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Investigative Analysis of Cognitive Radio Wireless Model for Reconfiguration and Adaptation Capabilities

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Abstract :*Wireless networks have become constant in our everyday life due to ever increasing users and applications. With newer and sophisticated protocols emerging every day, traditional distributed environments and static allocation of frequency spectrum could no longer meet the needs of current wireless technology. This problem is heightened by diverse technologies and inflexible spectrum management approaches as ordinary wireless network architecture cannot self-organize without a central control. Cognitive Radio (CR) technology as solution to spectrum under-utilization problem offered in this research implement learning and adaptation to reuse spectrum holes. A Cognitive Radio Multiple Interface (CORAMIF) model, configured with heterogeneous interfaces (IEEE 802.11, 802.16 and 802.22) are equipped via Software Defined radio (SDR) was simulated on Linux with development environment customized using C++ and Object Tool Control Language (OTCL) tools to model signal strength and propagation delay. OTCL enabled network configuration while C++ handled data traffic. NS2 implementation and binding of OTCL objects with C++ enabled the primary objective of providing highly reliable communication everywhere as needed. Using formulated spectrum-awareness configuration, intelligent adaptation at network layer enabled opportunistic channel access. Packet forwarding by Distributed Coordination Function (DCF) implemented at Medium Access Channel (MAC) layer is merged with routing at transport layer. Learning and adaptation is implemented for reconfiguration before signal fading. Based on received signal power, smooth handoff is enabled for seamless roaming. Results were obtained by comparing the performance of formulated Zone Based Routing (ZBR) algorithm with Ad-hoc Online Multipath Distance Vector (AOMDV) and Direct Sequence Distance Vector (DSDV) NS2 defaults. Measurement of performance of throughput, delay and delivery rates demonstrated remarkable prevention of interference and congestion using different algorithms. Furtherance to this, normalized power received by mobile users showed communication efficacy and traffic balance with minimal tradeoffs in design. Finally, the bridged function of developed model was evaluated for congestion control and the operating parameters evaluated for seamless roaming. CR technology will therefore, augment spectrum availability and communication efficiency in future generations.*

Keywords:*cognitive radio, mobility, reconfiguration,sdr, sdn, spectrum hole, zone based routing*

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I. Introduction

Cognitive Radio (CR) technology offer mechanism for flexible and improved utilization of radio spectrum. A CR node is a radio device capable of operating (transmitting and receiving) over multiple channels. Therefore, any network consisting of one or more cognitive radio nodes can adapt to varying channel availability in its geographical region by dynamically changing the channel nodes used for communication. Cognitive radio technology solution to spectrum underutilization problem is hinged on unique capability of providing ultimate spectrum-awareness communication paradigm in wireless communication via artificial intelligence techniques. Implementation of this technology delivered dynamic spectrum access, where users with no spectrum licenses are allowed to use the temporarily unused licensed spectrum. This plan is capable of alleviating spectrum scarcity illusion faced by wireless communication [1].CR system allow dynamic access of secondaryusers to licensed spectrum temporarilynot used or underutilized by the licensed users.

Furtherance to this, Cognitive Radio (CR) technology guided by IEEE 802.22, is a specification for Wireless Regional Area Networks (WRANs) defined by IEEE Working Group standardization [2]. CR networks are equipped with intrinsic features to offer distributed multi-hop architecture; dynamic network topology; time and location varying spectrum availability for wireless systems. As intelligent wireless communication system, cognitive radio learns from its environment to adapt its internal states to statistical variations in the incoming radio-frequency (RF) stimuli thereby making corresponding changes in its operating parameters for real-time to adjustment of transmission requirements of user needs and network [3]. CR configurations enable cross-layer optimizations and interoperability at transport and service layers to trigger agreements and result in increasing number of roaming subscribers.

While modern wireless systems aim at offering a wide variety of high data rate applications to its numerous users at the same time, practical constraints imposed by scarce resources must be removed. As iterated in literature, wireless system is evidently increasing rapidly causing higher demand for new wireless applications and resources becoming more of a vital problem. This rising number and capacity requirement contributed to the spectrum scarcity illusion observed in [4]. Wireless systems differ significantly though their architectural components are very similar across different technologies. This enables voice, video, image and data transmission over the wireless traffic to be characterized with differing *bandwidth* and *Quality of Service* (QoS) requirements. As wireless network of computing nodes communicate with radio waves on the move, an increasing use of small and portable devices/computers arises, hence the need for 'more spectrum', establishing spectrum scarcity illusion created. Against established factthat wired network is faster and more secured,continuous enhancement in wireless networking (standards and technologies) have eroded all security and speed differences. The immediate benefit of mobility implementation has evidently characterized wireless networks with massive scalability and improved reachability [4].

Existing wireless systems are limited in providing for seamless roaming as major challenge of service discontinuity persists as mobile node (MN) moves around. The condition deteriorates withmobility and bottleneck increases even as MN moves farther away from home network. Seamless roaming and service continuity suffers and network islands are created. Service quality deteriorates predominantly due to deficient infrastructures and poor handoff managementtechniques [5]. Devising astate-of-the-artwireless infrastructure to alleviatespectrum underutilization and fluctuating QoS is opined in agreement with [1]. Ittherefore became expedient for communication engineers to find newer ways to increase aggregate throughput while preserving existing QoS. With unanticipated exponential growth of Internet multimedia applications, which had resulted in 3.75G cellular networks neither possibly reaching nor exceeding available network capacities. As these problems persist and in line with submission in [6], this study is motivated by the following problems among others:

(i) existing wireless communication network infrastructures are characterised as single interface user elements,as they are not equipped for efficient self-organisation, which limit roaming capability while encouraging a multiplying effect of congestion to trigger already deteriorated service qualities [7];
(ii) poor performances of link failures and service disruptions due to mobility peculiar to TCP mechanisms implemented in existing wireless network and routers, which cannot self-organise to reconfigure parameters,causing unguaranteed continuous use of spectrum [8];
(iii) network simulation algorithms implemented for ordinary wireless networks exists but none had been developed for CR networksto offer multi-radio and multi-hop transmissions [9];
(iv) reliable communication not achievable in ordinary wireless sensor networks because the signal transmission is characterised with impairments of unreliable channels and these networks discourage co-operative and automated sensing techniques for collaborative techniques.

