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ProMAC: A proactive model predictive control based MAC protocol for cognitive radio vehicular networks

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ABSTRACT

Cognitive Radio (CR) is a recent network paradigm that allows Secondary Users (SUs), such as, wireless devices/users, to *intelligently* access portions of the radio spectrum not allocated to it, without interfering with the transmission of licensed users (Primary Users (PUs)) who are allocated certain dedicated portions of the radio spectrum. This paradigm in radio communication has been successfully used in vehicular networks wherein communication can be established within vehicles (vehicle-to-vehicle) or vehicles to static stations (vehicle-to-infrastructure) without allocating dedicated frequencies. However, the challenge in CR design lies in building intelligence that helps in efficiently sensing and transmitting data through available radio spectrum channels. This paper proposes a Model Predictive Control (MPC) based Proactive Medium Access Control protocol (ProMAC) for the SUs in a CR network. To the best of our knowledge this is the *first proactive MAC* reported in the literature for CR. Employing ProMAC in a architecture where the number of SUs and PUs were constant, we achieved **20**%, **13**.**5**% and **12**% improvement in channel utilization, backoff rate and sensing delay respectively as compared to the recently proposed PO-MAC protocol, which is so far the best reported in the literature. In an architecture where the numbers of SUs varied with time, ProMAC achieved **21**% and **13**.**17**% improvement in channel utilization and backoff rate, respectively, as compared to PO-MAC. The proposed protocol is based on a self-learning engine that can evolve and improve its prediction accuracy even after deployment on field.

1. Introduction

Cognitive radio for Vehicular Ad hoc Networks (CRVs or CR-VANETs) has emerged as a new technique for wireless communication in the automotive market. This technique facilitates present day vehicles to offer a dynamic platform for intra-vehicular transmission of commands as well as dynamic access to wireless services during the move. The main challenge in realizing the advantages of CRVs lies in effective use of the present day radio spectrum which is allocated and shared between licensed and unlicensed frequencies [1]. This policy being rigid has resulted in some frequency bands growing in scarcity thereby leaving a large portion of the radio spectrum temporally and spatially unused [2]. The Cognitive Radio (CR) is a software framework that is proposed as one of the key mechanism to resolve the problem of under utilization of radio spectrum [3]. The CR has the ability to ensure an efficient usage of the available radio spectrum, without requiring the allocation of new frequency bands. It exploits unused licensed radio frequencies, called the *spectrum holes*, by allocating them to the Secondary Users (SUs) intelligently without causing *harmful interference* to the Primary Users (PUs) [4]. The CR framework implemented in the SUs, is a self-aware radio that automatically chooses the transmission parameters and the access technology in a *dynamic* and *intelligent* manner, so as to maximize the channel utilization. The present and upcoming vehicles are expected to offer functionalities for the transmission of intra-vehicular commands and dynamic access to wireless services, while the car is in transit [5]. The CR as a technology for vehicular Ad hoc Networks can lead cars to monitor the available frequency bands and to opportunistically use them [6]. Hence CR becomes a major technology in improving vehicular communication efficiency [7].

The CR, which has emerged as a core technology behind spectrum reuse [3], consists of three essential components: (1) *Spectrum sensing*: The SUs are required to sense and monitor the radio spectrum environment within their operating range to detect the radio frequency bands that are not occupied by PUs; (2) *Dynamic spectrum management*: CR networks are required to dynamically carry out channel allocation to select the best available frequency

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bands for communications; and, (3) *Adaptive communications*: A CR device can configure its transmission parameters to make best use of the ever-changing spectrum holes opportunistically.

As highlighted in [8], a mobile terminal or vehicular node with CR capabilities can sense the communication environment, analyse and learn information from operating environment based on user preferences and demands, and reconfigure the operating parameters conforming to the system policies and regulations. Though CR issues can span across all the layers of the protocol stack, its vital core issues are mostly limited to physical and Medium Access Control (MAC) layers, because the control and co-ordination of communication over wireless channels happen at the MAC layer. As described in [9] the important functionality of the MAC protocols are, identifying the available spectrum through spectrum sensing; deciding on the optimal sensing and transmission times; and, coordinating with the other users for spectrum access. Although [10] discusses about the optimal time allocation for sensing and data transmission, the technique presented lacks adaptation to the changing environment. In [11], it is suggested that, in case of heterogeneous channel availability where *partial sensing* (sensing a selected subset of channels) is possible, a statistical sensing strategy which favours sensing of channels with higher availability may improve performance. However such a strategy is not presented in [11]. Thus, there is a need for a smart and efficient mechanism for **sensing and allocation of unoccupied RF channels of PUs, to successfully deploy CR networks that benefit SUs**.

The CR framework implemented on a *Vehicular Ad hoc Networks (CRVs or CR-VANETs)* exploits the latter's mobility over a period of time to *learn* the activities of the channels allocated to PUs across different regions through which the SU moves. This can speed-up the process of channel selection by the SU whenever it travels through these *known* regions in future. This knowledge acquired by SU, may provide higher protection to the PUs from channel interference. At the same time, this knowledge may turn pessimistic from the point of view of the SUs as it can result in them not meeting the dynamic Quality of Service (QoS) requirements set time-to-time by the applications executed on them [12]. Thus, the MAC protocol operation must be adaptive to the operating environment and suit the QoS requirements prescribed by the applications. Successful deployment of CR technology in the next generation wireless networks requires addressing all the research challenges described above.

In this paper, the issues of both spectrum sensing and dynamic spectrum management are addressed *together* by proposing an integrated MAC protocol, named ProMAC. The ProMAC employs a Model Predictive Control (MPC) [13] based algorithm that predicts the future states of a channel allocated to a PU. This prediction is used by the ProMAC to perform the spectrum sensing and dynamic spectrum management.

The rest of this paper is organized as follows: Section 2 presents the related work. Section 3 gives a brief introduction to model predictive control system. Section 4 lists the contributions of the paper. Section 5 presents the proposed ProMAC framework. Section 6 defines certain performance metrics. Section 7 presents the experimental results and Section 8 concludes the paper.

2. Related work

2.1. Common issues in CR based vehicular networks

CRVs or CR-VANETs are one of the most promising applications of cognitive radio. Each vehicle in a geographic area could communicate with other vehicles directly. The CR MAC protocols are expected to play a central role in these CRVs similar to the IEEE 802.11 wireless standard. A survey on CR standardization activities carried out by IEEE has been presented in [14]. The IEEE 802.22 Wireless Regional Area Network (WRAN) [15] and Standards Coordinating Committee 41 (SCC41) are the primary CR standard efforts of the current times. The IEEE SCC41 addresses the area of dynamic spectrum access networks and provides architectural concepts and specifications for network management between incompatible wireless networks.

The CR MAC protocols are different from their corresponding wireless MAC schemes. Specifically the physical layer of the CR framework may support the MAC layer in the implementation of the latter's sensing strategy [9]. This includes (a) providing sensing coordination support at MAC layer; (b) optimal partitioning of the time slot between sensing and data transmission phases; and, (c) coordinating the order of searching a spectrum band through its spectrum sensing unit [16,17]. Many MAC protocols have been published in literature [18], [19]. Multi-channel MAC protocol extensions have been proposed in IEEE 802.11, to enable a node to operate in multiple channels, in order to improve its network-wide throughput [20]. In general, multi-channel MAC protocols address the channel assignment problem by ensuring that between any two Tx-Rx pairs, if the Tx nodes are less than or equal to two hops from each other, then these nodes do not select the same channel simultaneously for data transmission. This is done to mitigate the Multichannel Hidden Terminal Problem (MHTP) [21].

