous cognitive radio networks. In *Sarnoff*, 2010.

87. L. Yang, L. Cao, and H. Zheng. Proactive channel access in dynamic spectrum networks. *Physical Communications Journal*, 1:103–111, 2008.

88. Abdelnaser Adas. Traffic models in broadband networks. *IEEE Communications Magazine*, Vol. 35, No. 7:82–89, 1997.
89. B. Vujicic, N. Cackov, S. Vujicic, and L. Trajkovic. Modeling and characterization of traffic in public safety wireless networks. In *SPECTS*, 2005.
90. H. Kim and K. Shin. Efficient discovery of spectrum opportunities with mac layer sensing in cognitive radio networks. *IEEE Transactions on Mobile Computing*, 7:533–545, 2008.
91. K. Sriram and W. Whitt. Characterizing superposition arrival processes in packet multiplexers for voice and data. *IEEE Journal on Selected Areas in Communications*, Vol. 4, No. 6:833–846, 1986.