Investigation of cognitive radio network (CRN) wireless model withheterogeneous interfaces is envisaged for dynamic spectrum access (DSA) and resource optimization through reconfiguration and adaptations. In CR systems, cognitive capability provides required spectrum awareness while reconfiguration enables dynamic programming of radio according to its environment. Therefore, the model is trained to sense (acquire operating parameters fromenvironment) and adapt network parameters dynamically to provide flexibility ofuse of access networks. Specifically, the objectives of this research include:

(i) Development of a cognitive radio wireless network (CRWN) model to perform complex techniques required to provide seamless roaming;
(ii) Simulation ofdeveloped model to test dependence of its performance objective on existing operating parameters; and
(iii) Evaluation of the developed model for reconfiguration and adaptation efficacy.

II. Review of Cognitive Radio Technology

Existing wireless systems, diverse technologies and network architectures is characterized with sservice qualities, which deteriorates predominantly due to deficient infrastructures and poor handoff managementtechniques implemented in mobility. To meetthe increasing demand of emerging wireless applications, CR technologyimplementation is envisaged assolution.

2.1 Cognitive Radio

Cognitive radio was inspired by [10] as evolving technology from software defined radio to offer solution to the significant under-utilization of the radio spectrum. Spectrum-sensing CR detects used and idle channels in radio frequency spectrum as licensed and unlicensed (white space) channels. The performance requirements for any CR system includes authentic spectrum hole and license user detection;precise link estimation between communicating nodes;fast and accurate spectrum frequency control;reliable communication between CR terminal nodes and non-interference to license users via methods of power control; and latent opportunities for safe and efficient use of spectrum in non-interfering and multidimensional area within frequency, time and space characteristics.

Discussed in [11], CR device boost up spectrum availability and utilization by dynamic access of unused primary spectrum while bringing no harm to the primary users (PUs). Also, DSA is implemented by CR in [4] to address spectrum scarcity illusion created by increasing demand of new applications and users. The main challenge for secondary user is ability to sense spectrum hole and target its use while primary user activity remain undisturbed. CR wireless system senses its operational environment by periodical scans, adjusting operating parameters to modify system operation autonomously to suit system and user needs. CR users, transmitters or receivers engaged in collaborative communication over the CR networks and these users do not need to have a license though the major issue of how to share spectrum sensed information with other cognitive users remains a challenge. Existence of heterogeneity inwireless access technologies, network types, user terminals, varied applications as well as multipleservice providers is a major stimulus for universal need of CR.

From inception, the pioneers [12]evolved CR from Software Defined Radio (SDR). Originally considered to improve spectrum utilization, the idea was endorsed by FCCas SDR isbetter suited for cross layer optimization with *cognition* defined as higher-layer application [13]. The Institute of Electrical Electronics Engineering (IEEE) also defined CR as one that alters its behaviour based on information received from environment and predefined objective of application/user. Being aware of its environment, it intelligently learns and adapts its internal states to statistical variations in incoming radio frequency (RF) stimuli. With corresponding real-time changes in the operating parameters (transmit-power, carrier-frequency and modulation strategy), primary objectives of highly reliable communication and efficient utilization of radio spectrum was guaranteed[14].

Also defined in [15], CR capability of changing transmitter parameters is based on interaction with environment. Designed in hardware or SDR, CR intelligently detectparticular segment of radio spectrum currently used without interfering with transmission of the authorized users. As posted in [16], subscription to broadband services is driven by mobile data growthhinged on HSPA+ and fixed wireless access technique of Worldwide Interoperability for Microwave Access (WiMAX). Though, yet to capture significant share of broadband as part of 4G, WiMAX provides portable mobile broadband connectivity across cities and countries, via varying devices and standards but user QoS is greatly sacrificed as they move around. This also account for existing limited interoperability featured among the different technologies [17]. In systems, aadjustment of system parameters to conform to certain policies and regulations to meet required QoS in next generation networks entails transceivers intelligently detecting communication channels in use while instantly moving to unoccupied bands as licensed users emerge [18]. As evolving technology, CR support of DSA to address spectrum scarcity illusion autonomously guaranteedetection of idle frequency band for allocation to unlicensed *secondaryusers* (SUs) even aslicensed *primaryusers* (PUs) may not use them. Idle band not used by PU iscalled *spectrum hole.*

2.2Cognitive Radio Technology (CRT)

CRT is guided by IEEE 802.22 specification for Wireless Regional Area Networks (WRANs). For convenience in small and large business, IEEE defined another standard, IEEE 802.20 as specification for mobile broadband wireless access. CRT is characterized with cognition and reconfiguration technology.By cognition, CR is enabled to sense and capture information from radio environment while reconfiguration techniques enable radio to dynamically adjust to the programmed environment.Generally, CRNs are equipped with: (i) cognitive capability - ability to sense the environment; (ii) self-organization - ability to analyze and learn sensed information and (iii) reconfiguration - ability to adapt environment. CR learns from these adaptations to make further decisions in its signal-processing cycle shown in fig. 1. CR nodes coherently receive signal while analyzing the radio scene to send feedback to trigger DSA. Through learning, transmission of modulated signal is effected over spectrum hole while node is adequately informed of sensed and signal-to-noise ratio parameters. Received powers at CR nodes donot exceed prescribed limit set by legacy primary users [18].

A Cognitive Radio Network (CRN) formed by collection of CR-enabled SUs (featured as generic mobile nodes, base stations (BSs) or access pointsand backbone network structure) and PUs. CRundergo cognitive process to perceive network condition to decide (plan) on end-to-end goal achievement. Categorized into infrastructure, ad-hoc or mesh architectures, primary and secondary signals of respective licensed and unlicensed users are orthogonal to each other [19]. Cognition by SU accomplish interference avoidance by knowledge of spectral gaps of PUsensedand used asidle band in RF environmentwhile controlling usage.CRN architecture is therefore geared towards major objective of improving entire network utilization [20] rather than just providing link efficiency.