As proposed in [22], the presence of multiple transceivers greatly help in avoiding MHTP and improve efficiency of channel negotiation process. However, having multiple transceivers at the SU node, increases its hardware cost and overall complexity of the node. To reduce the cost, most of the existing MAC protocols assume single transceiver. In this case the MHTP issue mentioned above can be effectively addressed by using a global Common Control Channel (CCC). The global CCC facilitates exchange of control messages among CR nodes [23] Channel contention has always been a issue. The CSMA based MAC proposes to negotiate a favourable channel for transmission based on the previous history of success on different channels [19]. CSMA verifies the absence of transmission in the channel before transmitting data on it. Thus, the performance of a CR network is mainly influenced by how *well* the channels are allocated. We shall now present details on the research contribution related to channel assignment that are reported in the literature.

2.2. Channel assignment problem in CRVs

The problem of *channel assignment* aims at allocating channels to the network links requiring transmission, so as to maximize the network utilization [24]. This is also referred to as *channel mapping*. The algorithms for channel assignment are classified into three types based on the channel allocation policy, channel types and network architecture. Based on channel allocation policy, *channel assignment* can be classified as *static (fixed)* [25] or *dynamic (continuously varying with respect to network conditions)* [26,27]. Based on the channel type, it can be classified as *orthogonal* [28] channel or *overlapping* [29] channel based algorithm. For example, IEEE 802.11b standard defines three of eleven channels as orthogonal in the 2.4GHz band. Based on the network type they are classified as *Master Slave or Centralized* [30]/ *Distributed* [31].

It is interesting to note that the algorithms vary in the way they perform the action related to channel assignment. HC-MAC proposed in [32] performs channel sensing *before* channel selection. It takes into consideration various hardware constraints in spectrum sensing and spectrum access. On the other hand, the OSA-MAC proposed in [18] inserts a sensing phase *after* channel selection. This suffers from the disadvantage of nodes ending up selecting unavailable channels. In general, channel selection happens *after* channel sensing. Opportunistic Multichannel MAC (OMC-MAC) [33] was proposed for distributed CR networks to specifically address the problem of QoS for delay sensitive applications and MHTP. Unlike other MAC protocols, OMC-MAC has a sensing phase as part of MAC Framework. This provides up-to-date sensing information, before getting into data transmission which is efficiently exploited by the protocol. The Preemptive Opportunistic MAC (PO-MAC) has been recently proposed in [34] to optimize end-to-end delay in a CR network for Distribute architecture. It consists of three phases: Network initialization, Reporting, and Contention. The channel sensing is performed in a concurrent fashion, wherein each SU senses a PU channel exclusively assigned to it during a *sensing phase*. Subsequently all the SUs share the results of the sensing phase among themselves in the reporting phase, in a systematic manner avoiding collision. Using the sensing results, SUs preempt and make use of available PU channels. A detailed survey on, (1) channel assignment algorithms in CR networks; (2) there open issues; and, (3) challenges in CR networks are discussed in [9] and [12]. It is also to be noted that, the channel assignment problem as such is independent of any Radio technology. The same solutions can be realized in current and upcoming radio technologies.

It is inherent to note that many of the CR architectures proposed in the literature were primarily designed to wait for an event to happen in order to make changes to their network configuration. Thus, most of the CR MAC implementation available in literature are based on the Observe-Orient-Decide-Act (OODA) loop [15] which is a **reactive system** by design. However, CR architectures can greatly benefit from a more **proactive mindset** that seeks to make changes on the run without being explicitly driven by an event. To some extent, the original Mitola architecture included feedback as part of the planning stage [3]. It used an historical archive of past decisions and events to provide a basis for predictive future decisions. Furthermore, [35] describes CR, as a highly interdisciplinary subject involving signal processing, communications engineering, artificial intelligence and control systems engineering. It has been highlighted in [36] that an effective solution can be arrived at by integrating contributions from a wide range of disciplines.

3. Model predictive control system

A CR MAC protocol, can be mapped into a multi-variable optimization problem with dynamically varying constraints. However, it needs to be *proactive* in selecting the optimal channels for transmission by the SUs. MPC based systems [37] are **best suited** for such problems as (1) they can predict the value of variables for several time intervals ahead (proactive); (2) they prevent drastic increase and decrease in the predicted values of the variables over adjacent time intervals (avoids frequent reconfiguration); (3) they can handle objectives that vary over time (varying network design); and, (4) they can handle optimization problems involving multiple variables with constraints. Many of these features are not addressed in prominent MAC protocols for CR networks like the PO-MAC [34]. MPC was originally designed to exploit an explicitly formulated model of the process; and, solve a series of open-loop deterministic optimal control problems in a receding horizon manner [38,39].

Comparison between the Reinforcement Learning (RL) and the MPC approaches has been discussed in [40]. It has been observed in [40] that for linear systems involving convex optimization, MPC techniques perform better than RL techniques. Further, the advantage of using MPC lies in the fact that the MPC framework handles input and state constraints explicitly in a systematic way [41].

MPC System: As highlighted in [42], a prediction problem that uses MPC contains, (1) Variables that need to be bounded by budgetary values (*constraint variables*); and, (2) Variables whose value need to be predicted (*prediction/manipulating variables*). A typical

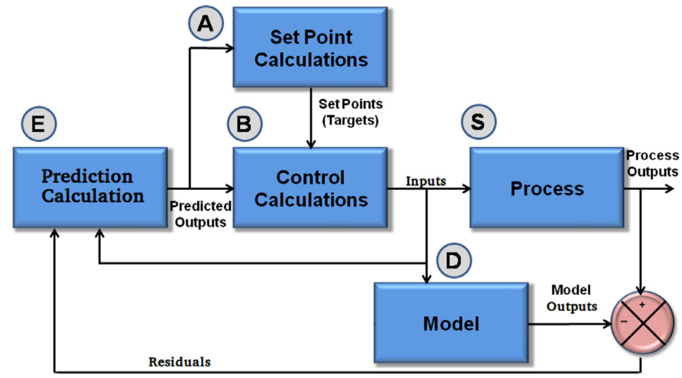

Fig. 1. Block Diagram: MPC.

MPC based system is as shown in Fig. 1 wherein, module A determines the bounds for the constraint variables; module B predicts values for the prediction variables subject to the constraints imposed by A; module S makes a decision based on the prediction and performs the execution on the system and hence the actual values of the constraint variables can be measured; module D is a model of the system which takes the predictions from module B and generates values of the constraint variables; and, module E compares the outputs of modules S and D and communicates the error if any, back to module A and B as feedback. Thus, an MPC system can be used as a control system with feedback. In this paper, we customize the generic MPC framework as shown in Fig. 1 to implement a control system that efficiently allocates channels to SUs in a vehicular network.

