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A Channel Aggregation Algorithm for Cognitive Radio under Collision and Misdetection Constraints

Emhamed A. Adaba[1]
Authority of communications and informatics-Libya
emhamed9846@gmail.com

Mohamed A. Alkelsh[2]
Electric & Electronic Communication Eng. Dept., Faculty of Eng. Gharyan University-Libya
mohamed.alkelsh@gu.udu.ly

Fayez W. Zaki[3]
Electronics & Communication Eng. Dept., Faculty of Eng. Mansoura University-Egypt
fwzaki2017@gmail.com

Ehab H. Abdelhay[4]
Electronics & Communication Eng. Dept., Faculty of Eng. Mansoura University-Egypt
ehab_eng@hotmail.com

***Abstract* — Cognitive radio (CR) is a form of wireless communication in which a transceiver can intelligently detect which communication channels are in use. Upon the result of the detection, the system instantly moves into vacant channels while avoiding occupied ones. To improve the capacity of CR systems, the unused sub-channels by primary user (PU) could be aggregated. However, when secondary user (SU) system aggregates more channels, more collisions may occur. This collision occurs due to the PU back to reuse its channels during SU transmission on them. Moreover, there are other reasons for collisions as misdetection which happens when wrongly detected absence of PU may occur as well.**

In this paper a Proposed Channel Aggregation Algorithm is introduced in which the CR data rate is maximized by aggregating multiple channels for the SU while satisfying the minimum collision requirements. Moreover, channel capacity is maximized under collision constraints. Matlab simulation is conducted to implement the proposed algorithm and the rustles showed that, very low collision probability was observed as compared to previous work. The capacity of CR was also improved as well.

***Keywords*: cognitive radio, primary user, secondary user, aggregation, collision, misdetection**

I. Introduction

Cognitive radio (CR) is a technology that enables supporting dynamic spectrum access. To do this CR operates over a spectrum pool which could cover from tens of MHz to several GHz creating a virtual unlicensed band. Hence it is widely accepted to overcome the spectrum scarcity problem existed in many countries. Therefore, CR is regarded as one of the most promising technologies for future wireless communication. Making wireless networks truly cognitive is by no means a simple task, and it requires the collaboration among different fields of research including communication theory, networking engineering, signal processing, game theory, software and hardware design engineering [15], antenna and R.F circuit design [1]. Due to the fact that; it is promising to introduce the solution to spectrum scarcity [2]. CR had become one of the main research topics which many authors have focused on it. This may be achieved by detecting the idle channels in the licensed spectrum then use it without interference with primary user (PU) using opportunistic access [3]. By opportunistic access in CR system, primary users (PUs) have the higher priority than secondary users (SUs) for getting to the channels. When PU requires its channel, SU must leave the channel and look for another free channel. To improve SU's throughput it is required to aggregate as many channels (spectrum fragments) as possible from idle channels to maintain on its quality of service (QoS) [4]. The utilization of an aggregated channel from various channels could bring about collisions. Hence, when SU system aggregate multiple channels, carefully should be consider the collision probability [5].

Recently, many researchers work on channel aggregation so far consider proficient methods to enhance the spectrum effectiveness for CR. In [6, 7] authors analyzed the aggregation just from dynamic strategy side to increase throughput of secondary user. In [8, 9] authors considered only one channel used for SU. In [10] the authors studied hardware scheme to improve network throughput. In [11] authors introduced a channel aggregation method where they considered one constraint that is when PU comes back during SU transmitting whereas they ignored misdetection constraint. All collision probabilities such as misdetection, and a return of primary user refer to the use of channel duration SU transmission, which in other cases SU may come to use the same channel that are introduced in [12]. Besides they didn't consider channel aggregation to improve SU data rate. In [13] authors optimized the modulation scheme, transmit power, and packet length of SU to avoid interference with hidden PU, however, they didn't consider collision probability and aggregation scenario.

In the present work, a channel aggregation algorithm for Cognitive Radio considered. Moreover, channel capacity under crash requirements is to be maximized. Matlab programming was considered to simulate this study.

II. System Model

The primary users in this model are non-cognitive users which operating in same unlicensed band as ZigBee, WI.FI, Bluetooth, and unlicensed LTE. And multiple cognitive radio network sensors (CRNS) are considered as shown in Fig.1.