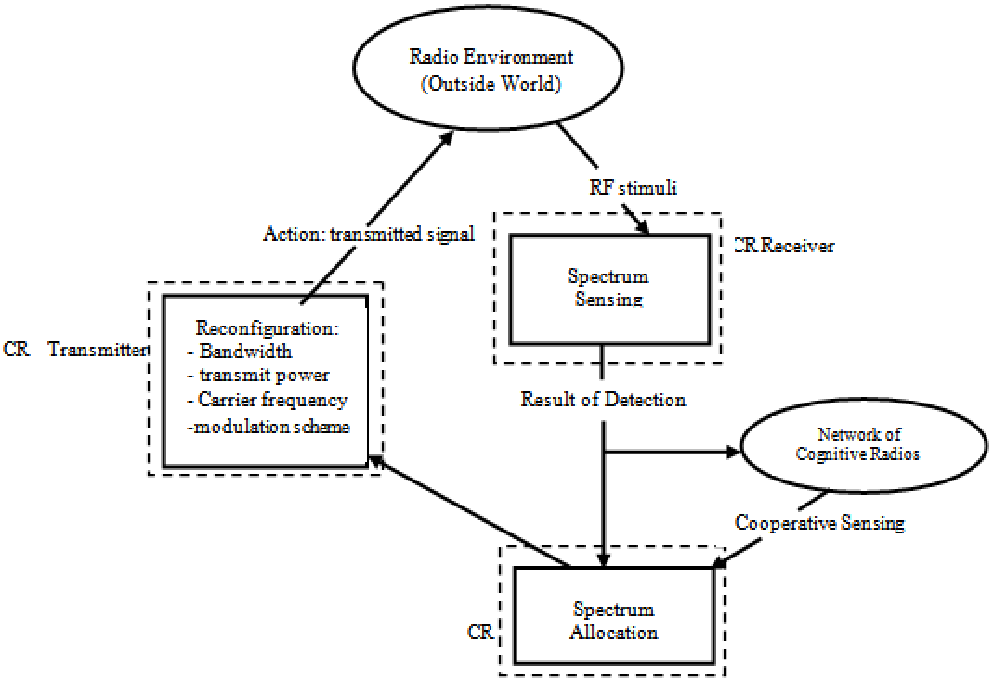


Fig. 1 Simplifiedcr processing cycle(adapted and modified)

2.3 Collaborative objective of CR and SDR in SDN

CRs have the capability to learn and adapt wireless transmission according to surrounding radio environment [1]. For cooperativeachievement, CRs collaborate to make decision to access spectrum while maximizing objective function of spectra utilization after considering common constraints. For such scenario, a central controller coordinates spectrum management. [21- 22]and [4] all attested to co-operative spectrum sensing as solution to 'hidden node problem' because the sensing scheme enables cognitive users closer to APs (licensed system) help the ones far away. Primary objective of CR providing highly reliable communication whenever and wherever needed is guaranteed and the radio spectrum is efficiently utilized and other resources (power, bandwidth) optimized. This is vital since static allocation of frequency spectrum does not meet the growing needs of current application and ever-increasing wireless users.

Software Defined Networking (SDN) is an emerging computer network paradigm that allow logically centralized software program control behaviour of entire network. SDN *framework*logically separates network into two parts: control and data planes and uses software program to perform the varying and complex networking tasks of usage management and resources control. Splitting network into controland data plane enables distributed control structure set up while handling traffic shaping from point-to-point within network layers [13]. As SDN technically separates network control plane from forwarding plane and all programmable agile devices are directly controlled from control plane. This separation offers centralization of control, enabling creation of more sophisticated policies by network operators to allow for easier network configurations, management, troubleshooting or debugging [23].

SDR infrastructure provides *software control* of variety of modulation techniques, wideband or narrowband operation, communication security functions and waveform requirements of current and evolving standards over a broad frequency range. As multi-band, multi-standard, multi-service and multi-channel device, cognitive radio waveform functionalities can be reconfigured through software as one device configured for many function [23].

III. Modeling System Parameters

System model for testing CRN parameters for analysis involve using simulation technique with simplified assumptionsto save cost of development. Modeling the CRN communication system provide an abstraction of interactions between network componentsas thesimulation helpin the description of all functioning components in the large and complex system formulated. CRNis modeled with collection of CR-enabled nodes, equipped as SU transceiver MNs (CR-MN) as shown in Fig.2. Configured elements are distinguished as *primary user(PU)* and *secondary users (SU)* elements.

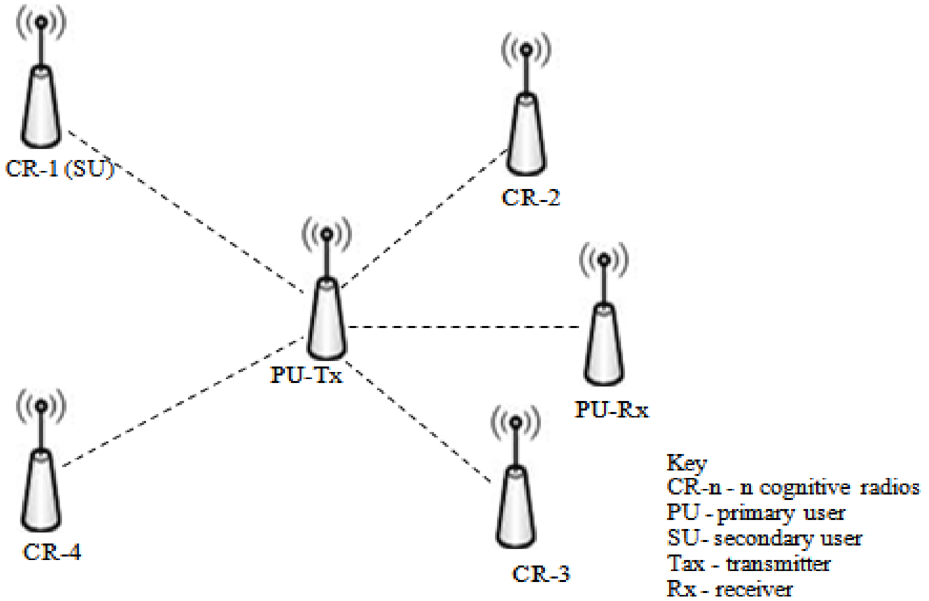


Fig. 2 Conceptual CRN architecture of PUs and SUs

To determine what channel(s) CR-MN will use for transmission, defined scenario is equated to ensuring every possible pair of nodes in CRN is able to communicate on every possible channel. CR-MN is either node, *Access Point (AP) ornetwork*. To establish this, Neighbour Discovery Problem was formulated as connected undirected graph of set of nodes with the following basic properties (definitions) of graph:

Definition 1:Let each node be assigned a unique identifier from range $[1...N]$, where *N* is the upper bound on total number of nodes in the CRN, and $A_U = \{c_1, c_2, ..., c_M\}$represent the universal set of available channels that can potentially be used by all nodes for communication.