4. Contributions of this paper

In this paper, a proactive CR MAC protocol, called ProMAC is proposed for channel sensing and channel assignment by a SU. We use both the architectures viz. Centralized Cognitive Radio Network (CCRN) architecture and Distributed Cognitive Radio Network (DCRN) architecture to evaluate ProMAC. The evaluation procedure is similar to the ones presented in [30,31]. A summary of major notations used in this paper are listed in Table 1. The salient features of ProMAC are as under:

1. ProMAC maps CR vehicular network into a closed-loop system, which converts the channel allocation problem into a satisfiability problem [43];
2. It uses a MPC based system to **proactively** determine the future state of the transmission channels thereby reducing channel sensing overhead and implementing the proactive spectrum sensing handoff by default [44];
3. It proposes a simple transmission channel selection algorithm to select the best of the available channels for transmission by a *mobile SU in vehicular network*;
4. It proposes a combined spectrum sensing and spectrum allocation protocol, which reduces vehicular SU node overhead and increase performance; and,
5. It reduces energy consumption of vehicular SUs in both DCRN and CCRN architectures by reducing the exchange of control messages and the number of channels to be sensed;

5. The proposed ProMAC framework

The problem to be solved by the proposed framework is as follows: Given a list of PU channels with their past M transmission states, the ProMAC predicts the *transmission state (idle or busy)* of PU channels for the next K time slots. It employs the MPC framework for this purpose. The time line of any wireless transmission is

Table 1
Summary of major notations.

Symbol	Description	Symbol	Description
CR	Cognitive Radio	PU	Primary User
SU	Secondary User	MAC	Medium Access Control
GHz	Giga Hertz	OODA	Observe Orient Decide Act
WRAN	Wireless Regional Area Network	ProMAC	Proactive MAC
CCC	Common Control Channel	MHTP	Multi Channel Hidden Terminal
QoS	Quality of Service	PO-MAC	Preemptive Opportunistic MAC
DCRN	Distributed CR Network	CCRN	Centralized CR Network
CTS	Clear to Send	RTS	Request to Send
Transmit	Tx	Receive	Rx
OMC-MAC	Opportunistic Multichannel MAC	Hp	History Polynomial
RCA	Reactive Channel Allocation	MPC	Model Predictive Control
MIMO	Multiple Input Multiple Output		

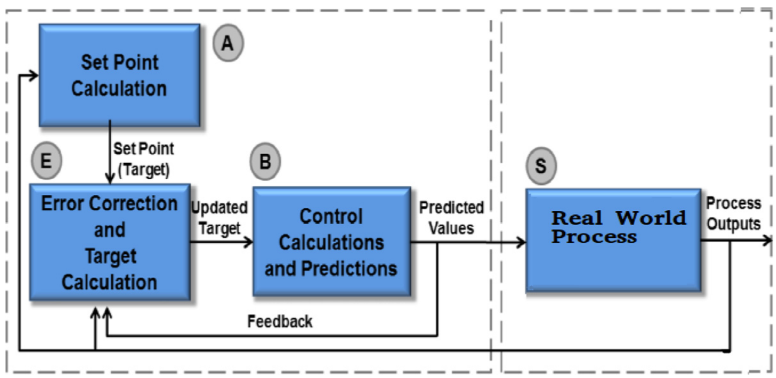

Fig. 2. Block diagram: ProMAC.

divided into equal sized *beacon intervals* or *time slots* [11]. First we describe how the framework can be used for predicting the states of PU channels for one immediately succeeding time slot and later proceed to describe how the same can be used for K time slots, $K > 1$. This paper assumes without loss of generality that each PU is associated with exactly one channel. Any PU channel is in *busy* state or *idle* state depending on whether the associated PU is transmitting or not, respectively.

Let the N channels associated with PUs be denoted by $\{X_1, X_2, .., X_N\}$. Let a^i_j denote the status of X_i in time slot j. For a given time slot t the history polynomial Hp_i associated with X_i is

$$Hp^i(x) = \sum_{j=t-M}^{t-1} a^i_j * x^{j-t+M} \ , \ a_j \in \{0, 1\}$$

$$a^i_j = \begin{cases} 1, & \text{if } X_i \text{ is busy at time } t. \\ 0, & \text{Otherwise.} \end{cases} \quad (1)$$

The MPC based framework used in this paper is as shown in Fig. 2. For every *prediction variable* z_i the desired bounds for *constraint variable* or the *target value* (TG_i) is set by module A. For each variable z_i, the module B predicts the probability of z_i through *control calculations* in MPC framework using the desired *target value* (TG_i) and the past history values using a mathematical model (Hp^i) of the real world system; module S is the real world system that makes a decision based on the prediction; carries out the operations; and, outputs the result of the operation as feedback to module E; module E computes the error in prediction of the variable z_i based on the predicted values output by module B for z_i and the actual value of z_i from the real world process. This feedback enhances the quality of future predictions. This paper maps the channel allocation problem for CR network onto the MPC framework. We now proceed to describe each module in the MPC framework shown in Fig. 2.

1. Module A of Fig. 2: set point calculation
   This module sets a target (busy/idle) value TG_i for each of the channel X_i as follows: TG_i is set to 1 ($TG_i = 1$), if X_i was *busy* for at least $M/2$ of the previous M time slots, else it is set to 0. The value of $M/2$ has been arrived at based on the following: (1) Assuming a channel to be busy in case it has been busy for more than 50% in the immediate past is intuitive and, also has been empirically ascertained. This is captured in Eq. (2).

$$TG_i = \begin{cases} 1, & \text{if } \sum_{j=t-M}^{t-1} a^i_j \geq M/2 \\ 0, & \text{Otherwise.} \end{cases} \quad (2)$$

2. Module E of Fig. 2: error correction and target calculation
   Module E computes for each channel X_i, the new TG_i for the next M timeslots based on the feedbacks received from module A, module B and module S. Module A provides E with the TG_i values of each channel X_i, based on the previous timeslots. Module S provides the actual status of each channel X_i in the previous timeslot. Module B provides the predicted state of channel X_i for the previous M timeslots. For each channel X_i, incase the values provided by module B and S are same i.e. the last prediction was correct then, the updated TG_i value is same as the TG_i value provided by A. Incase the last prediction was wrong the updated TG_i value is the compliment of TG_i value provided by A. Module E feeds this updated TG_i values for all channels X_i to module B.
3. Module B of Fig. 2: control calculations and predictions
   Module B is the heart of the ProMAC Framework which predicts the states of the channels for the next M time slots. The module B stores the set of *History Polynomials* (Hp^1, Hp^2, .., Hp^N) as described in Eq. (1). The a^i_j values ($t - M \leq j \leq t - 1$) in these polynomials are the actual states of the channel X_i (real world values) during the time slots

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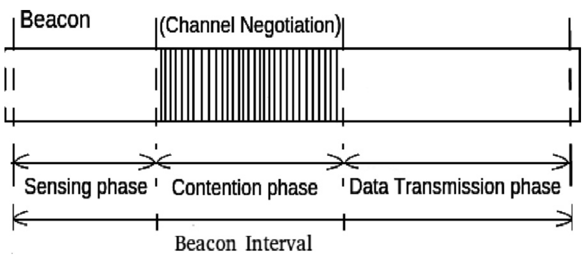

Fig. 3. Timing structure of beacon interval.

