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Quality-of-service-aware weighted-fair medium access control protocol for coexisting cognitive radio networks

Iffat Anjum[1], Md Abdur Razzaque[1*], Mohammad Mehedi Hassan[2], Abdulhameed Alelaiwi[2]
and Sk Md Mizanur Rahman[2]

Abstract

Opportunistic usage selection of a licensed channel by a secondary user (SU) and its contention for data transmission is a challenging problem in coexisting cognitive radio network (CCRN). This is caused by the presence of many SUs from different CRNs in a shared environment, and the problem is further intensified when the user applications, with heterogeneous quality-of-service (QoS) requirements, require prioritized access to the opportunistic spectrum. The state-of-the-art protocols did not address the problem of efficient coexistence following both the dynamic spectrum availability and prioritized medium access. In this paper, a weighted fair medium access control protocol, namely WF-MAC, has been developed for overlay CR network that gives users proportionate accesses to the opportunistic spectrum following their application QoS requirements. The channel availability prediction using autoregression (AR) model and channel utility perception using exponentially weighted moving average (EWMA) facilitate WF-MAC to achieve more stable and fair access to the opportunistic spectrum. Our simulation experiment results depict the efficiency of the proposed WF-MAC protocol in achieving better spectrum utilization, weighted fairness, throughput, and medium access delay compared to the state-of-the-art protocols.

Keywords: Coexisting cognitive radio network, Medium access control, Quality of service, Weighted fairness, Channel availability, Utility perception

1 Introduction

Over the past decades, with the rapid development of wireless technology, the spectrum demand and its scarcity have greatly been increased. Almost all the licensed frequency spectrum bands have already been assigned. However, they are mostly underutilized [1], and as a result, utilization of spectrum white spaces has become a major research challenge. To address those issues, the Federal Communications Commission (FCC) of the USA has endorsed a smart radio-based spectrum policy, called cognitive radios (CRs) [2].

Overlay CR is a form of wireless communication, in which a transceiver intelligently detects a channels' availability and instantly moves to a vacant channel while avoiding occupied ones [3, 4]. In cognitive radio network (CRN) environment, licensed or primary users (PUs) and non-licensed or secondary users (SUs) coincide in the same environment. Spectrum holes of the licensed channels are detected and accessed in an opportunistic manner by the SUs, securing the licensed rights of PUs.

The technology of CRNs and diverse wireless services are developing speedily, resulting in coexistence of multiple networks in the same vicinity [5]. Interference among those co-located CRNs degrades the system performance significantly [6]. When multiple CRNs operate using the same set of channels, the SUs may try to act greedily and occupy all the available channel bandwidth [5], resulting in starvation for many SUs. Furthermore, fair access to the opportunistic spectrum bands by the users with diverse quality-of-service (QoS) data traffic is a challenging problem in coexisting CRN (CCRN) environment. This work explores optimal strategies for channel selection and medium access to enhance spectrum utilization.

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*Correspondence: razzaque@du.ac.bd
[1] Green Networking Research Group, Department of Computer Science and Engineering, University of Dhaka, Dhaka-1000, Bangladesh
Full list of author information is available at the end of the article

In the state of the art, many research works have focused on evolving CR-MAC protocols [7–9] to boost spectrum utilization. However, the coexistence of CR networks with overlapping frequency spectrum has received less attention. Game theoretic approaches [10, 11] are developed to minimize the interference in coexisting CRNs. Fair medium access control (FMAC) [12, 13] is a pioneer work considering coexistence property as a whole that addresses the dynamic availability of channels and proposes a fair MAC protocol for CCRN environment. It allows the crowd of coexisting CRNs to share the channels effectively and achieves usage fairness. However, without any knowledgeable channel selection mechanism and QoS awareness of diverse data traffic, the FMAC fails to provide satisfactory performance in coexisting network environment. The FMAC users also suffer from channel starvation since they do not explore alternate available channels.

In this paper, we develop a distributed MAC protocol for infrastructure-based coexisting CRNs, namely WF-MAC, that maximizes the system throughput, minimizes the delay, and ensures weighted fair spectrum utilization. The WF-MAC formulates an intelligent channel selection mechanism for each SU using two-dimensional learning approaches—channel availability prediction and utility-based perception learning. A QoS-aware channel access mechanism is adopted for the SUs. Furthermore, a smart settlement between channel sharing and channel switching has been designed to avoid repeated interference and starvation events over a specific channel. We are using a three-state sensing model [14] to evade false interpretation of channel usage. The contributions of this work are summarized as follows:

- A distributed weighted fair channel selection and medium access control protocol, WF-MAC, has been developed for CCRN environment.
- Multilevel weighted fair resource utilization is maintained by the SUs through judicious channel selection and QoS-aware channel access.
- Efficient channel selection is performed through two-dimensional learning: channel availability prediction and channel utility perception.
- The results of performance study in ns-3 show significant improvements in throughput, weighted fair channel access, medium access delay, etc.

The rest of this paper organized as follows. The state-of-the-art methodologies and their limitations are discussed in Section 2. Section 3 discusses the network model and assumptions. In Section 4, we present operation details of the design components of the proposed WF-MAC protocol. The performance evaluation is provided in Section 5, and we conclude the article in Section 6.

2 Related works

Developing an efficient MAC protocol for CRN is a challenging problem as it requires an opportunistic spectrum access of SUs as well as the protection of incumbent PU rights. Many state-of-the-art protocols have been developed addressing the spectrum utilization efficiency in CR networks to balance the under- and overutilization of licensed bands. However, the criticality of the problem increases when multiple CRNs coexist in the same vicinity.

The IEEE 802.22 working group constructed a wireless regional area network (WRAN) and recently standardized a MAC layer based on CR for reusing the spectrum allocated to the TV broadcast service [15]. Recent research contributions opportunistic multi-channel MAC (OMC-MAC) [16], predictive MAC (PMAC) [8], and prioritized CR MAC (PCR-MAC) [7] emphasized mainly on designing synchronized MAC protocol for distributed CRN (DCRN). The OMC-MAC addressed QoS provisioning problem for DCRN using user application prioritization. The PMAC and PCR-MAC presented channel selection mechanisms using EWMA-based historical usage prediction to enhance the opportunistic spectrum utilization; the PCR-MAC also exploits the concept of backup channel, adopted from SWITCH [17], to further optimize the spectrum utilization.

Infrastructure-based CRN provides more flexibility in characterizing incumbent usage pattern and designing spectrum access policy of unlicensed users. The two-level MAC protocol [9] maintains a simple PU detection probability mechanism with CR-CSMA/CR-ALOHA-based packet scheduling framework. A PU arrival rate prediction and channel holding time estimation-based medium access mechanism is presented in [18]. In [19], a QoS-aware framework for characterizing spectrum availability and usage determination has been developed to enhance throughput and fairness.

The aforementioned protocols entirely avoid the concept of coexistence among multiple CRNs. Homogeneous coexistence or self-coexistence refers to the coexistence of networks that employ the same wireless technology; on the other hand, heterogeneous coexistence network employs different wireless technologies (e.g., the coexistence between WiFi and Bluetooth) [20]. ESC [21] proposes an efficient channel assignment taking into account the overlapping among WRANs to minimize interference. Several game-theoretic [10, 22] and learning-based [11] approaches are investigated to ensure interference minimized channel access. However, construction of a MAC protocol for heterogeneous coexisting cognitive radio network has received poor attention [6].

Our proposed WF-MAC protocol is inspired from FMAC [12], a coexistence-aware MAC protocol for CRN. However, our proposed WF-MAC protocol has some distinct features that differentiate it from FMAC. *First*, FMAC's channel selection is done based on the current channel status only, which cannot ensure a better spectrum utilization. Whereas, we propose a channel selection mechanism using historical availability prediction and utility-based perception learning, minimizing the possibility of interference and starvation. *Second*, the CSMA-based channel access mechanism of FMAC does not care about the diverse QoS requirements of different applications. We propose a prioritized channel sharing mechanism to ensure the weighted-fair access to the medium. *Third*, FMAC cannot secure applications from starvation, as it entirely eliminates the option of channel switching from consideration. However, our design provides knowledgeable channel switching mechanism, which can dynamically reshape the medium access policy of any user.

3 System model and assumptions

We consider a CRN, where multiple infrastructure-based CRNs are available in the same vicinity, as shown in Fig. 1. We assume that each CRN has multiple SUs and PUs, where the m number of licensed channels are conditionally and opportunistically accessible by the SUs. Each SU takes t time to sense a channel; we consider it as the sampling interval. We also assume that the users (PUs or SUs) arrive on channels independently and follow Poisson distribution, i.e., the arrival pattern is an *iid*.

Each SU is assumed to equip with two transceivers; both the transceivers can be tuned to any of the m licensed channels, the first one is for channel sensing and the second one for data transmission. The SUs exchange control messages over a dedicated common control channel (CCC) [23]. We are using three types of control messages, as shown in Fig. 2.