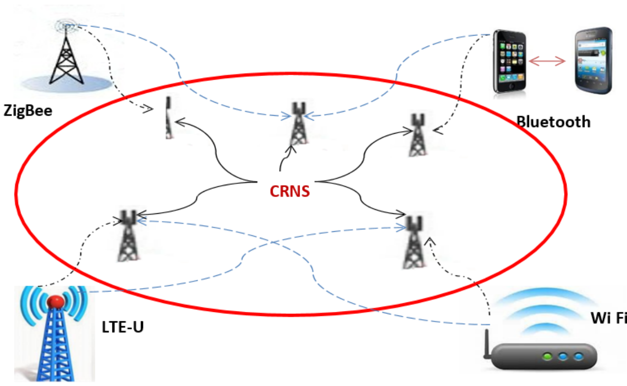


Fig1: Illustrates the basic System of Considered Model

All PU's have higher priority to use the channels. If the channel unoccupied by PU it is called idle channel (ch_i) whereas occupied channel is defined as busy channel ($\boldsymbol{ch_b}$). The base station (BS) of SU has ability to sense and aggregate random channels to use in data transmission. The busy and idle channels of PU are distributed with Poisson distribution.

The collision considered are assumed as *misdetection*, PU came back to use its own channel during SU using it. The aggregated channels denoted as (*n*), (*N*) denotes to number of available channels. SU is transmitting its information in period time denoted by T_s while τ_s denoted to channel sensing time. In general, $T_s \gg \tau_s$. Maximum collision probability should be under threshold that denoted by ($£_{th}$).

III. Channel Model

The probability of occupied channel is given as [12]:

$$\boldsymbol{P_{ch_b}} = \frac{\boldsymbol{ch_b}}{\boldsymbol{ch_i} + \boldsymbol{ch_b}} \qquad (1)$$

On the other hand, the probability of unoccupied channel:

$$P_{ch_i} = 1 - \boldsymbol{P_{ch_b}}$$

$$\boldsymbol{P_{ch_i}} = \frac{\boldsymbol{ch_i}}{\boldsymbol{ch_b} + \boldsymbol{ch_i}} \qquad (2)$$

For given Number of active SU (A_{su}), and Number of available unlicensed channels (N), optimal aggregated channels (n) should be calculate as in the calculation in equation (16). The SU is allowed to select channels randomly from N unlicensed channels. But these channels may be misdetected or required by PU coming back to use it at any time. The SNR for SU, and PU are calculated as:

$$SNR_{SU} = 10\text{Log}_{10}\left(\frac{Ptsu * Gsu}{Ptpu * Gpusu + \sigma}\right) \text{ [dB]} \qquad (3)$$

$$SNR_{PU} = 10\text{Log}_{10}\left(\frac{Ptpu * Gpu}{Ptsu * Gsupu + \sigma}\right) \text{ [dB]} \qquad (4)$$

Ptsu Transmit power of SU, *Gsu* secondary user gain; *Ptpu* transmit power of primary user, *Gpu* primary user gain, *Gpusu* the gain between PU and SU, and the σ is the noise.

IV. Problem Formulation

The collision is one of the main problems of sub-channels aggregated for SU. Moreover, most channels aggregated may be misdetected or the original PU may come back to use it during the transmission of SU. The Probability of detection (p_d) and Probability of false alarm (p_f) (e.g. the false detection for presence of PU are calculated for different signals and signal-to-noise ratio as: [12]

$$\boldsymbol{p_d} = Q\left(\left(\frac{£_{th}}{\sigma^2} - SNR - 1\right)\sqrt{\frac{\tau_s f_s}{2\boldsymbol{ch_i}+1}}\right) \qquad (5)$$

$$\boldsymbol{p_f} = \text{Q}\left(\left(\frac{£_{th}}{\sigma^2} - 1\right)\sqrt{\tau_s f_s}\right) \qquad (6)$$

Where,

$£_{th}$= threshold,

SNR= signal to noise ratio received from PU,

τ_s=channel sensing time,

f_s = Nyquist sampling theorem (2B).