[$t-M, .., t-1$]. These values are made available by the module S to module B. The TG_i is the second input to module B from module E. The module B outputs for each channel X_i, the probability that the channel X_i will be in the state TG_i in the immediately following time slot. This is achieved by the MPC *control calculations* wherein, the Hp^i is used as the *system model* and the TG_i is used as the set point *target*. This is precisely what is computed by the MPC framework described in [37]. Thus the paper uses the MPC framework as a black box to compute this probability.

Thus, for each X_i, the probability that X_i is in the state TG_i in the current time slot is computed. From this the probability that X_i is in the state $(1 - TG_i)$ could be computed. Thus, for each channel X_i, the module B has the probability of X_i being *busy* (pb_i) and *idle* (pid_i). Let $\tau = \frac{1}{N}\sum_{i=1}^{N} pb_i$. For each channel X_i, if $pb_i \geq \tau$ then predict channel X_i to be *busy* (1) else predict channel X_i to be *idle* (0). The ability to predict the *future* behaviour of the channels, makes ProMAC a proactive approach.

4. Module S of Fig. 2: real world process
The module S comprises the *Pro-TransRecv* algorithm which uses the output of module B to select the *best* channel for each SU desiring to transmit (Algorithm 1).

Algorithm 1 Pro-TransRecv Algorithm

begin
a) Collect the predicted channel status;
b) Arrange the channels in a list L such that all the *idle* channels are before the *busy* channels for the current time slot; In case more than one channel is idle, the channel which has been used in the previous instance by a PU located at the farthest distance from the SU is given priority i.e., kept at the leftmost in the channel list. Incase there is a tie even after this, a channel is selected randomly among the tied ones. The rationale behind this is farther a PU is from the channel, minimum is the interference it could generate.
c) Allocate the channels one-by-one in the order as stored in L till the successful transmission.
end

The output from the module S gives the actual transmission state of the channels, which is input as feedback to modules A and E during the current time slot.

The above steps described how the MPC framework is used to predict the N channel states for one immediately following time slot. The same is extended for K time slots succeeding the current one as the MPC control calculation can predict the values of *predicted variables* for many time slots. This calculation is performed as an iterative process as follows: In Fig. 2 after module B predicts the states of N channels for the time slot t, the same is used to calculate the predicted probability for time slot $t+1$, which is used again to predict the states of N channels for the time slot $t+1$ without changing the *target value* and assuming the output to be correctly predicted. This is repeated K times to obtain the predicted values of the N channels for K successive time slots.

The ProMAC is considered to operate in both the DCRN architecture and CCRN architecture. In a CCRN architecture, a centralized coordinator or base station manages the spectrum allocation and share the channel occupancy information among the SUs [30]. On the other hand in a DCRN architecture, CR entities operate without the support of a centralized controlling entity [31].

5.1. ProMAC for CCRN architecture

In the CCRN architecture the base station executes the modules A, E and B of Fig. 2 and generates the predicted states of the channels for the next K time slots. The SUs execute module S (Algorithm *Pro-TransRecv*) of Fig. 2 using these predicted values to decide on the channels for transmission. The SUs desiring to transmit, request the base station (Step (a), of *Pro-TransRecv*) for the predicted values. In addition the base station *senses* the channels during each of the K time slots to find their states, which it uses as feedback for module E and A. The base station does this prediction procedure *once* in K time slots.

5.2. ProMAC for DCRN architecture

In the DCRN architecture each of the SUs execute the modules A, E and B of Fig. 2 once in every K time slot. Every SU does the following before executing *Pro-TransRecv*. All the SUs exchange their predicted values with all other SUs. Each SU then computes for each channel X_i the number J_i, $1 \leq i \leq N$, of SUs, that have predicted channel X_i to be *idle*. The list of channels is now sorted in decreasing order of J_i values. This sorted list is used in order by the SUs for deciding the channel for transmission.

5.3. System model

All the available spectrum bands are spread over a wide frequency range. As highlighted in [45] CR networks do not guarantee interference-free transmission and only the interference constraints can be exploited. In this paper, we assume the CR networks to be aware of, (1) the bandwidth and frequency ranges of PUs; (2) the interference levels the PU can tolerate; and, (3) minimum signal-to-noise ratio needed to decode the receiver signal.

It is assumed that each SU node has one half duplex transceiver. A dedicated global CCC is used to exchange control messages between Transmitter and Receiver (Tx-Rx) pair in both the architectures. Further the PU activity is modelled based on the Continuous-Time Markov Chain model (CTMC) approximation described in [46]. As mentioned earlier, the time duration of a transmission is divided into equal sized beacon intervals. Further each beacon interval is further divided into sensing, negotiation and data transmission phases (Fig. 3). We assume that SUs are *synchronized* by the periodic beacon interval. Whenever a SU node joins the network, it first listens to the beacon signal on the CCC and synchronizes itself, with rest of the network. The time slots described in previous sections, are the same beacon intervals. For the sake of completion, we proceed to elaborate on these phases in detail.

5.3.1. Channel sensing phase

Each beacon interval begins with a sensing phase, where the PU channel states are sensed by every SU node. The SUs are refrained from transmission during the sensing period, thereby avoiding *false alarms* [47] triggered by unintended CR signals. The channel sensing phase is responsible to find the *spectrum holes* to be employed in the communication between Tx-Rx pair. The SUs are assumed to use energy detection for spectrum sensing. To have up-to-date sensing information before going in to transmission, ProMAC incorporates channel sensing as part of the MAC layer [33]. The optimum sensing time for a beacon interval is decided as in [45].

Note that due to hardware limitations, it may not be possible to scan all the available data channels in a given sensing period. The proposed protocol predicts a set of *idle* channels for both the CCRN and DCRN architectures, that are *selectively sensed*. The benefits obtained in employing the proposed framework specifically in the context of channel sensing is empirically justified in section 7.5.1.

5.3.2. Contention phase

In this phase, the SUs contend for and preempt a *idle* PU channel based on the multiple access mechanism proposed in IEEE 802.11 DCF [21]. Each Tx-Rx pair reserves, at the maximum one data channel. As a consequence of using the request-to-send/clear-to-send (RTS/CTS) mechanism to establish communication as proposed in IEEE 802.11 DCF, the MHTP issue is solved. This phase is the *testing* phase for the predictions made by the MPC based ProMAC framework. Specifically, the state of each of the sensed channel is input to the ProMAC. Thus the ProMAC *learns* whether its predictions matched the actual outcome and *evolve* itself towards better accuracy in future predictions. Eventually it reduces the chances of similar contentions happening in the next beacon interval.

5.3.3. Data transmission phase

During data transmission phase each Tx SU node that reserved a PU channel successfully in the contention phase, starts transmitting data to its intended Rx node using its reserved channel. All such data transmissions happen in parallel, as all Tx-Rx pairs are transmitting on different channels. Here we assume that the MAC packet data unit is of fixed size and one or more of it can be transmitted. During this phase, if any Tx-Rx pair happens to suffer from PU interference, the transmission is stopped and the SU node *backoffs*. If the Tx-Rx pair had a sensing error during sensing phase, a collision with PU can still happen during this phase. However the probability of that happening, is practically very low [11]. The Tx-Rx pair that is affected by collision, will go through the sensing and contention phase in the next beacon interval. Thus, *in case of collision only one beacon interval is wasted*.