We also assume that an SU can methodically sense the channel states and identify the channel of being idle or busy. However, two-state sensing model (idle or busy) fails to provide fair channel usage to the SUs of different CRNs [13]. In this work, we use three-state sensing model [14], as of Eq. 1, where each busy state is further divided into state 1 (accessed by PU) and state 2 (accessed by SU), using a distance-based estimation technique. Each SU shares the sensing result with its base station (BS) that determines the channel states through collaboration.

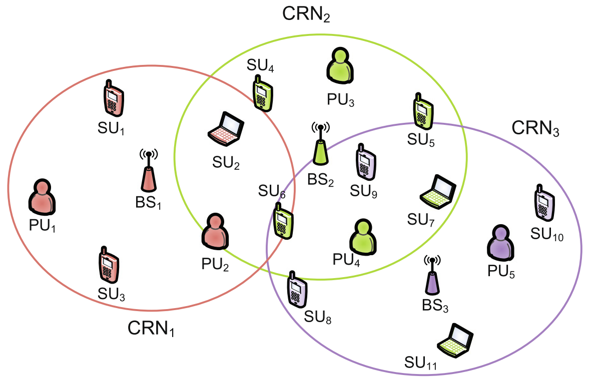


Fig. 1 Coexisting cognitive radio network

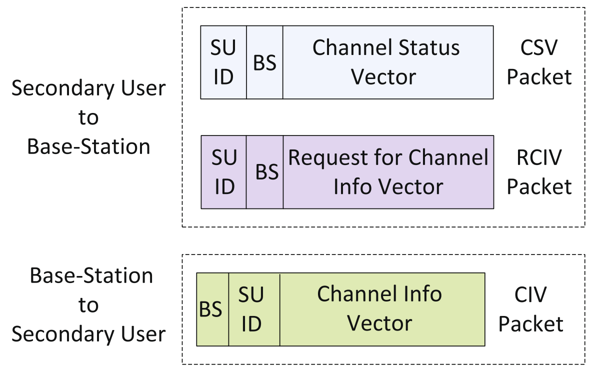


Fig. 2 Control packets transmitted over CCC

$$S_i = \begin{cases} n_i & 0, \\ s_p + n_i & 1, \\ s_s + n_i & 2. \end{cases} \tag{1}$$

Here, s_s represents the transmitting signal strength of an SU, s_p is the signal strength of PU transmission, S_i is the received signal strength by an SU, and n_i is the additive white Gaussain noise (AWGN) with zero mean.

A PU begins transmission over an idle channel immediately; however, if the channel is occupied by an SU, it waits for at most two sensing periods to allow the SU release the channel safely. Because, if the PU arrives at the middle or ending part of the SU's current sensing period (t), it may go unnoticed. Therefore, the tolerable maximum amount of time for PU is a system parameter and it is set as $t_{\max} \leq 2 \times t$.

We also assume that different types of applications, running on the SUs, are generating packets with diverse traffic sensitivity [24]. We classify the user traffic into four different priority (ρ) levels by following [25], as shown in Table 1; the set of all traffic classes is denoted by Ω. The notations and parameters used in this paper are listed in Table 2.

4 Weighted-fair MAC design

The operation of WF-MAC design components are presented in details below.

4.1 Design components

The proposed WF-MAC system allows the secondary users to opportunistically utilize unused licensed channels in a weighted fair manner. We minimize interference

Table 1 Traffic types for QoS provisioning

Type (Ω)	Description	Priority (ρ)
Voice	Highest priority (low latency) (e.g., voice call, audio streaming)	6
Video	Second highest priority (video conferencing, streaming)	4
Best effort	No QoS mentioned, bursty traffic (traffic less sensitive to latency, e.g. web surfing)	3
Background	Lowest priority (no strict latency) (e.g., print jobs, email, etc.)	1

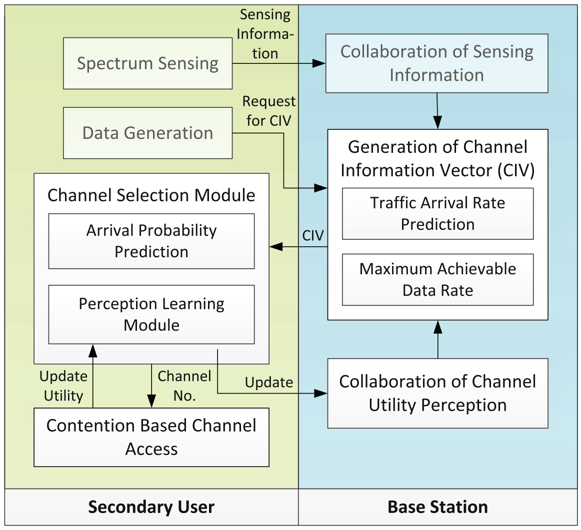


Fig. 3 WF-MAC design components

and channel switching probability by selecting channels with higher probability of being available and higher utility perception. We also propose a weighted fair channel access mechanism of the SUs from multiple CRNs with QoS provisioning. This knowledgeable channel selection and access mechanism gradually evolve a stable system with higher throughput. The protocol design components are demonstrated in Fig. 3.

Each WF-MAC SU has a *spectrum sensing module* that periodically senses the channel and informs BS through CCC to define channel states using *collaboration module*. Spectrum sensing and collaborative channel state determination techniques are well studied in the literature [12–14]; we have adopted [14]. If an SU has data to transmit, then its *Data Generation Module* requests the BS for channel information vector (CIV). The BS responds by sending CIV-containing channel state information, perception vector, traffic arrival rates, etc. The BS uses an autoregression-based SU and PU *arrival rate prediction* technique, measurement methods for collaborative *utility perception*, and *maximum achievable data rate* on different channels.

Table 2 Notations and definitions used for WF-MAC

Notation	Description
$\mathcal{M}$	Set of Licensed channels; $\{1, 2, 3, \ldots, m\}$
$\mathcal{N}_r$	Set of SUs of CRN r; $\{1, 2, 3, \ldots, n\}$
Ω	Set of traffic types
ρ	Priority value assigned to a specific traffic
H_i	Status of channel i; $\{0, 1, 2\}$
t	Time needed to sense a channel
σ_s	Number of retransmissions for collision with SU
σ_p	Number of retransmissions for PU appearance
λ_i^s	SU arrival rate over channel i
λ_i^p	PU arrival rate over channel i
$\mathcal{E}$	Channel availability vector
$\mathcal{U}$	Channel utility perception vector
$\mathcal{O}$	Channel usage outcome $\{o_1, o_2, o_3, o_4\}$
CW_ρ	Contention window for packet priority type ρ

The *channel selection module* of SU will elect the most favorable channel for access using the *utility perception* and *arrival probability* information. Each SU uses the selected spectrum using a QoS-aware *contention-based channel access* mechanism. Over the channel access process, upon different usage outcomes, SU *update the utility* of selected channel and share it with the BS.

4.2 Weighted fair channel selection

In CCRN environment, each CRN functions in a distributive and non-cooperative way. Every CRN should work towards maximizing the utilization of available spectrum, which can be achieved only by maximizing individual SUs' utilization over the course of time. Efficient spectrum utilization can be increased by acquiring the most advantageous channel for data transmission. Utility perception-based learning mechanism [11] with legitimate knowledge of system's current state will allow SUs to gain the finest and most rational channel distribution. But, only perception on channel utility is not enough in a non-cooperative and competitive coexisting environment; a probabilistic glimpse of channel availability is also important.

The amount of assistance or service received by utilizing a specific channel can be defined as the utility of that channel towards an SU. Each SU shares current channel utility with its BS. The BSs gradually build up an effective and stable perception about each channel using its population's experience, maintaining a utility perception vector $\mathcal{U}$, to be discussed in Section 4.2.2. Whenever an SU has some data to transmit, it sends a request for channel information vector (RCIV) packet to its BS. Then, the

BS prepares and sends the channel information vector, CIV $= \langle H_i, \lambda_i^p, \lambda_i^s, u_i, \beta_i \rangle, \quad \forall i \in \mathcal{M}^o$. Here, H_i is the status of channel i, λ_i^p and λ_i^s are the PU and SU arrival rates, respectively, u_i is the perception utility value, β_i is the achievable bandwidth of channel i, and $\mathcal{M}^o$ is the set of channels that are not occupied by PUs, defined in Eq. 2. Using contents of CIV, an SU generates the channel availability vector $\mathcal{E}$, containing the arrival probabilities of both types of users, to be explained in Section 4.2.1.

$$\mathcal{M}^o = \{i \in \mathcal{M} \,|H_i \neq 1\} \tag{2}$$

Now, using the directives of $\mathcal{E}$ and $\mathcal{U}$, an SU selects an optimal channel from the available channel set $\mathcal{M}^o$ for contention-based channel access. An SU tries to maximize both the channel perception value (u) and the probability of channel being free (ϵ), maintaining the SU and PU arrival probabilities within a certain threshold, as follows:

$$c = \arg\max_i \left(\frac{1}{1+e^{-u_i}} \times \epsilon_i \right), \tag{3}$$
$$\epsilon_i^s \geq \epsilon_{\text{th}}^s, \epsilon_i^p \geq \epsilon_{\text{th}}^p, \forall i \in \mathcal{M}^o$$

where ϵ_i^p and ϵ_i^s are the probabilities that PU and SU will not appear over channel i, respectively, ϵ_{th}^s and ϵ_{th}^p are the corresponding minimum thresholds, and ϵ_i is the probability of channel being free. If every SU selects its channel based on the probability of being free only, a certain high-quality channel may become overloaded and the spectrum distribution would be unfair. In addition to that, the interference may increase significantly in such a non-cooperative environment of CCRN. Equation 3 implements an effective utility-based resource distribution that enables the SUs of different CRNs to coexist with less interference and delay. The experience-based dynamic update of the utility values and channel availability predictions (to be described in following subsections) eventually facilitate weighted-fair distribution with more allocation in high-quality channels.