All nodes know N , M and A_U . Each node is equipped with *r* multiple-input-multiple-output (MIMO) receivers, where $1 \leq r \leq \min (M, N)$, and base station or access point capable of operating on any of the M *channels in* A_U . A node can receive on multiple channels at the same time (using different interface) and can also transmit on different channel same time. Each node i is aware of its channel availability set A_i and this is the same for every node.

Definition 2**:** Nodes i and j are *neighbours* represented by an undirected edge or a pair of directed edge in graph. Whenever i and j are within each other's radio range, transmission between nodes is achieved by single hops and $A_i \cap A_j \neq 0$.

Definition 3: Communication between nodes that are not neighbours is achieved by *multi-hop* transmission and a message transmitted by a node in time-slot t is delivered to all its neighbours in the same time slot.

SDN frameworkprovide dynamic shaping of network traffic from SDR, with core idea of using software to remotely control network hardware. Using associated application programming interface (API), large numberof network devices, services, topology, traffic paths, and packet handling policies were automatically managed as data and control planes, logically separated in programming [13] and [23]. The following lemma provides necessary tools for the design in the simulation context:

Lemma 3.1:Let $G = \{1,2,..., N\}$be the set of possible nodes in network where actual transmission occurs only if a node is present and channel/interface is available within group set.

Proof:It is observed that when a group of nodes $\{i_1, i_2, ..., i_x\}$ is scheduled to transmit/receive on channels $\{c_{j1}, c_{j2}, ..., c_{jx}\}$, each node in the group is scheduled to use at least one interface/channelin $\{c_{j1}, c_{j2}, ..., c_{jx}\}$. Within time-slot t, i_1 is scheduled to transmit on c_{j1}, i_2 on c_{j2}, …, up to i_x onc_{jx}.

Let r divides both N and M, set G is partitioned into $\frac{N}{r}$ groups $G_1, G_2, \dots, G_{\frac{N}{r}}$ each of size r . $G_1 =$ *1, 2,..., r,G2=r+1, r+2,..., 2r,...,GNr=N−r+1, N−r+2, ...,N*are the groups and nodes use exactly x interfaces or turn off remaining $(r - x)$ interfaces while transmitting since each node has r receivers.

Definition 4: Neighbour Discovery Algorithm (NDA) stated for a group of nodes $A = \{a_1, a_2, \dots, a_x\}$ and a group of channels $B = \{b_1, b_2, \dots, b_x\}$ ensure every node has at least x interface(s) to implement Divide And Conquer (DAC) approach to ensure every node in A is scheduled to listen to every other node in A on all x channels in $O(x \log x)$ time-slots.

Lemma 3.2: For every triplet $\{i, j, c\}$ where i and j are nodes and c is the channel, there is a time-slot t such that (i) only $i$is scheduled to transmit on c during t and (ii) at least one of the receivers at j is scheduled to receive on c during t.

Proof: Let $DAC(A_1, B_1)$ and $DAC(A_2, B_2)$ be two instances of the algorithm, we use $DAC(A_1, B_1) || DAC(A_2, B_2)$ to denote algorithm obtained by running the two instances concurrently and $DAC(A_1, B_1) \circ DAC(A_2, B_2)$to denote algorithm obtained by running the two instances serially.
The algorithm, therefore applies to three blocks:

(i) first block consist of x time-slots and all nodes in A_1 are scheduled to transmit on B whereas nodes in A_2 are scheduled to listen.
(ii) second block reverse the roles of A_1 and A_2, that is nodes in A_2 scheduled to transmit while nodes in A_1 scheduled to listen and
(iii) third block consist of two blocks recursively invoked (commutative property) by $\left(DAC(A_1, B_1) || DAC(A_2, B_2)\right) \circ \left(DAC(A_1, B_2) || DAC(A_2, B_1)\right)$.

Therefore, $A_1 \cap A_2 = \emptyset$ and $B_1 \cap B_2 = \emptyset$ is ensured such that $|A_1| = |A_2|$ or $|B_1| = |B_2|$ is guaranteed for cognition and reconfiguration in CRN.

3.1 Configuring SDN and SDR

SDN framework consist of control (TCL configurations) and data (C++ adaptations) planes. The model is configured to implement supervisory control and data acquisition (SCADA) technique and dynamically shape network traffic. SDR platform working within the CRN is equipped for cognition and reconfiguration. Reconfiguration is schedule on configured nodes, implemented by learning parameters acquired through sensing/scanning. Front-end SDR is programmed to feature control and data acquisition demand within the SDN framework, the Cognitive Radio Multiple InterFace (*coramif*) model, implemented in generalized flow table API of*coramif.tcl*. SDR processes effect signal processing and software radio divides functionality into layers. By permission in the SDN architecture, centralized control for data plane offered flexibility of reconfiguration viathe reprogrammable structure provided in defined *coramif* modules.

3.2 Analysis of SDN framework

Centralized spectrum pooling architecture of *coramif* enabled licensed subcarrier of Orthogonal Frequency Division Multiplexing (OFDM) transmission technique use APs for signals consisting of independently modulated symbols. Strict relationship between frequency subcarriers defined$f_n = n \cdot \Delta f$ and $\Delta f = \frac{1}{T_U}$ where T_U is the symbol rate. OFDM power spectrum of all sub-carrier demonstrated large amplitude variation obtainedfrom addition of carriers with different frequencies and modulation. This is expressed in (1)as proved in [11].

$$r(t) = \sum_{k=0}^{N_c - 1} x_k \cdot e^{(j 2 \Pi k \Delta f t)} \qquad (1)$$

The centralized architecture established an orthogonally principle for the two signal functions x_q and x_k respectively for PU and SU orthogonally defined over intervals$[a, b]$, given in (2) as obtained in [24].

$$\left\langle x_q \cdot x_k \right\rangle = \int_a^{bU} x_q(t)\cdot x_k(t)dt = \begin{cases} 1, k = q \\ 0, k \neq q \end{cases} \qquad (2)$$

This combination is zero for any combination except for $x_q(t) = x_k(t)$enabling coexistence of PU and SU signals on same spectrum band[24].

where $r(t)$ is received signal for x_k PU or x_q SU and N_c as number of carriers. Energy detection technique initiated cognitionvia CR transmitter for *coramif*to distinguish used and unused spectrum band as expressed in(3):

$$r(t) = \begin{cases} n(t)H_0 \\ hx(t) + n(t)H_1 \end{cases} \qquad (3)$$

where $r(t)$is received signal, $x(t)$ the transmitted signal of PU while $n(t)$is Additive White Gaussian Noise (AWGN) for *h* amplitude gain of transmitting channel. Designating $n(t)$and $hx(t)+n(t)$respectively as null H_0 and alternate H_1 hypothesis of transmitter detected license user signal existence and non-existence, respectively, permissibletransmitted power of allocated spectrum is established as (4):

$$C = B\log\left(1+\frac{S}{N+1}\right) \qquad (4)$$

bandwidth of allocated spectrum, *S* received signal power on channel *C*while*N*and*I*is the respective noise and interference component experienced at receiving node in agreement with [15].