6. Performance metrics

We evaluate ProMAC by using three performance metrics viz. 1) *Channel utilization*, defined as the percentage of time a channel is used for effective data transmission; 2) *Backoff rate*, is the average number of backoffs per second by the SUs; and, 3) *Sensing delay*, which gives the average number of channels sensed by the SUs before a successful transmission.

6.1. Channel utilization

Considering unit transmission rate for simplicity, the channel utilization for an error-free channel is same as the traffic load on the channel. The channel utilization denoted by γ is given as,

$$\gamma = [(t_{busy}) \div (t_{simulation})] * 100 \tag{3}$$

where, $t_{simulation}$ = Total duration of simulation; and, t_{busy} = Total time where the channel was *busy* in transmission. Channel utilization measures the capability of a MAC protocol to maintain equal load on every error-free channel.

6.2. Backoff rate

The backoff rate, denoted by β measures the capability of ProMAC protocol to make correct predictions. It also provides a way to evaluate the robustness of the feedback and learning mechanism of each protocol. Backoff rate (β) is given as,

$$\beta = \frac{N_{backoffs}}{SU_{busytime}} \tag{4}$$

where, $N_{backoffs}$ = Total number of times the SUs backed off in the *Data Transmission* phase; and, $SU_{busytime}$ = Total duration when SU was transmitting.

6.3. Sensing delay

The sensing delay denoted by α is the average number of channels sensed by a SU before successful transmission of the given packet.

$$\alpha = \frac{N_{failures}}{SU_{packets}} \tag{5}$$

where, $N_{failures}$ = Total number of channels sensed before successful transmission of packets in the *Channel Sensing* phase; and, $SU_{packets}$ = Total number of SU packets transmitted.

7. Experiments and results

To realize the effectiveness of ProMAC approach, it was imperative to compare it with a **reactive** mechanism. Thus, we also proposed and implemented a simple Reactive Channel Allocation (RCA) protocol which carries out channel allocation based on the states of the channel in recent past without using any prediction model. The RCA selects the channel which has been free for the maximum number of time slots in past and allocates the same for transmission in the next time slot. We also use RCA as the baseline to compare our proposed ProMAC protocol. In this section, a comparative study of ProMAC, PO-MAC and RCA protocols is presented.

7.1. Experimental setup

The experimental setup uses a standard vehicular CR environment for simulations. The experiments for all the three algorithms have been carried out in the network simulating 10 PUs and 10 PU channels. Simulations were carried out for both *Fixed Network Architecture* and *Variable Network Architecture*. The prediction horizon K, for MPC was set at 3. the value of M used in the simulation is 8. An optimal channel sensing time of 14.2 ms and a frame duration of 100 ms as proposed in [10] was used for the experiments. It is assumed that a global CCC exists, for the SUs to exchange control packets/ state messages. The SU nodes are assumed to transmit data only through PU channels and not through unlicensed channels. This was done in-order to highlight the limit to which SUs can use PU channels. Scalability was tested using a network architecture, where the number of SUs vary over time.

The PU activity was modelled as an *ON/OFF* process based on CTMC model described in [46]. The distributions $F_T(t)$ and $F_I(t)$ are functions of time, that describe the holding times in *transmit* and *idle* states respectively Eq. (6). The variables μ and λ are the parameters of the CTMC model.

$$\left.\begin{array}{l} F_T(t) = 1 - exp(-\mu t) \\ F_I(t) = 1 - exp(-\lambda t) \end{array}\right\} \tag{6}$$

There are eight different combinations of λ and μ, from which different traffic profiles can be derived [46]. Three traffic profiles *high, medium* and *less* were derived from it, where each profile corresponds to the associated PU usage in there channel. These profiles were designed by randomly selecting one of the eight combinations for a random period of time. Then randomly selecting another one. On an average the channel activity is maintained to be

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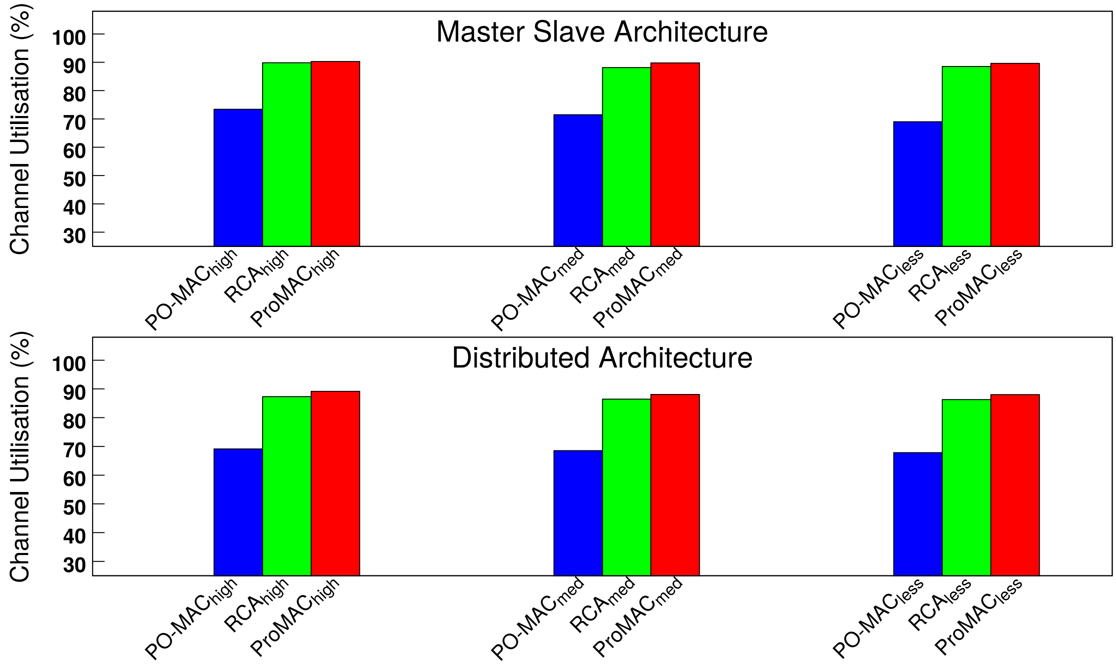


Fig. 4. Channel utilization.

more in *high* followed by *medium* and *less*. This ensures the randomness of PU channel activity and the randomness in variation of channel usage across different times. The results obtained from the experiments are described below.

7.2. Performance in fixed network architecture

In a *Fixed Network Architecture*, the number of vehicular SUs were frozen to 20 and simulations were carried out. The SUs were assumed to generate exponential random traffic. The vehicular SUs were mobile in a diameter of 10 Kms moving with speeds varying from 10 to 60 Km per hr.

7.2.1. Channel utilization

The *channel utilization* of all three MAC protocols viz. ProMAC, PO-MAC and RCA is as given in Fig. 4. The *channel utilization* is observed to be best in ProMAC. This feature is attributed to ProMAC's ability to predict the correct state of the channel in future. RCA exhibits better channel utilization than PO-MAC. In RCA, a channel is allocated based on past states without any consideration of its behaviour in future. PO-MAC fares poorer among the three. It might be because of the fact that after acquiring a channel, transmission is started a time slot later. Also the channel selection is random in PO-MAC. It is to be noted that, the channel utilization described in Fig. 4 includes the utilization due to both SU and PU. As seen in Fig. 4, ProMAC has a overwhelming SU channel occupancy of 29% compared to PO-MAC's 19%. The ProMAC achieved on an average 20% and 5.3% improvement in overall *Channel Utilization* as compared to PO-MAC and RCA respectively.