Now, our channel selection problem comes down to the derivation of probability of each channel being idle and its utility perception. The whole process of channel selection is summarized in Algorithm 1.

4.2.1 Channel availability prediction

Every SU can determine the probability of each channel being available on its entire transmission time and determine the channel availability vector $\mathcal{E}$. This probabilities are determined using the PU and SU arrival rates over each channel received from its BS. Since the arrival pattern of PU and SU follows Poisson distribution, probability that no SU or PU will appear over the data transmission time can be generated, which will lead to the overall probability of a channel being idle.

Algorithm 1 Weighted fair channel selection algorithm for each SU $n \in \mathcal{N}$

```
while SU is active do    ▷ SU continuously senses each channel and periodically sends sensing data to BS
    if SU has data to transmit then
        Send an RCIV packet to BS
        Receive an CIV packet from BS
        Define $\mathcal{M}^o$ using Eq. 2
        Calculate $\mathcal{T}_i^t$ using Eq. 8,  $\forall i \in \mathcal{M}^o$
        Calculate $\epsilon_i^p$, $\epsilon_i^s$ and $\epsilon_i$ using Eqs. 4, 5 and 6, $\forall i \in \mathcal{M}^o$
        Select channel $c$ using Eq. 3
    end if
end while
```

Probability that no PU will come over the transmission period of SU can be determined using Eq. 4 for each channel $i \in \mathcal{M}$. Here, $\mathcal{T}_i^t$ is the expected time needed to transfer the current packet in the buffer of the SU over channel i and λ_i^p is the PU arrival rate over channel i.

$$\epsilon_i^p = e^{\left(-\lambda_i^p \times \mathcal{T}_i^t\right)} \tag{4}$$

Similarly, probability that no other SUs attempt to transmit during the transmission period of an SU on a channel i can be determined using Eq. 5.

$$\epsilon_i^s = e^{(-\lambda_i^s \times \mathcal{T}_i^t)} \tag{5}$$

Here, λ_i^s is the SU arrival rate over channel i. Using the definitions of Eqs. 4 and 5, the SU can determine the probability of each channel $i \in \mathcal{M}$ being idle during the transmission period of SU as follows:

$$\epsilon_i = \epsilon_i^p \times \epsilon_i^s. \tag{6}$$

Now, the SU can determine the $m \times 3$ channel availability vector $\mathcal{E}$ as of Eq. 7.

$$\mathcal{E} = \begin{bmatrix} \epsilon_1^p & \epsilon_1^s & \epsilon_1 \\ \epsilon_2^p & \epsilon_2^s & \epsilon_2 \\ \vdots & \vdots & \vdots \\ \epsilon_m^p & \epsilon_m^s & \epsilon_m \end{bmatrix} \tag{7}$$

What follows next is the details of how the expected transmission time and user arrival rates for each channel $i \in \mathcal{M}$ are calculated. The expected time an SU needs to transmit its current data packet can be derived using the maximum achievable data rate β_i of each channel and average medium access delay in between two consecutive data packet transmissions, denoted by $\mathcal{T}^d$. The expected transmission time $\mathcal{T}_i^t$ can be derived as follows:

$$\mathcal{T}_i^t = \frac{\ell_j}{\beta_i} + \mathcal{T}^d, \tag{8}$$

where ℓ_j is the length of the current data packet, the average medium access delay $\mathcal{T}^d$ includes back-off time, control packet transmission time, inter-frame spaces (e.g., SIFS, DIFS), and propagation delay, and it can be defined as follows [26]:

$$\mathcal{T}^d = \left(E\left[b_\rho\right] \times t\right) + \text{DIFS} + \mathcal{T}^{\text{RTS}} + \text{SIFS} + \mathcal{T}^{\text{CTS}} \\ + \text{SIFS} + \mathcal{T}^{\text{ACK}} + \text{SIFS} + 4 \times \delta, \tag{9}$$

where δ is the propagation delay; $\mathcal{T}^{\text{ACK}}$, $\mathcal{T}^{\text{RTS}}$, and $\mathcal{T}^{\text{CTS}}$ are the time intervals required to transmit the acknowledgement (ACK), request to send (RTS), and clear to send (CTS) control packets, respectively; $E[\,b_\rho]$ is the expected value of back-off counter b_ρ; and t is the length of single time slot.

The BS calculates the maximum achievable data rate β_i of each channel $i \in \mathcal{M}$ using Shannon's theorem, as follows:

$$\beta_i = B_i \log_2(1 + \text{SINR}_i), \tag{10}$$

where B_i is the bandwidth of channel i, SINR_i is the signal-to-interference-plus-noise-ratio on SU-BS transmission link over channel i.

The SINR at each channel measures the possible interference due to simultaneous transmission of multiple SUs to a specific BS over a single channel. A BS can receive simultaneous transmissions from $|\mathcal{N}_i|$ number of SUs on a certain channel i. In that case, the BS can calculate the SINR for the transmission with SU n ($n \in \mathcal{N}_i$) over channel i, as follows:

$$\text{SINR}_i = \frac{S_n}{S_{\text{noise}} + \sum_{k \in \{\mathcal{N}_i - n\}} S_k} \tag{11}$$

where S_{noise} is the signal strength of Gaussian noise, which is determined depending on the environment, and S_n and S_k are the received signal strengths from SU n and other SUs ($k \in \mathcal{N}_i - n$), respectively. The received signal strength from any node r ($r \in \mathcal{N}_i$) is measured as follows:

$$S_r = \frac{s_r}{d^\alpha} \tag{12}$$

here, s_r is the fixed transmission power of an SU r ($r \in \mathcal{N}_i$), d^α stands for the distance between BS and SU, and α is the parameter for considering power decay due to distance.

The derivation of PU and SU arrival rates is a continuous process, and it needs to analyze the channel usage pattern for all users in the network. As every BS takes the final decision on channel states and has access to all the channel usage information over the time. Therefore, a BS is able to provide a generalized arrival rate prediction of SUs and PUs of each channels in the environment. The autoregressive (AR) [27] model can be used to forecast an arbitrary number of periods into the future and has been widely used to predict channel state transitions over fading channels. We are adopting the AR model of order Δ to predict the arrival rates of each type of users. Higher value of Δ provides more accurate prediction with increased complexity, and the lower value offers simplicity with possible prediction error [27]. The PU arrival rate λ_k^p can be derived using the equation below at the kth instant:

$$\lambda_k^p = \sum_{j=1}^{\Delta} \alpha_j \lambda_{k-j}^p + \xi_k, \tag{13}$$

where $|\alpha_j| < 1$ is the autoregressive coefficient that can be computed using the Yule-Walker algorithm [27] and ξ_k is the prediction error.

Similarly, the SU arrival rate λ_k^s can be calculated as follows:

$$\lambda_k^s = \sum_{j=1}^{\Delta} \alpha_j \lambda_{k-j}^s + \xi_k \tag{14}$$

The arrival rate at each time instant can be calculated using the packet inter-arrival time. After the discussion above, now our subject of concern goes down to the derivation of utility perception vector.

4.2.2 Channel utility perception vector

We have adopted reinforcement learning-based [28] mechanism to model the utility perception of SUs on different channels that helps the BSs of different CRNs to build a perception about each spectrum band. The perception model observes the outcomes of the action events and updates utility gains or losses experienced by the SUs. This utility-based perception along with channel sensing information helps to develop a dynamic channel usage mechanism among the users of coexisting CRNs. Each SU only updates its selected channel's utility; the corresponding BS aggregates the perception utilities from SUs over several channels.