3.3 CR node routing technique

By default, NS2 provides support for one propagation model by an interface and MN architecture consist of modules emulating the link layer, MAC protocol, ARP, interface queue and network interface as contained in ‘real-life’ protocol stack. The entities are connected to share same wireless channel and one propagation model. Within the multiple channel homogeneous support provided for each MN, one propagation model simulates the effect of real wireless channel on transmitted signals. Chain of all module entities is multiplexed as number of channels at MN for routing and transport layer agents to responsibly create and destroy packets [25]. Zone Routing Protocol (ZRP) route packets and transport layer agents handle queued packets for reliability of data flow. Multiple interface MN architecture implements only one propagation model to support network objects as contained in *coramif.tcl.*

3.4 Multi-channel heterogeneous cr-mn interface architecture

Network entities, routing and transport agents required to provide required support for multiple channels and heterogeneous interface MN model is depicted in fig. 3. As a modification to single (homogeneous) interface mobile node presented in [26], an heterogeneous multiple interface CR-MN design is presented in [27].

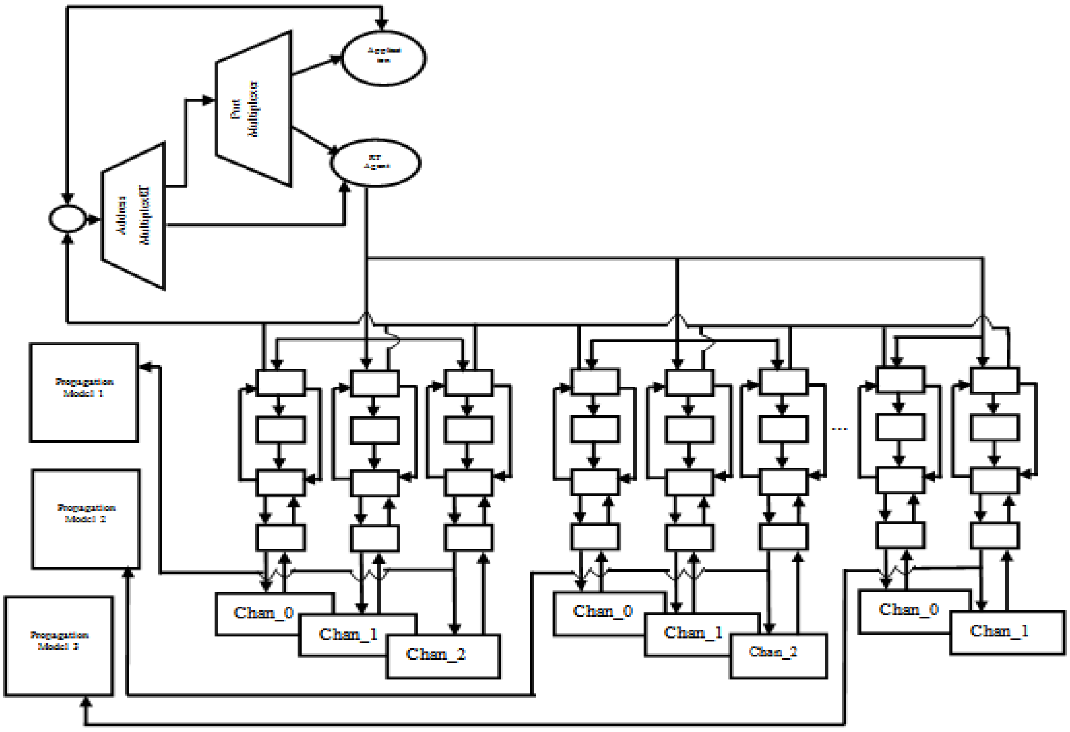


Fig. 3 Multi-channel heterogeneous interface MN architecture

Each MN is equipped with multiple interfaces to implement Gauss Markov Mobility (GMM) model of simplified movements. Time-dependent transition $a_{ij} = P[q_t = j | q_{t-1} = i]$ $1 < i, j \leq N$ implemented by MN moving from home network (HN) to foreign network (FN) at time t within network area is defined in configuration setup. The node states $Q = \{q_1, q_2, \dots, q_n\}$ for Mevents represented as $E = \{e_1, e_2, \dots, e_m\}$where$T$ is the final time output $t = \{1,2,3, \dots, T\}$ is established in agreement with Markov model sums up all transitions to unity $\left(\sum a_{ij} = 1\right)$ for A = matrix of transition probabilities a_{ij} s.

Random Waypoint Algorithm is implemented by *setdestin* configuration setup to enable convex set $A \in R^n$ definition for all possible locations occupied by MN within CRN. Waypoints $P_i$along source-destination routes has velocity v=1for probability distribution function (*pdf*) defined in (5) provides required *cognitive capability* for spectrum awareness.

$$f(MN) = \frac{1}{dA^2} \int_0^{\pi} a_1 a_{2+} (a_1 + a_2)\, d\varphi \qquad (5)$$

where a_1 and a_2 are x and y locations of MN on the surface plane provided for mobility. Distance d moved along direction φ is measured as performance variable for mobility in the CRN coverage area.