7.2.2. Backoff rate

The backoff rate describes the re-usability of a PU channel. Backoff Rate achieved by ProMAC, PO-MAC and RCA is as given in Fig. 5. From Fig. 5, it is observed that, on an average ProMAC has the least average Backoff rate. PO-MAC seems to have a comparative backoff rate as ProMAC for *busy* traffic profile and it might be attributed to the principle of pausing for a time slot initially before transmission. Hence a potential backoff in the first time slot is avoided. Note that in *busy* traffic profile the PU channel activity is the highest. The ProMAC achieved on an average 13.5% and 6.35% reduction in backoff rate as compared to PO-MAC and RCA respectively.

7.2.3. Sensing delay

The sensing delay achieved by simulating ProMAC, PO-MAC and RCA under high, medium and less traffic scenario in the CCRN and DCRN architecture are as given in Fig. 6. ProMAC achieved 12% and 2% reduction in Sensing delay as compared to PO-MAC and RCA.

7.3. Performance in variable network architecture

In a *Variable Network Architecture*, the number of vehicular SUs were gradually increased from 10 to 50 and performance metrics were recorded at each interval. As in the case of *Fixed Network Architecture*, the SUs were assumed to generate exponential random traffic moving in a diameter of 10 Kms with speeds varying from 10 to 60 Km per hr.

7.3.1. Scalability

We verified the scalability of ProMAC by varying the number of SUs from 10 to 50 and analysing its behaviour with respect to the performance metrics defined in Section 6. From the Fig. 7(a) and Fig. 7(b), it can observed that the channel utilization and backoff rate increases with the increase in the number of SUs. The Fig. 7(b), shows the ability of different protocols to avoid interfering with the PU transmission. It can be seen that in Fig. 7(a), ProMAC plots for different number of vehicular SUs are very flat. It reflects the consistency with which ProMAC identifies less contentious PU channel through feedback and learning. The stable behaviour of ProMAC protocol, with increase in the number of SUs ascertains its scalability. Variable SU model is an example of Real Time Traffic. ProMAC due to its adaptive design is able to perform better under Variable SU model. The comparative performance of the three protocols as regards to backoff rate calculated to a precision of four digits after decimal point is, (a) ProMAC does not undergo variation; (b) PO-MAC had a variation of 0.63 from mean; and, (c) RCA had a variation of 0.33 from mean.

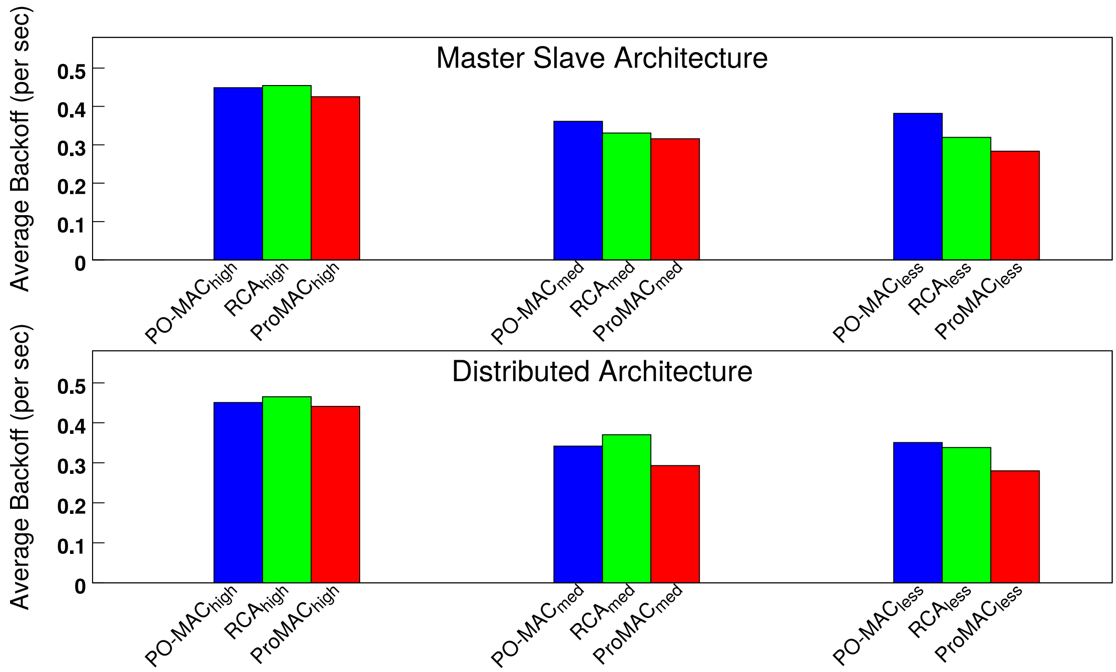


Fig. 5. Average backoff rate.