When an SU has selected a channel c for access and started its process of transmission, it can experience several usage outcomes. The set of possible outcomes is defined as $\mathcal{O} \in \{o_1, o_2, o_3, o_4\}$.

o_1 : SU has successfully transmitted a data packet.
o_2 : SU transmission was deferred by collision with another SU or bit error.
o_3 : SU transmission was deferred by PU arrival.
o_4 : SU has to switch from the current channel.

By experiencing outcome o_1 over the selected channel c, an SU gains a certain amount utility. On outcome o_2 and o_4, the SU loses the utility by some amount. We have to rationalize the utility gain and utility loss values with channel quality. The channel quality can be defined by channel's probability of being free; the higher the value of channel quality, the higher the corresponding utility loss or gain will be. In the case, when any channel is accessed by a PU (o_3), we do not alter the utility value, as we cannot gain stability with licensed network users. Let u_c be the perception utility of the selected channel $c \in \mathcal{M}$ by an SU and it is updated after each usage outcome as follows:

$$u_c = \begin{cases} u_c + (\phi_g \times \epsilon_c) & o_1, \\ u_c - (\phi_p \times \epsilon_c) & o_2, \\ u_c - (\phi_s \times \epsilon_c) & o_4, \\ u_c & o_3, \end{cases} \tag{15}$$

where ϕ_g is the constant utility gain received on successful transmission and ϕ_p is the utility loss on collision with transmission from another SU. ϕ_s is the constant loss for channel switching.

Each SU only updates the utility of its selected channel and shares the information with the BS periodically. Every BS aggregates the received utility values from different SUs and maintains a utility perception vector, $\mathcal{U}$, as shown in Eq. 16. Each entry of $\mathcal{U}$ indicates the aggregate perception utility for each channel $i \in \mathcal{M}$. Initially, we set a small constant value for all channels, i.e., the system starts with equal biasness towards all channels.

$$\mathcal{U} = \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_m \end{bmatrix} \tag{16}$$

The process of calculating aggregated perception utility by a BS is illustrated as follows. Assume that a CRN has $|\mathcal{N}|$ number of SUs, among them $|\mathcal{N}^i|$ SUs access a channel $i \in \mathcal{M}$ and shares their individual utility perception ($u_{i,n}, n \in \mathcal{N}^i$) with the BS during a timer interval τ. Then, the BS determines an aggregated utility perception ($u_{i,\tau}$) for that channel using exponential weighted moving average (EWMA) as follows:

$$u_{i,\tau} = \gamma \times u_{i,\tau-1} + (1-\gamma) \times \left\{ \frac{\sum_{n \in \mathcal{N}^i} u_{i,n}}{|\mathcal{N}^i|} \right\} \tag{17}$$

where γ is a weighting factor used to give different weights to historical and current utility measurements, $0 < \gamma < 1$.

Every BS maintains this utility information about each channel and sends it to a requesting SU as CIV. An SU uses the utility values in channel selection process and periodically notify the BS about its experience on the selected channel.

4.3 QoS-aware medium access

Once a suitable spectrum band (channel) is selected by an SU using the channel selection module of WF-MAC, the next issue is to gain an effective usage of that channel. This channel access scheme should avoid interference and starvation and consider QoS requirements of different types of application data. Each WF-MAC SU adopts a QoS-aware CSMA/CA-based channel access policy, which has two distinct collision avoidance schemes for two types of traffics (PU traffic and SU traffic); these approaches differentiate this channel-sharing mechanism from the IEEE 802.11n [29]. Again, the SUs do not follow the binary exponential back-off mechanism; they adjust the contention window (CW) and back-off value by considering the data priority (ρ) and penalization statistic.

The value of back-off counter is decremented whenever the channel is sensed idle. Now, if a transmission from another SU is detected ($H_i \equiv 2$), the counter will be paused and will be re-activated when channel is sensed idle for a period equal to distributed inter-frame space (DIFS). An SU starts to transmit when the back-off counter reaches the value of zero. Collision with the SUs of other CRNs can occur very often, as they take transmission decision in distributed fashion and cannot overhear the RTS/CTS transmission from the SUs of other CRNs. On collision or bit error, an SU repeats the competition process by adjusting the size of CW and selecting a new back-off counter until the endurance threshold reached. If a PU emerges on the selected channel, all the SUs contending over that channel adjust the CW size, select a new random back-off counter, and start contention after the end of PU transmission. That is, after a PU transmission, the contention process will restart for most of the SUs, but some SUs may decide to look for other spectrum opportunities if their QoS sensitivity prohibits further waiting on the current channel. The channel sharing mechanism is summarized in protocol 1.

The size of CW_ρ depends on the priority ρ of current data flow and the number of times the SU's transmission has been deferred by a PU (σ_p), collided or deferred by another SU (σ_s). Initially, an SU selects CW_ρ for the current data packet only considering the traffic class value. If the transmission is collided with another SU, the CW should be increased, as the channel appears to be more crowded than anticipated before. But a PU arrival does not mean that the channel is too much overloaded. As a result, the SU should try to use lower back-off value for accessing the channel sooner than other competing SUs. In other words, this approach makes the SU greedy to opportunistically use the available licensed channels. The value of CW_ρ is determined as follows:

$$\mathrm{CW}_\rho = \begin{cases} \left\lceil \frac{2^{|\Omega+1|}}{\rho} \right\rceil & \sigma_p = 0, \sigma_s = 0, H_i \neq 1, \\ \left\lceil \frac{2^{|\Omega+1|}}{\rho + \sigma_p} \right\rceil & \sigma_p \geq 1, H_i = 1, \\ \left\lceil \frac{2^{|\Omega+1|}}{\rho} \times \sigma_s \right\rceil & \sigma_s \geq 1, H_i = 2, \end{cases} \tag{18}$$

where Ω is the set of traffic classes considered and ρ is the traffic class value of current data packet. The back-off counter b_ρ is selected by taking a random number from the range $[0, \mathrm{CW}_\rho]$.

Protocol 1: *Weighted Fair Medium Access Control*

```
Step 1 Select channel $c \in \mathcal{M}^o$ using Algorithm (1)
Step 2 Determine traffic class $\rho$ of current data packet using
    Table (1)
Step 3 Calculate $CW_\rho$ using Eq. (18) and randomly select $b_\rho$
    from $[0, CW_\rho]$
Step 4 Check the status of channel $c$, $H_c$
Step 5 If $H_c \equiv 2$, go to Step (4)
    If $H_c \equiv 1$, freeze until PU transmission ends, go to Step (3)
    If $H_c \equiv 0$, decrement $b_\rho$
Step 6 If $b_\rho \equiv 0$, Start Data Transmission
    On Successful Transmission, Update $u_c$ using Eq. (15). If
    the SU has more data packet to send, go to Step (2). If all
    packets are sent, return to Algorithm (1).
    On Collision with SU, Update $u_c$ using Eq. (15) &
    increment $\sigma_s$. If endurance threshold reached, look for
    other spectrum opportunities, as discussed in Section 4.4.
    Otherwise, go to Step (3).
    On PU reappearance, Update $u_c$ using Eq. (15) and
    increment $\sigma_p$. If endurance threshold reached, look for
    other spectrum opportunities, as discussed in Section 4.4.
    Otherwise, go to Step (3).
Step 7 go to Step (4).
```

4.4 Channel switching mechanism

The SUs schedule their spectrum usage in order to maximize spectrum utilization or throughput. To avoid starvation and maximize throughput, the SUs should have the ability to rationalize between channel access and channel switch in a smart way. Any SU selects a channel $c \in \mathcal{M}^o$ with the assumption that the channel has the most probability of being available over the required transmission time $\mathcal{T}_c^t$ of the current data packet. So the expected throughput of the SU on the time of channel selection can be defined using following equation:

$$\theta_c = \epsilon_c \times \mathcal{T}_c^t \times \beta_c. \tag{19}$$

With the arrivals of PUs and other SUs, the packet transmission delay increases, hence decreases the throughput. The WF-MAC SUs start to look for other spectrum opportunities, when the expected throughput decreases below a certain threshold (θ_{th}) on the current channel. The throughput threshold value can be defined in proportional to the traffic priority of the current transmission. The higher the criticality, the higher the threshold value, which is defined as follows:

$$\theta_{\text{th}} = \frac{\theta_c}{|\Omega + 1|} \times \rho \times \kappa, \tag{20}$$

here, κ is a constant value of which is application dependent.

Now, if the selected channel is unable to preserve the threshold, an SU will try to isolate another spectrum opportunity. The SU will request for CIV from its BS, and upon receiving of CIV, it will select new channel for transmission using Eq. 3. But before the channel selection, the SU has to define a new channel set $\mathcal{M}^o$, contemplating channel switching cost, to achieve a more realistic precision. For that, the SU will calculate the expected throughput on each available channel $i \in \{\mathcal{M} - c\}$ as follows:

$$\theta_i = \epsilon_i \times \mathcal{T}_i^t \times \beta_i - \mathcal{T}_{\text{switch}} \times \beta_i \tag{21}$$

where, $\mathcal{T}_{\text{switch}}$ is the time needed for channel switching. The channel set the SU will consider for channel selection should contain only those channels, which have higher expected throughput than the current one and also not accessed by PU. The channel set $\mathcal{M}^o$ can be defined like this:

$$\mathcal{M}^o = \{i \in \mathcal{M} \mid \quad H_i \neq 1, \quad \theta_i \geq \theta_c\}. \tag{22}$$

The SU selects a channel for data transmission from the channel set $\mathcal{M}^o$ if the $\mathcal{M}^o$ is not empty; otherwise, the SU keeps contend over the previously selected channel.