The probability of ($\boldsymbol{p_d}$) and ($\boldsymbol{p_f}$) are depending on occupied ($\boldsymbol{P_{ch_b}}$) and unoccupied channel ($\boldsymbol{P_{ch_i}}$), for that eq. (5) and (6) to be as:

$$\boldsymbol{p_d} = \boldsymbol{P_{ch_b}}\ \text{Q}\left(\left(\frac{£_{th}}{\sigma^2} - SNR - 1\right)\sqrt{\frac{\tau_s f_s}{2\boldsymbol{ch_i}+1}}\right) \qquad (7)$$

$$\boldsymbol{p_f} = \boldsymbol{P_{ch_i}}\text{Q}\left(\left(\frac{£_{th}}{\sigma^2} - 1\right)\sqrt{\tau_s f_s}\right) \qquad (8)$$

Otherwise the probability of misdetection (P_{md}), which wrongly SU detect the channel to be as:

$$P_{md} = \boldsymbol{P_{ch_b}}(1 - p_d)$$

p_d=The probability of detection,

$\boldsymbol{P_{ch_b}}$ =probability of channel occupied.

By using the fact that *Q (-x) =1-Q(x)*, the probability of misdetection in any channels can be given by:

$$P_{md} = \left(\boldsymbol{P_{ch_b}}\boldsymbol{Q}\left(\left(SNR + 1 - \frac{£_{th}}{\sigma^2}\right)\sqrt{\frac{\tau_s f_s}{2\boldsymbol{ch_i}+1}}\right)\right) \qquad (9)$$

The collision probability of primary packet arrival in aggregated channel may be expressed (PUr) as:

$$P_{PUr} = (\boldsymbol{P_{ch_i}}(1 - P_f))(1 - (1 - Pc)^n) \qquad (10)$$

Where,

Pc is the probability of collision caused by PU packet arrival.

The primary packed arrival is given by Poisson process as:

$Pc = 1 - \exp(-pp_{ar}.T_s)$

For given n aggregated sub-channels,

$$Pc1 = 1 - (1 - Pc)^n$$
$$Pc1 = 1 - \exp(-pp_{ar}.T_s.n) \qquad (11)$$

Where,

(T_s) is the transmission time of SU,

(pp_{ar}) is the primary packet arrival rate.

Applying equation (11) into equation (10) yields a new form of collision probability ($Pc2$) which is considered as the proposed algorithm introduced in the current work.

$$Pc2 = P_{PUr} = (\boldsymbol{P_{ch_i}}(1 - P_f))(1 - e^{-T_s pp_{ar} n}) \qquad (12)$$

The objective here is to maximize the total data Rate (C_{total}) of secondary user under collision constraints. The objective function is given by the following equation. That is

$$\text{Max } C_{total} = max\frac{n}{N}\sum_{i=1}^{N}\left[log_2\left(1 + \frac{g_i * P_{max}}{n * \sigma^2}\right)\right] \qquad (13)$$

Subject to,

$$(P_{md})(P_{PUr}) \leq £_{th}$$

Where,

g_i=$|hi|^2$,

hi= the coefficient of sub-channel

V. A Proposed Channel Aggregated Scheme

The problems occur during spectrum sensing is the collision with PU coming back and misdetection of hidden PU as well. The objective of the aggregation method is to maximize total data rate (C_total) of SU under collision constraints. Hence the collision probability with PU in Eq. (10) should be less than or equal a threshold level defined by:

$$(\boldsymbol{P}_{ch_i}(1-P_f))(1-(1-Pc)^n) \le \pounds_{th} \quad (14)$$

$$(1-(1-Pc)^n \le \frac{\pounds_{th}}{(\boldsymbol{P}_{ch_i}(1-P_f))}$$

$$(1-Pc)^n \le 1-\frac{\pounds_{th}}{(\boldsymbol{P}_{ch_i}(1-P_f))} \quad (15)$$

By tacking the logarithm of both sides of equation (15),

$$n\,log\,(1-Pc) \le log\,(1-\frac{\pounds_{th}}{(\boldsymbol{P}_{ch_i}(1-P_f))})$$

The optimal aggregated channels (n^*) for a given threshold ($\pounds_{th}$) is expressed as:

$$n^* = \left\lfloor log\,(1-\frac{\pounds_{th}}{(\boldsymbol{P}_{ch_i}(1-P_f))}) \Big/ log\,(1-Pc) \right\rfloor \quad (16)$$

Where,

$Pc = 1-\exp(-pp_{ar}.T_s)$

Applying Pc into equation (16) yields:

$$n^* = \left\lfloor \frac{log\,(1-\frac{\pounds_{th}}{(\boldsymbol{P}_{ch_i}(1-P_f))})}{-pp_{ar}.T_s} \right\rfloor \quad (17)$$

Where,

$\lfloor . \rfloor$ stands for the largest value.