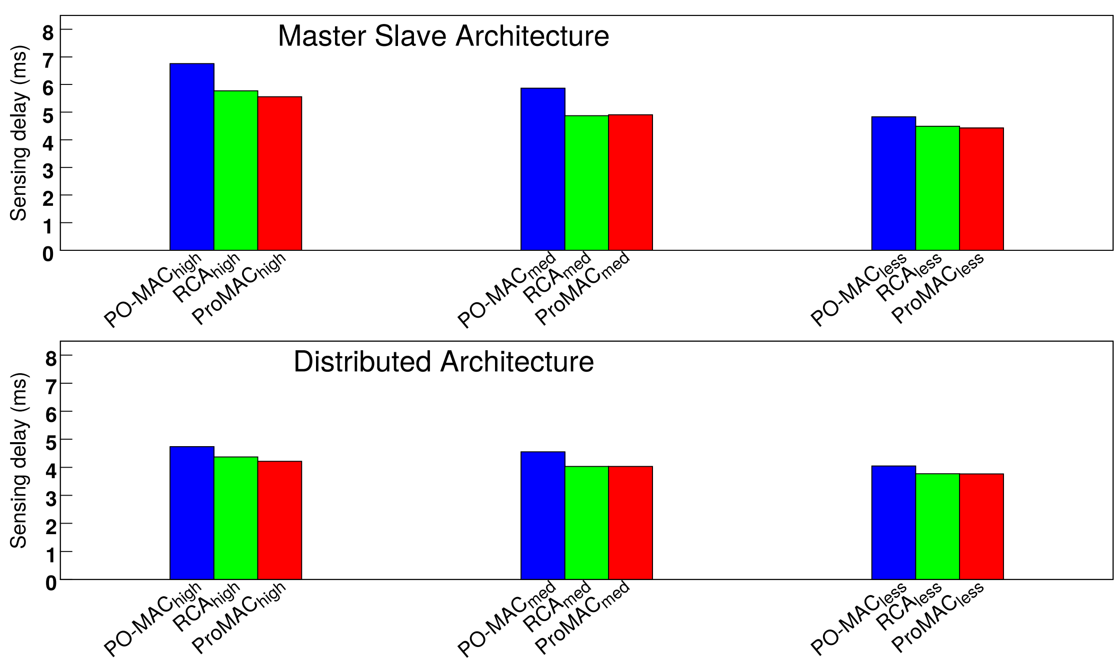
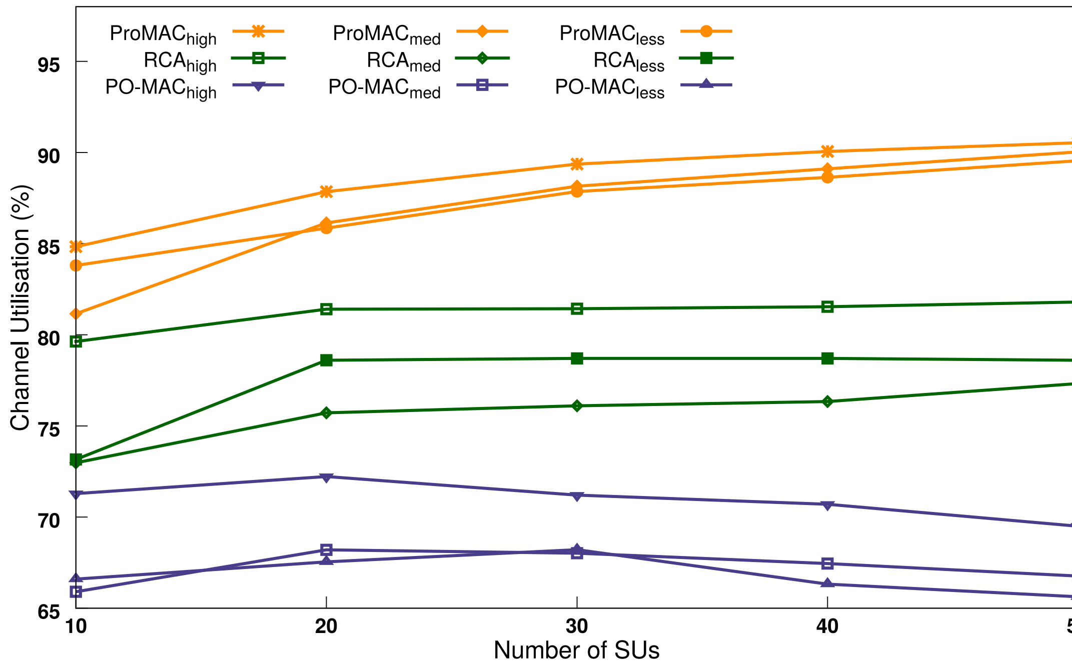


Fig. 6. Sensing delay.

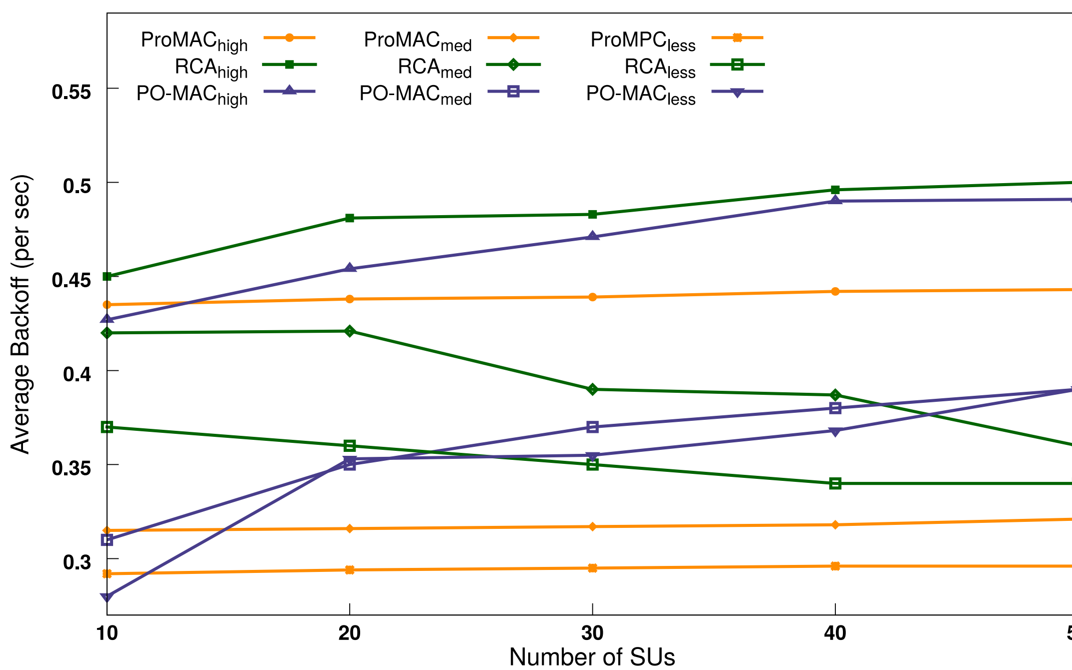
It is interesting to note that from Fig. 7(b) that for smaller number of SUs, the PO-MAC performs slightly better than ProMAC with respect to average backoff time. The reason for this behaviour is as follows: PO-MAC acts in a conservative manner to transmit only when a channel is free. Also, the actual transmission happens after one time slot. Hence, for that one time slot, the channel is left unused. Thus, it waits for a longer time to achieve its goal and thereby avoids a chance of backoff in that time slot. This behaviour is appreciable only with lesser number of SUs. However, as the number of SUs grow, this behaviour results in reduced channel utilization.

The other scalability study is to increase the number of PU channels by keeping the number of SUs constant. The number of PU channels were gradually increased from 10 to 50 and performance metrics were recorded at each interval. As shown in Fig. 8(a), the ProMAC protocol performed better than the counterparts. It is to be noted, that the channel utilization decreases with the increase in number of PU channels. Also it can be seen from Fig. 8(b), that the Backoff Rate gets reduced with the increase in number of channel. The reason is that, with increase in number of PU channels the SUs are being serviced now by greater number of PU channels.

It is interesting to note that the sensing delay unlike the other two performance metrics namely channel utilization and backoff rate is independent of number of SUs and number of channels as it is more due to the fixed characteristics of the radio. Thus, there are



(a) Channel Utilization



(b) Backoff Rate

Fig. 7. Performance comparison of ProMAC, PO-MAC and RCA in variable SU model, distributed architecture.

no significant dependencies between sensing delay on one hand and the number of SUs or number of channels on the other hand.