4.5 Discussion

Setting an appropriate value for the constants ϕ_g, ϕ_p, and ϕ_s for each SUs in the network environment is an important performance turning issue, especially for achieving a stable spectrum sharing among overlapping CRNs. The higher the values are, the more utility gain or utility loss will be experienced by the SUs. As a result, its perception towards a specific channel will alter frequently. On the other hand, if we choose very low values, the utility perception changes very slowly and put little contribution towards channel selection process. In order to trade-off the above facts, we have to define optimal values of the constants adaptively for the users of each network. Such an adaptive measurement process requires a system modeling based on the continuous learning of the environment feedback. If we could be able to develop such a mathematical model, it would be much helpful for further increasing the performances of WF-MAC, which we have kept as a future work. For performance evaluation of WF-MAC in this work, we have set the parameters $\phi_g = \phi_p = 3$ and $\phi_s = 10$ found from numerous simulation experiments.

5 Performance evaluation

In this section, we implement WF-MAC, random WF-MAC (with random selection of channels), non-QoS WF-MAC (that avoids QoS awareness), and a state-of-the-art protocol FMAC [12] in a discrete-event network simulator, ns-3 [30], and present the comparative performance results.

5.1 Simulation environment

We have deployed seven CRNs in an area of 1600 × 1600 m^2. Each CRN has varied number of SUs and PUs with mobility following RandomWalk2dMobilityModel, and each BS follows ConstantPositionMobilityModel of ns-3. Each SU opportunistically uses the licensed channels only; no unlicensed channel is considered. Each SU senses all the channels using three state sensing model [14] and reports results to its BS. The traffic class of the generated packets from SUs is randomly chosen from the list given in Table 1. The interval between two traffic generation phases of any SU is randomly chosen from the range of 10 $\sim$ 20 s and the number of data packets in each generation phase from 5 $\sim$ 25. We have considered the IEEE 802.11af [29] standard; other OFDM-modulated standards are adaptable too, like IEEE 802.16 (WiMAX), IEEE 802.15 (Bluetooth), and IEEE 802.22 (TV white-space) [31]. The simulation is conducted for 1000 s, and for each of the graph data points, we have taken the average of the results from 20 simulation runs with different random seeds. Simulation parameters are listed in Table 3.

Table 3 Simulation parameters

Parameter	Value
Deployment	
Number of Channels	10(data)+1(*CCC*)
Number of CRNs	7
Number of PUs	10
Number of SUs per CRN	15
Physical Layer Model	YansWifiPhy
MAC Layer Model	ApWifiMac
Transmission Range	250 m
Channel Data Rate	7 Mbps
Channel Bit Error Rate	10^{-3}
Packet Size	1200 bytes
Simulation Time	1000 s
Control	
Propagation Delay, δ	0.83 μs
Size of RTS	20 bytes
Size of CTS, ACK	14 bytes
SIFS	10 μs
DIFS	50 μs
WF-MAC	
Timeslot Duration, t	60 μs
$\mathcal{T}_{switch}$	120 μs
RCIV, CIV	20, 260 bytes
$\epsilon^{s}_{th}, \epsilon^{p}_{th}$	0.4
ϕ_g, ϕ_p	3
ϕ_s	10
γ	0.7

5.2 Performance metrics

We have used following metrics for the comparative performance analysis.

- *Throughput for SUs*, $\mathcal{P}^{th}$: Throughput is one of the major performance metrics used to evaluate the performance of any MAC protocols. It indicates the number of data bits that are delivered per second to the receivers. For our work, we are only concerned about the throughput performance of SUs, calculating the number of data bits they successfully transmit per second to their BSs.
- *Average medium access delay*, $\mathcal{P}^{md}$: It is defined as the average time taken for a secondary user to get access of the medium before transmitting a packet, that is the time before SU could transmit the first bit of a packet. It is preferable to retain this access delay as minimum as possible.
- *Protocol operation overhead*, $\mathcal{P}^{oh}$: It can be measured as the amount of control bytes exchanged per successful data byte transmission, i.e., we are measuring the portion of cost a MAC protocol pays for each byte of data transmission. It is always expected to lower this overhead for improving the performance of a protocol.
- *Integrated performance improvement*: The introduction of CIV and RCIV packets in the proposed WF-MAC forces to experience more protocol operation overhead compared to others. However, the integrated performance of WF-MAC is much better. We measure the integrated performance of the studied protocols as follows, $\mathcal{P}^{\mathrm{ip}} = \frac{\mathcal{P}^{\mathrm{th(bps)}}}{\mathcal{P}^{\mathrm{md}}(s) \times \mathcal{P}^{\mathrm{oh}}}$, which quantifies the cost compensation for the increased throughput and reduced medium access delay performances. We then calculate the performance improvement of WF-MAC by $\frac{\mathcal{P}^{\mathrm{ip}}_{\mathrm{WF-MAC}}}{\mathcal{P}^{\mathrm{ip}}_{X}}$, where, $X \in \{$FMAC, nQ WF-MAC, random WF-MAC$\}$.
- *Channel selection percentage*: We categorize the set of channels based on their availability into three quality levels, high, mid, and low. We measure the average percentage of selection from each category of channel over the total simulation period. A higher quality channel should have higher percentage of selection compared to a lower one.
- *Medium access delay of traffic classes*: It indicates the QoS awareness in medium access in our protocol. We calculate the average medium access delay of each type of traffic class over the active periods of the SUs. The average medium access delay experienced by a higher priority packet should be less than a lower priority packet.

5.3 Simulation results

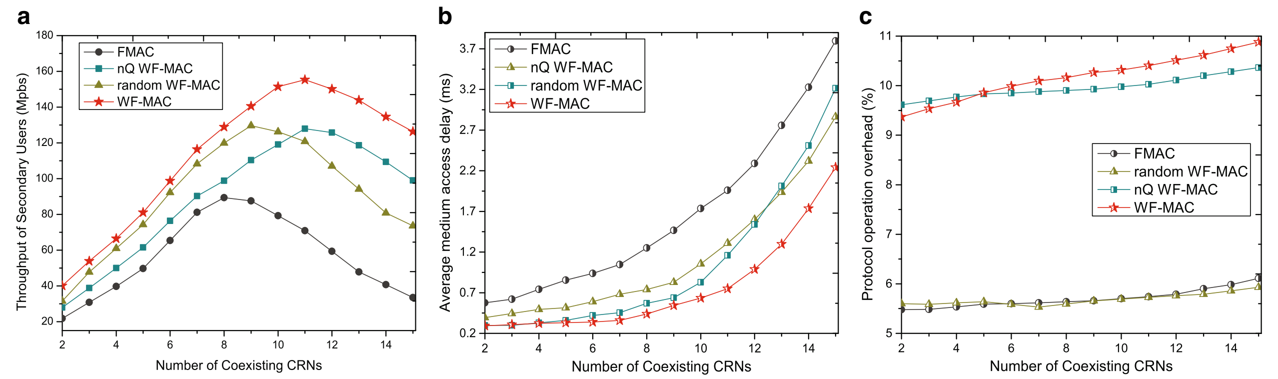
In this section, we present the comparative performance evaluation results of the studied protocols for varying number of PUs, SUs, and channels available in the network.

5.3.1 Impact of number of CRNs

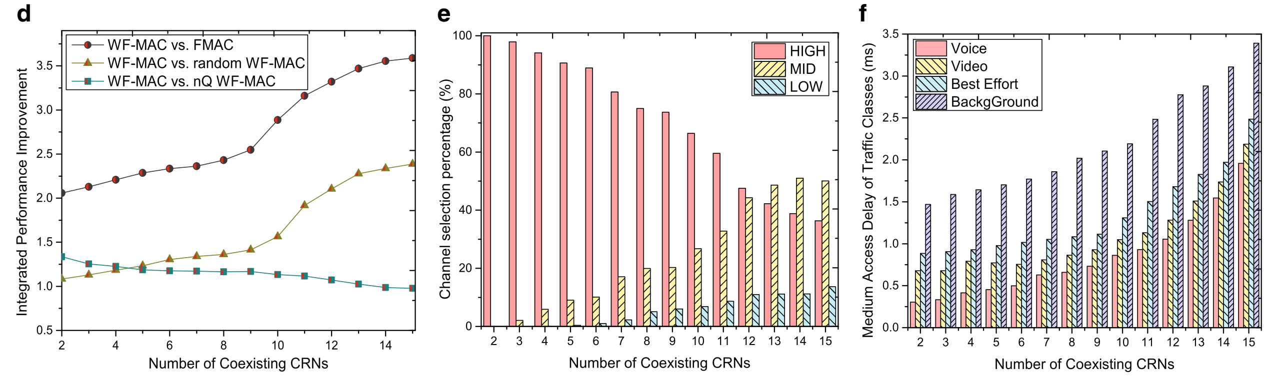
In this section, we discuss the impacts of different numbers of coexisting CRNs on the performance of the studied protocols.