3.5 Network selection function definition

Formulating a multiple-attribute wireless network selection function (WNSF), defined on a set of attributes as objective function was used to measures the efficiency of radio resources utilization. Testing for improvement in QoS while handing off to another network interface was proposed with defined events including(a) new service request made; (b) user changing preferences; (c) MN detecting availability of a new network; (d) severe signal degradation or complete signal loss of current radio link detected. Attributes defined as parameters to evaluate the selection function are signal strength (S), network coverage area (A), data rate (D), service cost (C), reliability (R), security (E), battery power (P), mobile velocity (V) and network latency (L). An algorithm, Wireless Network Selection Algorithm (WNSA) ddeveloped to test the fitness of these attributes is expressed in (6):

$$fi(x) = \sum_{j=1}^{N} w_j \cdot \mu_{C\,j}(A_i) \qquad (6)$$

where $fi(x)$ is the fitness of access network i on Cj channels and w_j is the weight of each parameter, while μ is degree of membership by fuzzy reasoning on A_i set of attributes. Maximized *f(x)* therefore, select best access network for communication after evaluating defined objective function while an optimized WNSA enhances smoothhandover as suitable normalized function. Access network for MN initiates handoff and associated spectrum mobility is enabled whenever the fitness function is optimized [28].

3.6 Handling packets at cr nodes

Successfully transmitted packets are acknowledged (ACKED) while *errored* packets dropped (status_= DROP) are retransmitted when not acknowledged (NACKED). Packets are retransmitted until status indicates DROP. Acknowledgements [ack()] reduces number of retransmissions scheduled for transmitted packets while non-acknowledgements increases [nack()] increases time to live at routing node as indicated in flow diagram shown in fig. 4. Resume function defined enabled dropped and *errored*(non-acknowledged) packets re-scheduling for retransmission. Retransmitted (RTx) packets increases time to live and reduces throughput of transmission subsequently.

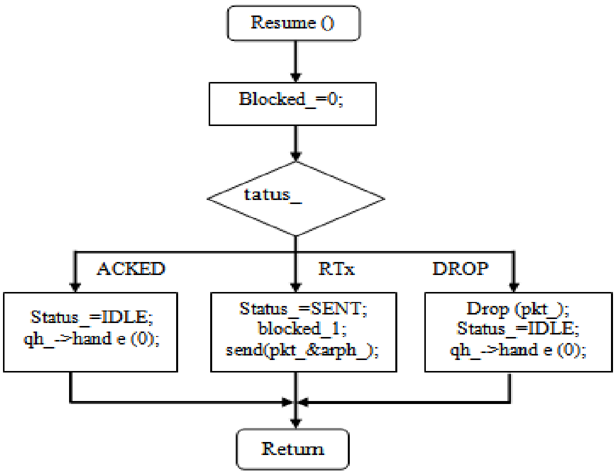


Fig. 4: Packet handling in CR node

IV. Implementation Techniques

Network Simulator 2 (NS2) used for the simulation implements two languages: Object Tool Control Language (OTCL) and system language, C++. Other components are Network Animator (NAM), Xgraph and GNU Plot [29]. Simulation environment was setup in Ubuntu Linux and OTCL handles design control (network configuration, protocol and application specification) while C++ handles data flow within simulated network. NS2 environment provided details for implementing both default and formulated (hybrid) protocols. Operation and procedures were defined to generate, transmit and destroy packets in cost-effective manner, NS2 being open source. Real-time events as *enqueue* (+) , *dequeue* (-), *received* (*r*), *dropped* (*d*), *sent* (*s*) were also defined within processing time. Though, written in two object-oriented languages in two separate files, NS2 enable OTCL linkage/binding with C++ implementation to handle discrete data while scheduling events.

4.1 Simulation environmentparameters

With NS2 provision, configured mobile node featured as multiple interface cognitive radio while Access Router (AR) provisioned to provide service to other mobile node (MN) was conceptually connected through wired links to Internet backbone. CORAMIF Configuration parameters and modification to existing NS2 module are based on the following definitions:

(i) three mobile nodes (MNs) and an access point randomly scattered within an area of (500 x 500)m^2, where each mobile node was equipped with radio technologies to include Universal Mobile Telecommunication Service (UMTS), Wireless LAN and Wireless MAN respectively represented by UMTS, IEEE 802.11g (Wi-Fi) and 802.16e (WiMAX).
(ii) Gauss-Markov Mobility (GMM) model was adopted for MN's physical mobility effect Random Way Point movement for all users within simulation scenario.
(iii) Packet generated/transmitted is modeled to exponentially arrive at receivers/routers and expectedly received by Random Waypoint user following Poisson distribution.
(iv) CR mobile node configured as access router (CR node) is equipped with multiple interfaces as shown in algorithm 4.1. Three interfaces incorporated are UMTS (MAC/CDMA_2000); Wi-Fi (MAC/802.11) and WiMAX (MAC/802.16).
Intel R Core ™ 2 Duo processor at 2.0GHz and 4.00GB of RAM was used for the research. With hard disk capacity 500GB and operating system Linux (Ubuntu) 64 bit version installed, NS2 version 2.35 was used for the simulation. A summary of simulation parameter is presented in Table 2 with modifications listed.

Table 2: Simulation Parameters

Parameters	Definition
Processor	Intel Dual Core
OS, RAM	Ubuntu Linux 12.04, 4GB
NS-2 / OTCL version / NAM	2.35 / 1.14 / 1.15
AOMDV, DSDV	NS default
ZBR	Hybrid
Number of nodes, Base station	3, 1
Traffic Type/ Data Type	Variable bit rate (VBR)/FTP
Packet size	1MB (1048576 bytes)*
Simulation time	360 seconds**
Topology size	500 x 500
Maximum speed	5m/s
Packet rate	2.9kbps (approx. 3packets/sec)**
Queue management	Drop Tail
Number of sources, receiver	1,2
Number of node agents	2 (HA, FA)

4.2 Simulation Results

Within *OTCL coramif.tcl* script, delay experienced in sending 1MB FTP application between AP (CR-MN^1) and CR-MN^2 for simulation time of 360 seconds was measured using different protocols. Distance covered for each scenario within defined area of 550x550m^{2}was also measured, where 1m approximated 500m on ground surface. Simulation was run three times each for selected protocol to obtain an average for grouped results based on protocol selected. The results are shown in Tables 3 – 7.

Table 3: Average end-to-end delay for FTP agent

Distance moved by MN (m)	Transmission Delay (m/s)		
	AOMDV	DSDV	ZBR
150	165	300	195
230	189	320	215
367	217	350	235
430	230	360	268
485	246	385	130
550	255	455	150

AOMDV reactive routing allows dynamic, self-starting and multi-hop routing among mobile nodes to preserve an ad-hoc networking and communication between intermediate nodes. Unlike ZBR, which implement dynamic source routing combining reactive and proactive approaches, AOMDV enables mobile node respond quickly while handling changed routes. Therefore, associated queue-awareness algorithm defined in AOMDV provides for reduced end-to-end delay than ZBR or DSDV. ZBR increased delay suggests increased overhead.