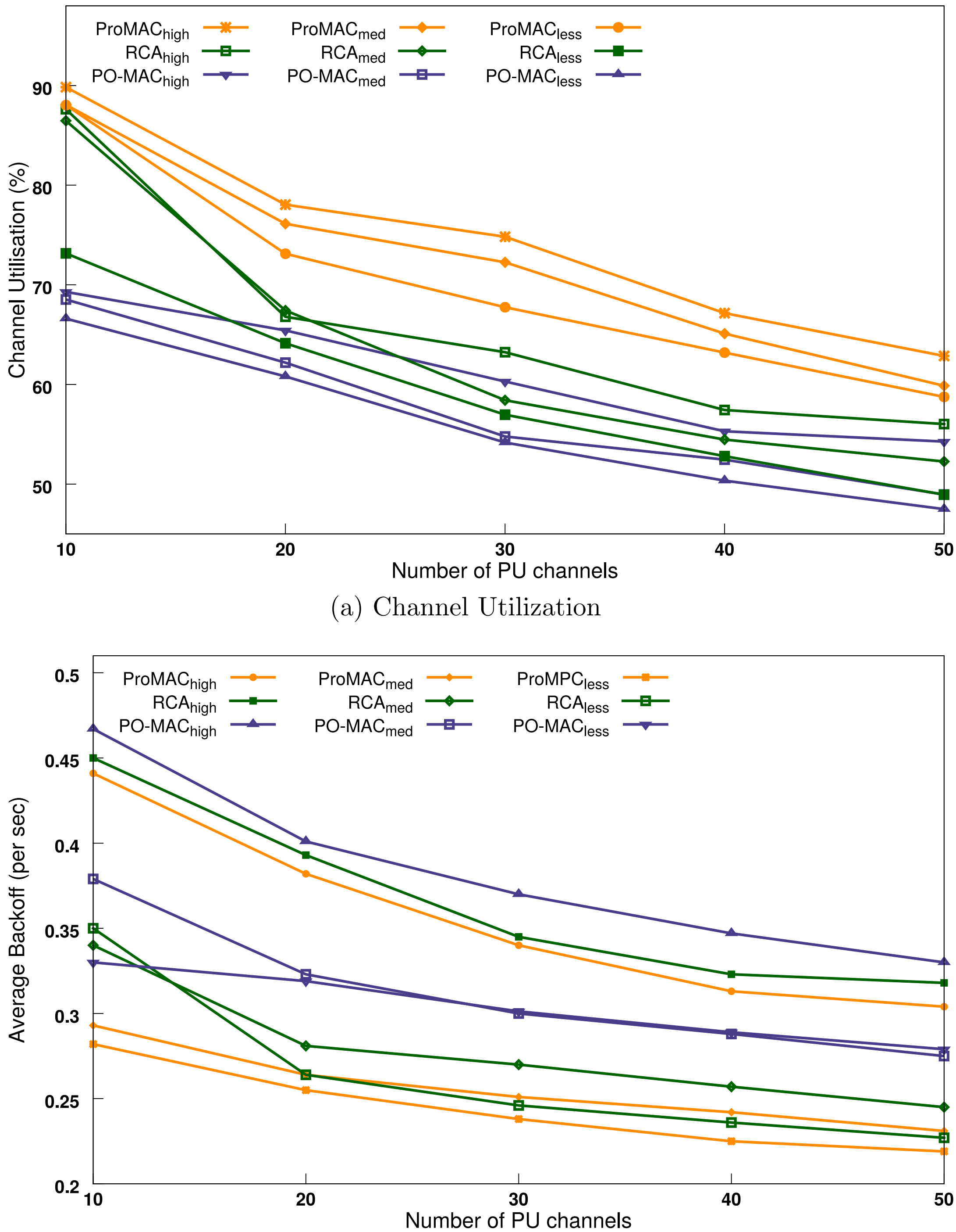
7.4. Salient features and advantages of ProMAC

There are several advantages in using MPC based prediction method over the static methods as explained below.

7.4.1. Reducing sensing overhead

As mentioned earlier, the ProMAC uses a MPC framework, to model the CR vehicular network and predicts the future transmission states of the PU channels. By analysing the predicted future behaviour of channels, the SU nodes can also decide on which channel to sense and which to avoid. **This avoids the practical difficulty of sensing all channels within the sensing period and also the hardware, power and performance related costs incurred for sensing many channels**.

There is a trade-off between interference and sensing time [45]. To avoid interference the sensing time should be long enough to achieve sufficient detection accuracy. But as the sensing time increases, the time available to SU node within a time slot for the purpose of data transmission decreases. As highlighted in [45],



(a) Channel Utilization

(b) Backoff Rate

Fig. 8. Performance comparison of ProMAC, PO-MAC and RCA with multiple channels, distributed architecture.

sensing and transmission time are the parameters that influence both the interference avoidance and channel utilization of a SU. We know that the SU node in ProMAC framework has the predicted values of the PU channels, for the next *K* time slots. **Having this database provides a comfort to SU node in terms of deferring the sensing of certain channels to next time slot, particularly the ones having a higher probability of PU usage**. As an example, by observing the principle of deferring the channel with higher probability of being *busy*. The number of channels that are sensed during peak PU usage time will be less in number in ProMAC, compared to the other schemes. Usually during peak usage time (high traffic), PU channels require a greater sensing time to achieve sufficient detection accuracy. In such a case, SU node in the ProMAC framework has the flexibility to sense fewer channels and also with greater detection accuracy. Also the sensed channels have a greater chance of being *idle* in next time slot. From a greedy perspective, PU channels with lesser probability of being free in next *K* time slots, can be left over from sensing.

7.4.2. Reduced energy dissipation

The major contributors to energy dissipation in wireless networks are channel sensing and interference [48]. The smart sensing technique enabled through ProMAC not only reduces the number of channels to be sensed by a SU, but also reduces interference during transmission. The reduced backoff rate due to ProMAC when compared to other CR MAC protocols as seen in Fig. 5 justifies the above claim.

In the context of the DCRN architecture, the predicted results of several time slots can be used to limit the frequent exchange of control messages. The above claim is valid in the case of CCRN architecture also, as the base station can abide from sending predicted values to the slave SU nodes often. The reduced transmission and reception of control messages due to ProMAC, eventually reduces the congestion in the global Common Control Channel (CCC) and allows the SU node to spend more time in sending data instead of competing for CCC. Thus, the energy dissipated by each SU node in sensing and selection of channel, will be significantly less than the energy dissipation in other reported CR MAC protocols.

7.4.3. Proactive spectrum handoff

Proactive spectrum handoff [44] is a technique that determines the probability of a PU channel being busy in the next succeeding time slot. If the probability is above a threshold the SU currently holding the channel *shall hand it over* to the concerned PU. Such a feature can be easily realized on the ProMAC framework wherein, prediction of the states of the PU channels are available for K time slots ($K > 1$).

8. Conclusion

An architecture that incorporates a **proactive mindset** and capable of predicting when and where communication pathways exist is significantly required for effective implementation of CR vehicular networks. It must be capable of devising multiple contingency plans based on available networks, radio environmental conditions, and, user quality of service, along with prediction of user mobility.

It is therefore imperative for the present day CR framework to include a proactive approach to facilitate the cognitive procedure at all stages. The proposed ProMAC approach not only improves the channel utilization by effectively *learning* the environment but also helps the system to take better decisions over a period of successive time slots. This not only resulted in reducing the OODA loop time but also optimized the overall performance of the CR network. The above statement is justified empirically in this paper.

Interestingly, ProMAC which starts with addressing the issue of channel assignment in a proactive manner, *inadvertently* solves the other issues addressed by the best reported PO-MAC, namely, reducing the number of channels to be sensed by a SU node by using the results from the MPC framework; increased channel utilization by assigning channels to SU node in a systematic manner; and, minimizing the energy dissipation by using predicted results to limit the exchange of control messages. As described in [34], PO-MAC was designed to work in a less disturbed environment. The ProMAC which works in a environment with more unpredictability and movement, also outperform PO-MAC in performance. Thus, the proposed ProMAC protocol provides a proactive channel allocation framework that incorporates some of the best practices reported in the literature for building an effective CR vehicular network.

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