The graphs of Fig. 4 indicate that the performances of the protocols follow specific trends with the increasing number of CRNs, as theoretically expected. However, the rate of performance degradation or elevation varies greatly between the protocols. From Fig. 4a, we can see that, initially, very low number of CRNs (< 4) in the environment results in reduced traffic injection in the network from a few numbers of active SUs and thus the network achieves lower throughput. Even in this favorable environment, our protocol WF-MAC, outperforms the other three. With the increasing CRNs, the input traffic is increased and we observe performance improvement of WF-MAC as high as 48.98, 18.73, and 17.64 % over the FMAC, random WF-MAC, and nQ WF-MAC protocols, respectively. Our in-depth look in the simulation trace file reveals that when the number of CRN is increasing, FMAC fails to maintain its throughput growth, collision, and starvation and scales it down after a certain point. However, the proposed WF-MAC has a significant improvement in throughput for its QoS-aware medium access and also able to sustain the growth, as its two-dimensional learning mechanism provide an accurate insight of the current environment. The perception learning with the help of channel availability prediction enables WF-MAC to counter balance the available resources among the coexisting CRNs minimizing interference. Also, the historical prediction-aware channel selection and channel switching decision in WF-MAC keeps the SUs of different CRNs away from starvation. But after a certain point when the overlapping CRN increases greatly (> 11), the system becomes overcrowded, SUs start to experience longer delay and repercussion of the distribution or selection process of available spectrum wanes out slowly, and coexisting CRNs start to cause entanglement to each other.

For the same arguments as above, our protocol experiences low medium access delay with respect to other implementations, as shown in Fig. 4b. Initially, the random WF-MAC experiences less delay than the nQ WF-MAC, as the consequence of its QoS-aware medium



Throughput for SUs Avg. medium access delay Protocol operation overhead



Integrated Performance Channel selection percentage $\mathscr{P}^{md}$ of different traffic classes

Fig. 4 Impacts of increasing number of Coexisting CRNs access mechanism, but as the system load increases, its indiscriminate channel usage mechanism prohibits it from maintaining the trend and medium access delay increases greatly. On the other hand, nQ WF-MAC's groomed resource usage mechanism insulates it from higher increasing rate of medium access delay.

Now, all the improvements in throughput and medium access delay do not materialize without any outlay. The two-dimensional learning and channel selection mechanism in Wf-MAC running in each SU needs the insight of entire environment, which is only available to their BSs. For that reason, each SU exchanges two additional control packets RCIV/CIV, along with the others, RTS/CTS and ACK. These additional load of RCIV (20 bytes) and CIV (260 bytes) notably increase the protocol operation overhead of WF-MAC. As shown in Fig. 4c, the operation overhead of our protocol is much higher than FMAC and random WF-MAC, approximately 42 %. And, with the increasing number of CRNs, the overhead rising trend of FMAC and WF-MAC is more or less similar. At the maximum number of CRNs ($\equiv 15$), the overhead of WF-MAC is 43.8 % higher than that of FMAC, slight increase due to the channel switching mechanism.

The rationale of enduring that much higher overhead is studied in integrated performance improvement metric as shown in Fig. 4d. We see that the overall performance of WF-MAC is double than that of FMAC initially, as the QoS-aware medium access enables it to gain higher throughput and lower delay. And as the number of CRN increases, the unplanned spectrum distribution and QoS avoidance policy of FMAC decreases its integrated performance greatly, as much as 72.13 % than that of WF-MAC. Therefore, we can undoubtedly say that the additional overhead of WF-MAC is compensated with enforced performance prosperity. The random WF-MAC follows similar trend with FMAC with much lower values. The nQ WF-MAC initially experiences low integrated performance than WF-MAC, as in sparse environment QoS awareness is the only game changer, available resource is well-matched with system crowd. On the contrary, as the number of CRN increases, the judicious channel selection will come into effect and both WF-MAC and nQ WF-MAC will provide almost similar performance.

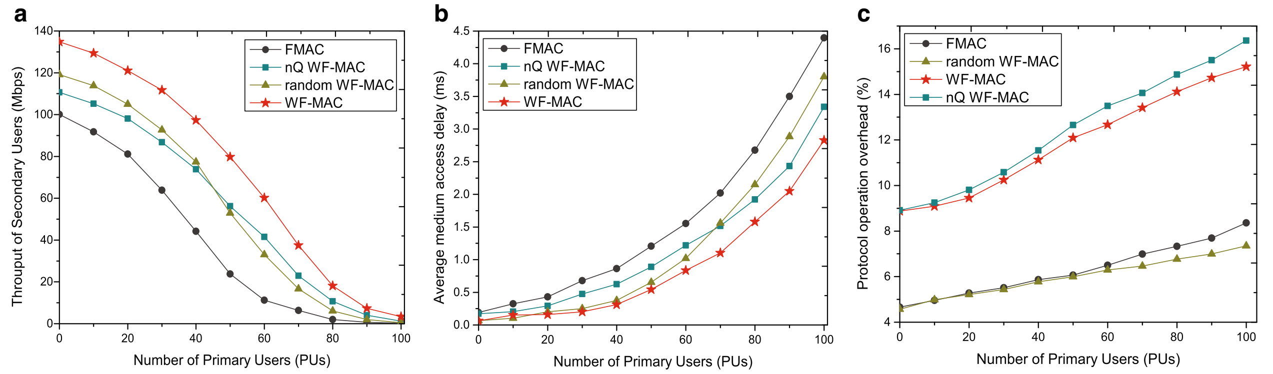
The channel selection mechanism of WF-MAC promises the selection of higher quality channels (channels with higher probability of being free) and a well-balanced distribution of traffic load. In our experiment, we have categorized the channels in three classes, high ($\epsilon_i \geq 0.7$), medium ($\epsilon_i \geq 0.4$), and low ($\epsilon_i < 0.4$), considering the channel availability. When the number of CRNs is low in the environment, most of the channels have low traffic arrival probability and WF-MAC intelligently distributes the load among them and opts for the best channels. Now, with the increasing number of CRNs, the quality of channels decreases, leading to comparatively higher number of selections from medium- and low-quality channels, as shown in Fig. 4e. Furthermore, we have analyzed the average medium access delay experienced by different traffic classes in our proposed WF-MAC protocol. The graph of Fig. 4f depicts that, as expected theoretically, the most critical packets (voice traffic) experience the lowest delay and the background application traffics are exposed to the highest delay.

5.3.2 Impacts of increasing number of PUs

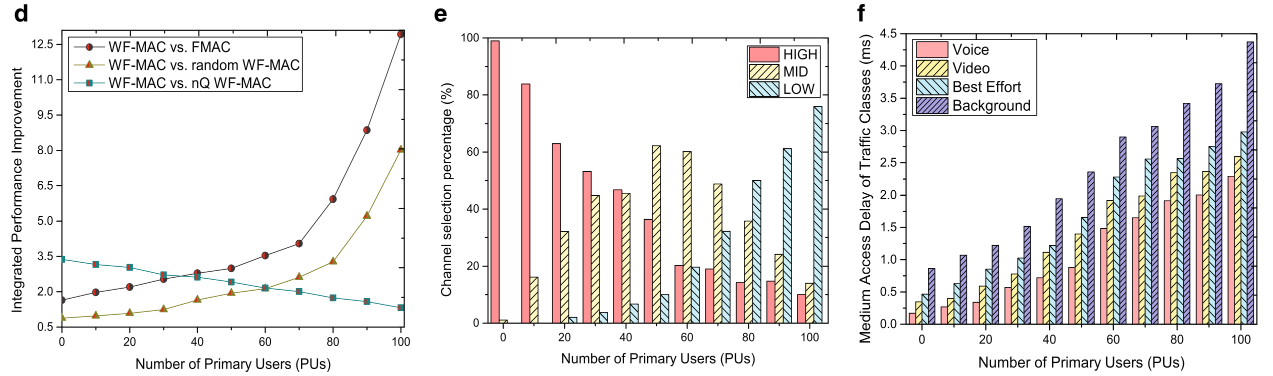
In this section, we evaluate the performances of the implemented protocols for various numbers of primary users in the environment.