The misdetection probability should be added to collision probability that might occur. Doing that equation (10) may be reformulated as the following:

$$Pc2 = (P_{md})(\boldsymbol{P}_{ch_i}(1-P_f))(1-(1-Pc)^n \quad (18)$$

Where,

$Pc = 1-\exp(-pp_{ar}.T_s)$

To obtain the optimal aggregated channels n^* equation (18) should be less than or equal a certain threshold ($\pounds_{th}$) as shown in equation (19):

$$(P_{md})(P_{ch_i}(1-P_f))(1-(1-Pc)^n) \le \pounds_{th} \quad (19)$$

Following the same procedure above, the optimal aggregated channels n^* in equation (19) will be given as:

$$n^* = \left\lfloor \frac{log\,(1-\frac{\pounds_{th}}{(P_{md}).(\boldsymbol{P}_{ch_i}).(1-P_f)})}{-pp_{ar}.T_s} \right\rfloor \quad (20)$$

From equation (20), it can be observed that, n^* increases inversely with $(pp_{ar}.T_s)$. If there is an increasing in pp_{ar} or T_s optimal aggregated channels n^* will be decreased. That is at low packet arrival rate from PU in time duration of SU, more aggregated channels will be collected, and that leads to improve the capacity of SU. Moreover when $(\frac{\pounds_{th}}{(P_{md}).(\boldsymbol{P}_{ch_i}).(1-P_f)})$ increases (towards 1) at $pp_{ar}, T_s and\ \pounds_{th}$ are constant in equation (20). That indicates more sub-channels to be aggregated too. Applying equation (20) into equation (13) yields:

$$C_{total} = \left\lfloor \frac{log\,(1-\frac{\pounds_{th}}{(P_{md}).(\boldsymbol{P}_{ch_i}).(1-P_f)})}{-pp_{ar}.T_s} \right\rfloor log_2 \left(1 + \frac{k}{\left\lfloor \frac{log\,(1-\frac{\pounds_{th}}{(P_{md}).(\boldsymbol{P}_{ch_i}).(1-P_f)})}{-pp_{ar}.T_s} \right\rfloor} \right) \quad (21)$$

Where,

$k = (\frac{g_i * P_{max}}{\sigma^2})$,

$\lfloor . \rfloor = n^*$.

It can be seen from equation (21) that C_{total} increasing monotonically with increasing $n^*. and\ n^*$ inversely increasing with $(pp_{ar}.T_s)$. However, to keep$(pp_{ar}.T_s)$ in low level, if PU packet arrival (pp_{ar}) increase, transmit time of SU (T_s) should be decrease.

At high values of $(\frac{\pounds_{th}}{(P_{md}).(\boldsymbol{P}_{ch_i}).(1-P_f)})$ but, should be ≤ 1, another reason to increase C_{total}. It is easy to say that C_{total} increase with low misdetection (P_{md}) where $(\boldsymbol{P}_{ch_i}).(1-P_f)$ are constant.

VI. Matlab Simulation & Results

In this section Matlab simulation and results are presented and analyzed. The flow chart in Fig.2 shows the procedure followed in the Matlab simulation. The Fig. starts by parameters initialization for the CR system to starts aggregating sub-channels. Table 1 below shows the values used in simulation. The CR system has the ability to aggregate random multiple sub-channels n to improve its capacity.

Then the probability of misdetection (*P_md*), and the collision probability that caused by PU coming back (*P_PUr*) are calculated from equations (9), (10) respectively.