Table 4: Packet Delivery Ratio for 1MB packet size

Distance moved by MN (m)	Packet Delivered (Bytes)		
	AOMDV	DSDV	ZBR
150	415	325	205
230	420	328	215
367	425	333	235
430	436	348	243
485	442	355	248
550	460	363	255

AOMDV has highest packet delivery ratio with minimized RERR messages but ZBR was not very suitable for heterogeneous environment due to inter-zone routing used by neighbours outside a zone. More overhead was incurred in the management of routing table while finding alternative route paths outside zone.

Table 6: Throughput of sending 1MB packet

Distance moved by MN (m)	Packet Received (Throughput in Kbps)		
	AOMDV	DSDV	ZBR
150	200	215	195
230	228	235	218
367	325	338	236
430	356	368	268
485	448	370	215
550	485	393	305

AOMDV broadcasts RREQ to all neighbours to reduce overhead in route discovery. This lead to highest throughput at different locations even as MN moves farther away from home. At foreign zone, AOMDV allows sending MNto use destination sequence number for route entry to ensure loop-free routes [30]. As MN moves farther away from home,fading becomes insignificant with ZBR and DSDV protocols, due to singular multiple interfacesCR-MN model intelligently switching channel to alleviate the fading.

Table 7: Estimated packet rate of transmission

Distance moved (m)	Estimated Round Trip Time (s)	Packet size (KB)		
		AOMDV	DSDV	ZBR
150	60	938	907	950
230	120	930	890	925
367	180	890	790	915
430	240	850	750	899
485	300	825	790	890
550	360	790	855	850

Rate of packet transmission linearly reduces with ZBR and AOMDV as MN moves away from HN. With DSDV, as MN moves away from HN, packet transmission rate drastically dropped at 180s of simulation time when fading slightly sets in as MN moves away from HN.

4.3 Analysis of Measurement metric

Implementing AOMDV, DSDV and ZBR protocols based on standard operating parameters, end-to-end delay, packet delivery ratio and throughput measurements were taken at quantified distances for estimated packet arrivals. At definite intervals of 60s, 120s, 180s, 240s, 300s and 360s until simulation elapsed over the distance of 550m covered, the graphical results are shown in fig. 5 – 8.

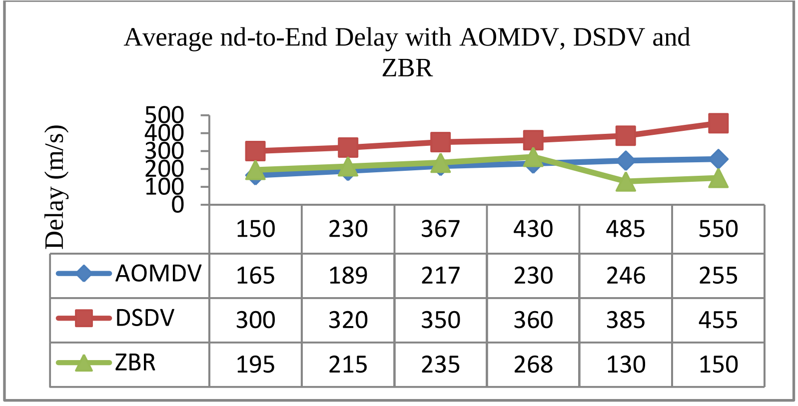


Fig. 5: Routing protocol performance on transmission delay

Delay experienced while implementing AOMDV and DSDV protocols were linearly dependent on distance moved away from HN than ZBR routing agent. Increased delay observed with DSDV than AOMDV is attributed to delay in routing table update as MN moves to use foreign agent. While implementing with ZBR agent, as MN moves farther away from HN to use a foreign agent, delay stabilizes offering improvement in service, hence a sudden drop from 268 to 130 signifying multiplicative decrease of$\left(\frac{W}{2}\right)$analyses, catering for expected throughput in inter-zone transmission. Warm-up time for each round of simulation is 50 seconds.

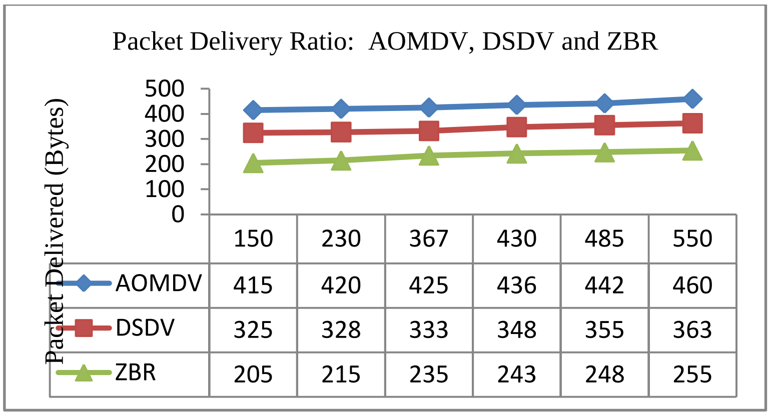
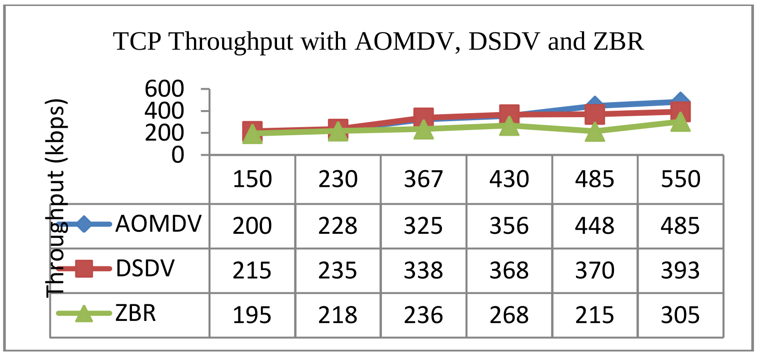
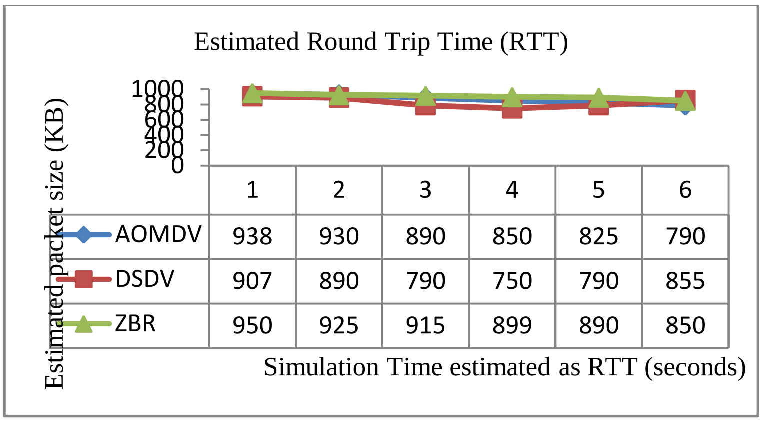