In Fig. 5a, we can visualize the relationship between the throughput of SUs and the number of PUs in the environment. When the number of PU is zero, then, all the channels in the environment are available for opportunistic access by SUs. However, random spectrum usage policy of FMAC makes it to earn much lower throughput (26.84 % less than WF-MAC) even in the most favored environment. With the increasing number of PUs in the network, the PU arrival rate on a channel is also increased, resulting in reduced SU throughput experience for all the studied protocols. Although the WF-MAC experiences sharp throughput degradation as others, but the knowledgeable channel selection and smart back-off value adjustments allow it to sustain a minimal throughput in the most bazaar environment. Even at the extreme stage (when number of PUs is 100), WF-MAC obtains SU throughput that outstands nQ WF-MAC, random WF-MAC, and FMAC by 41.65, 68.65, and 88.56 %, respectively. The comparative study of the medium access delay of implemented protocols is shown in Fig. 5b; comparing with Fig. 4b, it is depicted that the increasing number of PUs have much extreme effect on access delay than the increasing number of CRNs. The gap between the performance of WF-MAC and FMAC increases from 33 to 64 % with the number of PUs ranging from PUs 0 to 100, respectively.

The impact of increasing PUs on protocol operation overhead as shown in Fig. 5c is also worse than the effect of increasing CRNs of Fig. 4c. When the number of PUs is less than 30, the WF-MAC and nQ WF-MAC experiences almost double (48.49 %) overheads than FMAC and random WF-MAC. Afterwards, the overhead of WF-MAC increases linearly as the SUs experience vacating channels more often forcing them to look for other spectrum opportunity, by exchanging more RCIV/CIV packets. Overhead of FMAC also increases rapidly, but as it does not possess any special packet, the increase is much less sharper. From Fig. 5d, we can see that the overhead experience does not go into vain, as WF-MAC has huge performance improvements over FMAC and random WF-MAC.



Throughput for SUs
Avg. medium access delay
Protocol operation overhead



Integrated Performance
Channel selection percentage
$\mathscr{P}^{md}$ of different traffic classes

Fig. 5 Impacts of increasing number of PUs

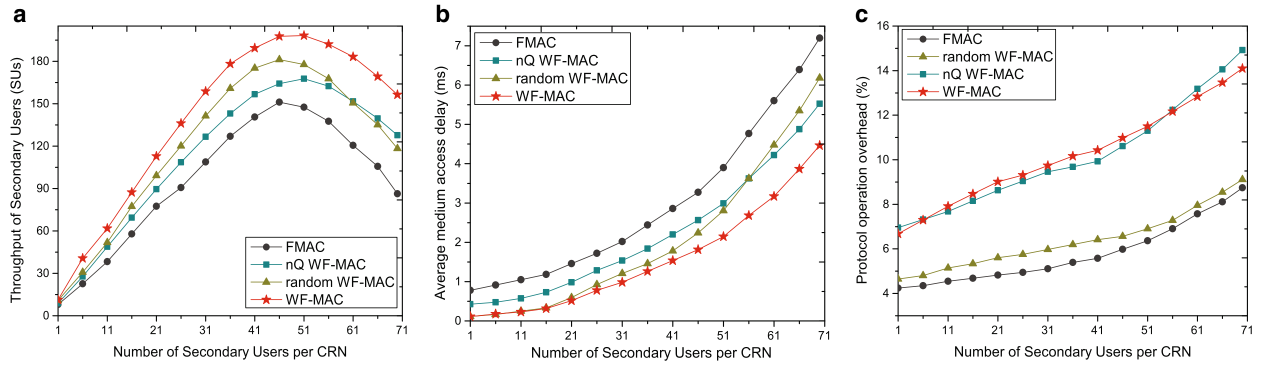
Also, nQ WF-MAC almost reaches the performance of WF-MAC as the number of PU increases, as expected.

From Fig. 5e, we can observe the channel selection rationality of WF-MAC. As we have already discussed about the categorization of channels, the selection pattern changes significantly with the increasing number of PUs. Initially, with lower number of PUs in the system, the entire channel set will have higher rate of being free and WF-MAC is capable to intelligently distribute the traffic load among those channels using the channel availability prediction and perception learning mechanisms. But, as the number of PUs increases, the channel quality degrades resulting in increasing percentage of selection from mid and low channel groups. When the number of PU increases more than 70, the system becomes too crowded with PUs and the available channels become very rare, forcing WF-MAC to select lower quality channels. We can observe the QoS-aware weighted fair medium access mechanism of WF-MAC in Fig. 5f, which follows the expected trend in terms of medium access delay.

Comparing the graphs of Fig. 4 with Fig. 5, we observe that the higher number of PUs have worse effect on the system performance than increasing number of coexisting CRNs. The perception learning-based channel selection mechanism of WF-MAC makes it more tolerant to higher coexistence. Also with availability prediction, it can tolerate moderate level of PU activities but when the crowd of PUs continues to expand rapidly, the available resource decreases and leaves no alternatives of sustaining performance growth.

5.3.3 Impacts of increasing number of SUs

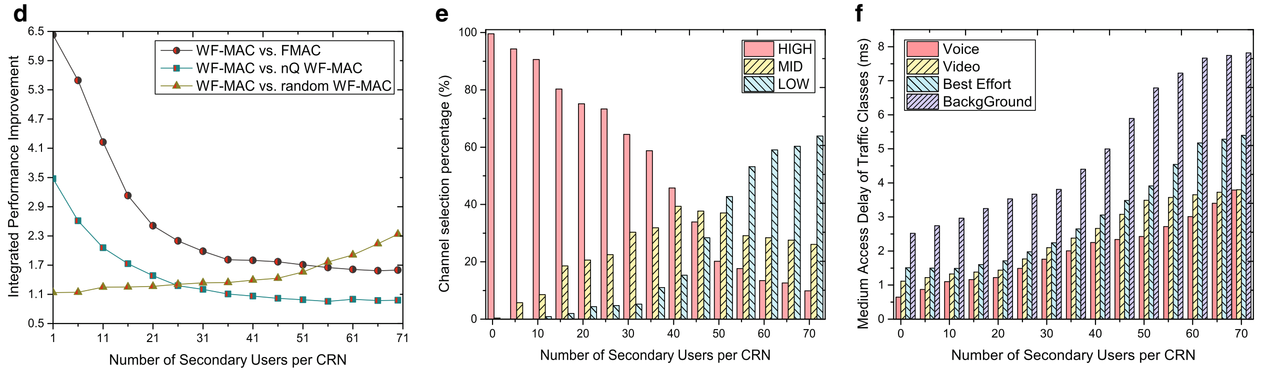
We have also carried out performance evaluations for varying number of secondary users per coexisting CRN. The number of SUs clearly has a great impact on the throughput of SUs. In Fig. 6a, we observe that all the studied protocols gain rapid throughput escalation up to approximately 46 SUs per CRN, since the system resources can tolerate additional traffic from SUs. However, FMAC and other versions of WF-MAC suffer from reduced throughput performance due to poor policy of channel selection and usage. The channel distribution, selection, and access mechanisms of WF-MAC help it to gain higher throughput than FMAC, random WF-MAC, and nQ WF-MAC approximately 34, 10, and 16 %, respectively. We also observe that, the further increase of number of SUs causes the throughput to decrease gradually, and it happens due to increased amount of collisions and starvations. As expected, the performance drop of FMAC and random WF-MAC is heftier than the other two. The



Throughput for SUs

Avg. medium access delay

Protocol operation overhead



Integrated Performance

Channel selection percentage

$\mathscr{P}^{md}$ of different traffic classes

Fig. 6 Impacts of increasing number of SUs

medium access delay of the studied protocols is shown in Fig. 6b, which initially exposes very similar performance like Figs. 4b and 5b. However, with the increase of SUs (> 44), the protocols start to experience worse delays because of the increased traffic, repeated collisions, and channel switching.

Figure 6c shows that, the protocol operation overheads of WF-MAC and nQ WF-MAC are much higher than those of FMAC and random WF-MAC. We can see the integrated performance improvement of WF-MAC over the other three, as shown in Fig. 6d, which proves the compensation of WF-MAC in terms of throughput and medium access delay over additional protocol operation overhead. The weighted fair channel selection policy of WF-MAC is visualized in Fig. 6e; we can observe that, initially, it tries to distribute the loads among the higher quality channels, but as the channel quality decreases, it has to select different types of channels to well distribute the increasing load. At the extreme cases, the whole system becomes overcrowded, so overall channel quality decreases very rapidly as well as the selection outcomes. Figure 6f shows the weighted fair channel access mechanism which follows the QoS-based categorization of Table 1 with respect to medium access delay.

The graphs of Figs. 4e, 5e, and 6e depict that the increasing number of PUs and SUs have more impact on good quality channel usage compared to that for the increasing CRNs. Note that each CRN adds a set of new users and channels in the system environment. However, the overlapping causes a little degradation in the quality of the channels. On the other hand, increasing the number of PUs and/or SUs causes rapid exhaustion of the available spectrum resources and the overall channel quality degrades significantly, resulting in the upsurge of low-quality channel usage.