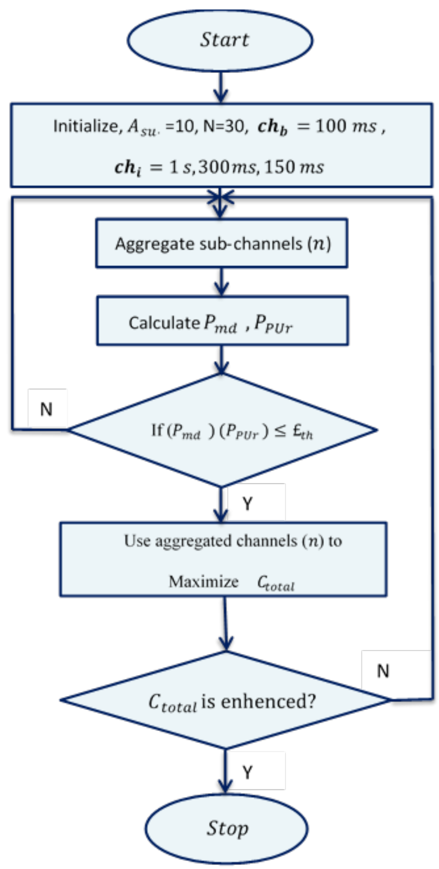


Fig.2. Illustrates the Flow Chart for Aggregating Sub-Channels

A series of simulation experiments were conducted to compare our algorithm in equation (18) with that in equation (11) reported in ref. [11]. The simulation parameters used are listed in Table 1 below.

Table 1: Parameters values

Parameters	***Definition***	***Value***
$\boldsymbol{ch_b}$	Busy channel	100 m sec
$\boldsymbol{ch_i}$	Idle channel	[1 sec, 300m sec, 150m sec]
A_{su}	Number of active SU	10
N	N. available channels	30
n	Aggregated channels	[1, 5, 10]
N_O	Thermal noise	-171 dB/Hz
SNR	Signal to noise ratio	[-20 to -10 dB]
$£_{th}$	Threshold	0.005
Bw	Bandwidth	1MHz
fs	Nyquist sampling	2 Bw
σ	Noise power	N_O. Bw
T_s	Transmission time	0.001 sec
τ_s	Channel sensing time	0.002 sec
pp_{ar}	Arrival data rate	[0.02 to 0.6]/sec
P_{max}	Maximum power	1 w

Fig. 3 shows the collision probabilities P_{C1} and P_{C2} versus primary packet arrival rate $PPar$ for both algorithms. Different values of aggregated channel n used were (8, 9, and 10) and values of arrival rate varying in the range of (0.1 to 0.6). It can be seen from Fig. 3 that the collision probabilities increase as the packet arrival rate increases. Moreover, the collision probabilities also increase as the number of aggregated channels n increase. However, the increase in collision probabilities resulted from our algorithm is much less than those resulted from the other algorithm.

The number of sub-aggregated channels n versus primary packet arrival rate PP_{ar} with idle channel time ch_i illustrated as a parameter, shown in Fig.4. It can be seen in this figure that optimal aggregation channels number are decreasing with increasing in pp_{ar} as given in equation (17). Moreover, it is observed that maximum optimum values of aggregated channels stay constant for packet arrival rate of (0.02-0.04) for the algorithm reported in reference [11]. However, for the algorithm introduced in this work the maximum optimum stays constant up to 0.06 for idle channel time of *chi*= 300msec. and to 0.08 for idle channel time of *chi*= 150 msec and then slowly decreasing. That means in the proposal algorithm until PU packet arrival of 0.08, the SU systems can possess maximum aggregated channels.

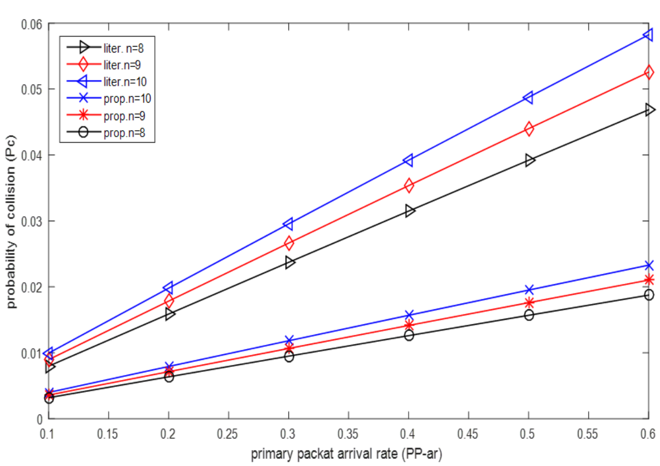


Fig. 3. Illustrate the Relationship Between pp_{ar} and Pc in literature and Proposed