Fig. 6: Packet delivery to destination node



	150	230	367	430	485	550
AOMDV	200	228	325	356	448	485
DSDV	215	235	338	368	370	393
ZBR	195	218	236	268	215	305

Fig. 7: Throughput of packettransmission with node mobility



	1	2	3	4	5	6
AOMDV	938	930	890	850	825	790
DSDV	907	890	790	750	790	855
ZBR	950	925	915	899	890	850

Fig. 8: Packet arrival for errored packets (estimated)

ZRP as hybrid protocol combined best properties of both proactive and reactive routing algorithms to show minimal *errored* packets. Performance measure with ZRP on nodes with distances farther from HN showed optimized trade-off between throughput and packet delivery rate. RTT linearly varies with simulation time using AOMDV and ZBR while DSDV showed remarkable drop in packet size. As MN moves back home, *errored*packet is reduced with DSDV but stabilizes with AOMDV and ZBR[31 - 32] in agreement with [33].

4.4 Evaluating developed modelsfor performance

Trust is essential for CR nodes to actively participate as routing points working within CRN. As MNs change distances with respect to home and foreign agents, trustτ required in CRN is therefore a function of routing path. An overall trust (multiplication of trust) in each segment of entire CRN is expressed as (7): where L is number of participating nodes. Trust and distance measured as routing metric between nodes i and j for selected algorithms becoming a kind of Markov decision process $\left(d(i,j),\tau(i,j)\right)$ defined as policy for all participating nodes.

$$\tau(n_0, n_1, \dots, n_L) = \prod_{i=0}^{L-1} \tau(n_1, n_{l+1}) \qquad (7)$$

Consequently, CRs involvement in collaborative spectrum sensing eliminate zero trust and Markovian decision process associated with state-space policy make trust generally irreversible, $\tau(n_0, n_1, \dots, n_l) \neq \tau(n_1, n_L)$ [34].

Routing protocols implemented wereanalyzed and compared to observed effect of defined metrics on network performance of cognition and reconfiguration. The summary of observations based on characteristic behavior of default protocol as well as developed protocol is enumerated in Table 8.

Table 8: Comparison between routing protocols

Metric	DSDV	AOMDV	ZBR
Average E-2-E Delay	Highest	Medium	Lowest
Packet Delivery Ratio	Lowest	Highest	Linear
Throughput	Lowest	Highest	Medium
Overhead	Highest	Lowest	Medium

4.5 Discussion on observation

Shown in the research, CR exhibit intelligent tasks of learning and adaptations, reusing spectrum holes to implement DSA techniques discussed in [31]. With CRT, wireless systems are characterized with entities of no fixed operating frequency band since its components dynamically utilize idle bands to exploit collaborative function on used bands. CR provision of opportunistic access via*cognition* and *reconfiguration* techniques is established. Cognitive cycle was characterized with the following processes, in agreement with [15], [22] and [32] as:

- *spectrum sensing*, determination of PU presence on used channel and detection result shared with other CRs. Cooperative sensing assist CRs gather all sensing information for centralizationto detect spectrum holes. This technique offered solution to hidden node problem as PU cognitive transmitters in far distance are assisted to collaborative in sensing [35];
- *spectrum allocation*,decision by CR on which band to use for transmission while multiple secondary users agitate spectrum usage and all users (including PUs) are enabled to share available spectrum;
- *reconfiguration*, technique by which CR reconfigures to transmit in idle band, potentially changing its carrier frequency, transmit power and modulation scheme to match available band sensed and detected free [15]; and
- *transmission*,where enabled reconfiguration offer seamless communication while transiting from one channel/band to another using fast *handoffs* and spectrum mobility[36 – 37].

V. Conclusion

Optimizingimplemented techniques reliably for end-to-end reconfiguration and adaptation, CRN infrastructure undergo self-healing to provide for continuous monitoringand discoveryviacognition.Investigating the adaptation and autonomous capabilities of CRN model for real-time data communication was carried out and verification of dynamic resource allocation in reconfiguration was investigated for seamless roaming. SDN modeled demonstrated CR networking technology as enhancement of public safety communication aside its efficiency in mitigating interferences and congestion. Using multiple interfaces (SDR), CRscollaborate to facilitate communication for other devices operating in different bands. This scheme alsoimproves device interoperability [31-32].

Through spectrum agility and interface adaptability, CRT efficiently utilize scarce spectrum to support fast-growing demand of wireless applications. CR/SDR framework as SDN technology offer solution to issues identified in [37] and [38]. The technology supports priority delivery and routing of content, protecting time-sensitive information from interference and congestion bottlenecks. In addition, CRtechnologies augment next generation cellular networks (including Long Term Evolution (LTE) and WiMAX) to dynamically use newly available spectrums for conventional data services of web-browsing.Cognitive Radio (CR) technology offer mechanism for flexible and improved utilization of spectrum. As solution to underutilization problem, the technology is hinged on unique capability of spectrum-awareness communication paradigm and artificial intelligence techniques of CR nodes.

More so, the heterogeneous multiple interface model, characterized with insignificant delays, suitablyprovide support for qualitative continuous service delivery and seamless roaming. Therefore, the heterogeneous networksimplement hybrid handover schemes for handoffs. The model is feasible and beneficial to offer mobile Internet users multi-vendor support in future generationsas it interoperates with lower standards. Associated benefits of spectrum mobility, fast and efficient handoff essential for roaming efficacy [27] is facilitated. Unlimited interoperability enabled for seamless experience using the emerging technology [39] is established. Self-organization and self-healing of CRN architectureenlists the developed model for implementation in public safety and emergency networking [40].

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