6 Conclusions

In this paper, a WF-MAC has been developed for QoS-aware traffic delivery in coexisting cognitive radio networks. In WF-MAC, decision on the medium access by the secondary users is fully distributed and driven by traffic class priorities and opportunistic spectrum availabilities. The two-dimensional learning mechanism consisting of utility perception and channel availability prediction helps the proposed WF-MAC protocol to achieve as high as 88.56 and 64 % improvements in throughput and medium access delay, respectively, compared to FMAC for increasing arrival rates of primary users.

Competing interests

The authors declare that they have no competing interests.

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Author details

[1]Green Networking Research Group, Department of Computer Science and Engineering, University of Dhaka, Dhaka-1000, Bangladesh. [2]College of Computer and Information Sciences, King Saud University, Riyadh, Kingdom of Saudi Arabia.

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References

1. Y Sun, B Zhou, Z Wu, Q Ni, R Zhu, Multi-channel MAC protocol in cognitive radio networks. J. Netw. **8**(11), 2478–2490 (2013)
2. Facilitating Opportunities for flexible, efficient, and reliable spectrum use employing cognitive radio technologies. Washington, D.C. 20554; (2003). https://www.fcc.gov/document/facilitating-opportunities-flexibleefficient-and-reliable-spectrum-use-employing-cognitive
3. IF Akyildiz, WY Lee, MC Vuran, S Mohanty, A survey on spectrum management in cognitive radio networks. IEEE Commun. Mag. **46**(4), 40–48 (2008)
4. A De Domenico, EC Strinati, M Di Benedetto, A survey on MAC strategies for cognitive radio networks. IEEE Commun. Surv. Tutor. **14**(1), 21–44 (2012)
5. V Gardellin, SK Das, L Lenzini, Self-coexistence in cellular cognitive radio networks based on the IEEE 802.22 standard. IEEE Wirel. Commun. **20**(2), 52–59 (2013)
6. C Ghosh, S Roy, D Cavalcanti, Coexistence challenges for heterogeneous cognitive wireless networks in TV white spaces. IEEE Wirel. Commun. **18**(4), 22–31 (2011)
7. R Hossain, R Rijul, MA Razzaque, AM Jehad Sarkar, Prioritized medium access control in cognitive radio ad hoc networks: protocol and analysis. Wirel. Pers. Commun. **79**(3), 2383–2408 (2014)
8. GP Joshi, SY Nam, SW Kim, Decentralized predictive MAC protocol for ad hoc cognitive radio networks. Wirel. Pers. Commun. **74**(2), 803–821 (2014). Available from: http://dx.doi.org/10.1007/s11277-013-1322-6
9. Q Chen, YC Liang, M Motani, WC Wong, A two-level MAC protocol strategy for opportunistic spectrum access in cognitive radio networks. IEEE Trans. Veh. Technol. **60**(5), 2164–2180 (2011)
10. S Sengupta, R Chandramouli, S Brahma, M Chatterjee, in *Global Telecommunications Conference, 2008. IEEE GLOBECOM 2008*. A game theoretic framework for distributed self-coexistence among IEEE 802.22 networks (IEEE, New Orleans, LO, 2008), pp. 1–6
11. S Buck, M Beetz, T Schmitt, in *Intelligent Robots and Systems, 2002. IEEE/RSJ International Conference on*. Approximating the value function for continuous space reinforcement learning in robot control, vol. 1 (IEEE, 2002), pp. 1062–1067. doi:10.1109/IRDS.2002.1041532
12. Y Zhao, M Song, C Xin, in *INFOCOM, 2013 Proceedings IEEE*. FMAC: a fair MAC protocol for coexisting cognitive radio networks (IEEE, Turin, Italy, 2013), pp. 1474–1482. doi:10.1109/INFCOM.2013.6566942
13. Y Zhao, M Song, C Xin, in *Wireless Algorithms, Systems, and Applications - 8th International Conference, WASA 2013, Zhangjiajie, China, August 7-10, 2013. Proceedings*. FMAC for coexisting ad hoc cognitive radio networks (Springer Berlin Heidelberg, Berlin Heidelberg, 2013), pp. 391–401
14. Y Zhao, M Song, C Xin, M Wadhwa, in *INFOCOM, 2012 Proceedings IEEE*. Spectrum sensing based on three-state model to accomplish all-level fairness for co-existing multiple cognitive radio networks (IEEE, FL, USA, 2012), pp. 1782–1790. doi:10.1109/INFCOM.2012.6195551
15. C Stevenson, G Chouinard, Z Lei, W Hu, SJ Shellhammer, W Caldwell, IEEE 802.22: The first cognitive radio wireless regional area network standard. IEEE Commun. Mag. **47**(1), 130–138 (2009)
16. SC Jha, U Phuyal, MM Rashid, VK Bhargava, Design of OMC-MAC: an opportunistic multi-channel MAC with QoS provisioning for distributed cognitive radio networks. IEEE Trans. Wirel. Commun. **10**(10), 3414–3425 (2011)
17. MA Kalil, A Puschmann, A Mitschele-Thiel, in *Vehicular Technology Conference (VTC Fall)*. SWITCH: a multichannel MAC protocol for cognitive radio ad hoc networks (IEEE, Quebec City, QC, 2012), pp. 1–5. doi:10.1109/VTCFall.2012.6399238
18. X Li, SA (Reza) Zekavat, in *Wireless Communications and Networking Conference, WCNC*. Traffic pattern prediction and performance investigation for cognitive radio systems (IEEE, Las Vegas, NV, USA, 2008), pp. 894–899. doi:10.1109/WCNC.2008.163
19. B Canberk, IF Akyildiz, S Oktug, in *Personal Indoor and Mobile Radio Communications (PIMRC), 2010 IEEE 21st International Symposium on*. A QoS-aware framework for available spectrum characterization and decision in cognitive radio networks (IEEE, Instanbul, Turkey, 2010), pp. 1533–1538. doi:10.1109/PIMRC.2010.5671959
20. K Bian, JM Park, B Gao, *Cognitive radio networks: medium access control for coexistence of wireless systems*. (Springer International Publishing, New Delhi, India, 2014). doi:10.1007/978-3-319-07329-3
21. P Camarda, C Cormio, C Passiatore, in *Proceedings of the 5th IEEE International Conference on Wireless Pervasive Computing. ISWPC'10*. An exclusive self-coexistence (ESC) resource sharing algorithm for cognitive 802.22 networks (IEEE, Modena, Italy, 2010), pp. 128–133. doi:10.1109/ISWPC.2010.5483784
22. S Sengupta, R Chandramouli, S Brahma, M Chatterjee, in *Global Telecommunications Conference, 2008. IEEE GLOBECOM*. A game theoretic framework for distributed self-coexistence among IEEE 802.22 networks (IEEE, New Orleans, LO, USA, 2008), pp. 1–6. doi:10.1109/GLOCOM.2008.ECP.598
23. MNS Miazi, M Tabassum, MA Razzaque, M Abdullah-Al-Wadud, An energy-efficient common control channel selection mechanism for cognitive radio ad hoc networks. Ann. Telecommun. **70**(1), 11–28 (2014)
24. V Mishra, LC Tong, C Syin, in *Networks (ICON), 2012 18th IEEE International Conference on*. QoS based spectrum decision framework for cognitive radio networks, (2012), pp. 18–23
25. WF Alliance, Wi-Fi certified for WMM—support for multimedia applications with quality of service in Wi-Fi networks. Wi-Fi Alliance (2004). https://www.broadcom.com/docs/features/WMM_QoS_whitepaper.pdf
26. P Chatzimisios, AC Boucouvalas, V Vitsas, in *Global Telecommunications Conference Workshops, 2004. GlobeCom Workshops*. Optimisation of RTS/CTS handshake in IEEE 802.11 wireless LANs for maximum performance (IEEE, 2004), pp. 270–275. doi:10.1109/GLOCOMW.2004.1417586
27. RA Yaffee, M McGee, *Introduction to time series analysis and forecasting: with applications of SAS and SPSS*, 1st ed. (Academic Press, Inc., Orlando, 2000)
28. KLA Yau, P Komisarczuk, PD Teal, in *Communications Workshops (ICC), 2010 IEEE International Conference on*. Applications of reinforcement learning to cognitive radio networks (IEEE, Capetown, South Africa, 2010), pp. 1–6. doi:10.1109/ICCW.2010.5503970
29. IEEE 802.11. standards.ieee.org/about/get/802/802.11.html. Accessed December 2014
30. Network Simulator 3. www.nsnam.org. Accessed January 2015
31. H Arslan, *Cognitive Radio, Software defined radio and adaptive wireless systems*, 2nd ed. (Springer, Dordrecht, The Netherlands, 2007)