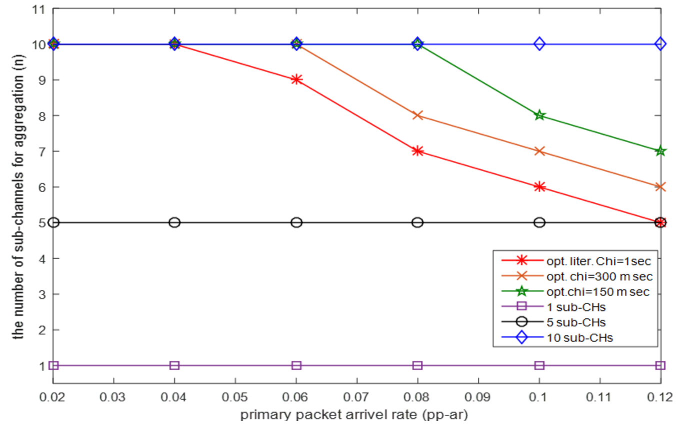
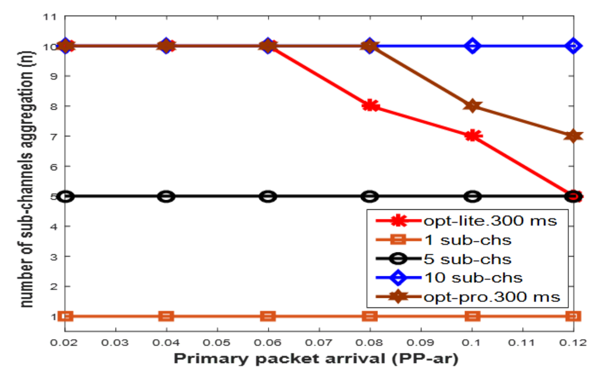
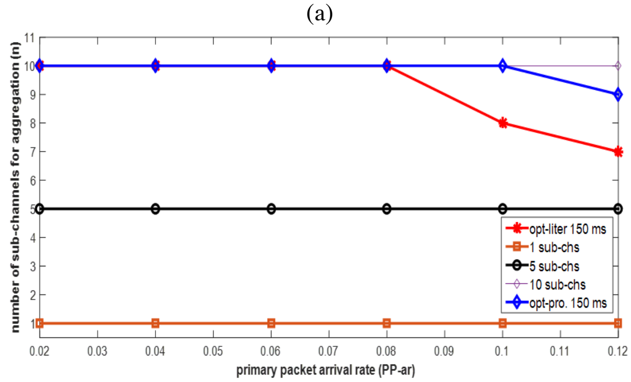


Fig.4.Illustrates Number of Aggregated Sub-channels Versus Primary User Packet Arrival Rate with chi = 1 sec and chi = 300 ms, and chi =150ms for the Proposed Algorithm.

Adding misdetection probability Pmd to equation (17) yielded equation (20) above. This equation produced the results given in Fig.5 (a,b). From this figure it is observed that more channels are to be aggregated after adding the effect of misdetection probability for the two cases *chi*= 300msec and *chi*= 150 msec.



(a)



(b)

Fig.5 Illustrates the Relationship between Primary Packet Arrival Rate (pp_{ar}), and Aggregated Sub-channels a: at ch_i=300 msec, and b: at ch_i =150 msec.

Fig.6 (a), Illustrate collision probability (Pc) with respect to primary packet arrival (pp_{ar}) for the algorithm reported in reference [11], whereas Figure 6(b) shows the results from our introduced algorithm. It can be seen that for n^* aggregated channels, the collision probability results of our algorithm are decreased than those obtained from the algorithm reported in reference [11].

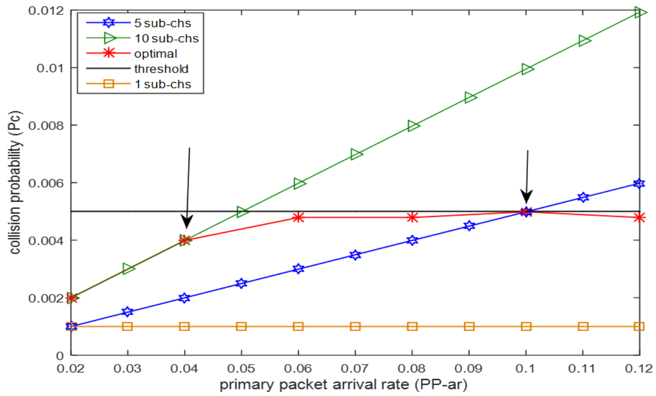


Fig.6 (a) Illustrates the Relationship between (Pc) and (pp_{ar}) for the Work Reported in Reference [11].

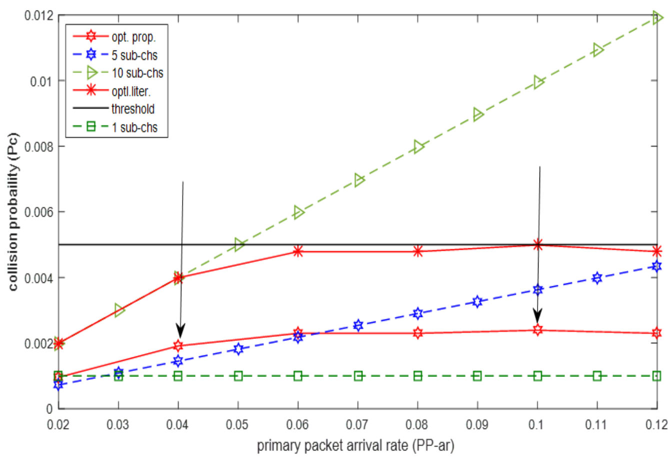


Fig.6 (b) Illustrates the relationship between (Pc) and (pp_{ar}) resulted from both our algorithm and those from the algorithm in reference. [11]

Fig.7 shows the relationship between $Ctotal$ of SU versus primary packet arrival rate for our algorithm (equation 21), and the corresponding results in reference [11]. It is observed that the capacity stays constant for pp_{ar} =[0.02 to 0.04] at the maximum value then start decrease in the results from the algorithm of reference [11]. However, the capacity stays constant at maximum for our proposed algorithm until pp_{ar} = 0.06. This clearly shows an improvement in capacity of SU system.

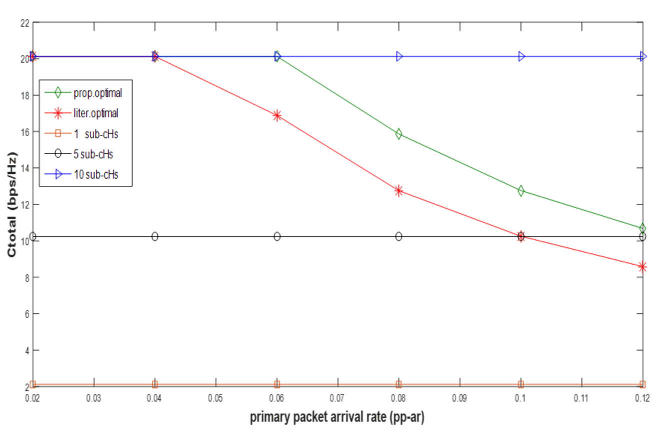


Fig. 7 illustrates the Relationship between pp_{ar} and C_{total} for the Proposed Algorithm as Compared to Reference [11].

VII. Conclusion

In this proposed paper, a channel aggregation algorithm for Cognitive Radio under collision and misdetection probabilities. The study considered primary packet arrival rate (pp_{ar}), SU transmission time (T_s), probability of idle channel, and misdetection under collision probability. Moreover, an unlicensed spectrum was considered [14].

The results of this study are summarized as; The collision probability is reduced as compared to the reported work. On the other hand, increase in the number of aggregated channels as the probability of idle channel decreased. Otherwise, the number of aggregated channels increased with probability of misdetection decreasing. Besides, the capacity of SU was increased as well with aggregated channel, whereas the number of aggregated channels is increased inversely with $pp_{ar} . T_s$. However, to keep ($pp_{ar}. T_s$) in low level, PU packet arrival (pp_{ar}) increases, transmit time of SU (T_s) must be decreased. In this proposed method if $\left(\frac{£_{th}}{(P_{md}).(P_{ch_i}).(1-P_f)}\right)$ boundary is increased (towards 1) there will be an increased optimal aggregated channel, namely C_{total} increase with an increase in $\left(\frac{£_{th}}{(P_{md}).(P_{ch_i}).(1-P_f)}\right)$.

In summary, (by lower primary packet arrival rate, short interval time for SU transmission, and low misdetection) leading to high capacity (high data rate). In addition, with proposed method there are clearly decreasing in collision probability as compared to previous work.

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