Opportunistic Spectrum Access Study of CORAL Platform

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***Abstract*—As the requirement of spectrum is increasing with the advent of new technologies, cognitive radio networks have got tremendous attraction in recent days. Since the concept of cognitive radio is new, there are a few number of cognitive radio platforms have been introduced in the literature. CORAL is WiFi like cognitive radio platform developed by communication research centre (CRC) operated in license exempt band 2.4 GHZ and 5.8 GHZ. This platform is aimed to coexist with IEEE 802.11 network through TDD/TDMA access protocol. In this work, we have done some data analysis (collected by CRC) in order to determine interference statistics at the payload level. We have proposed a secondary user's strategy in order to access the WiFi channels intelligently and afterward we have applied neural network in order to extrapolate traffic statistics during the future time interval.**

I. INTRODUCTION

CORAL is WiFi like cognitive radio platform developed by communication research centre (CRC) operated in license exempt band 2.4 GHZ and 5.8 GHZ. This platform is aimed to coexist with IEEE 802.11 network through TDD/TDMA access protocol. Station or AP in the CORAL platform is called CORAL node. Each CORAL node has two interfaces - one for data transmission, reception and another for the purpose of sensing spectrum in order to encounter different obstacles existent in the spectrum. Through the ethernet interface one laptop is connected to a CORAL node where CR-NMS software is running. The database where all sensed information is located is called REAM. Having collected all information from REAM database, CR-NMS is the management software which controls all APs resided in the spectrum. CORAL node has the ability to sense environment through both omni and unidirectional antenna. Message interchange between CR-NMS software and coral node (WiFi-CR) is called SSURF message. In the literature, very few cognitive radio platforms have been developed except the prototype established in [1]. People only have proposed the idea of cognitive radio network from the architectural point of view.

As the DCF protocol mechanism is complex, people have not solved the problem of opportunistic channel access considering the exact protocol specification. We have proposed a novel opportunistic channel access scheme for the secondary network with sensing and cognitive abilities on the top of WiFi network. Opportunistic channel access scheme is basically different on the transmission statistics of primary users. In order to extract the spectrum hole from ISM band, CRC collects data at the granular packet level and store all information relevant to packet capture e.g. capture time, payload size etc. Given that we have traffic information in the form of data collected by CORAL platform, we have developed an opportunistic channel access procedure on ISM. Till the date, people have given the solution of cognitive channel access on slotted primary user network, and some on unslotted ones. Sloution on slotted network is much easier than the unslooted one. Cognitive radio operation over unslotted network is even more challenging. IEEE 802.11 based WiFi network is unslotted and DCF protocol is used by the users in order to access channel. Having observed overheads in DCF protocol, we propose an overlay network which achieves better performance than following DCF protocol while affecting regular WiFi users slightly. We define users of overlay network as secondary users and users who follow DCF protocol are primary users. Secondary users have dynamic spectrum sensing ability. In this paper, we have developed a novel opportunistic channel access scheme for a single secondary user on the existence of several primary users.

Moreover, we have applied artificial neural network (ANN) framework for traffic prediction on a channel because ANNs can model the complex relationship between multiple inputs and the output in a way similar to biological neural networks. An important aspect of ANN-based traffic prediction framework is the time scales of prediction. That is, the duration of input (past traffic history) to the projected duration. In this work, we design traffic prediction frameworks that involve predicting future traffic at minute level. Later on, because of the limitation of collected data, we have shown prediction results of next 250ms based on the data received on previous 250ms. In addition, our prediction criterias are traffic's data rate and payload mean inter-arrival time.

Rest of the paper has been divided as follows: section II belongs to the thorough literature survey for the opportunistic channel access scheme, section III represents the experimental results, IV is the analytical model for our novel strategy of the secondary user, performance evaluation of the proposed model has been in section V and finally the neural network prediction results in VI.

II. RELATED WORK

Opportunistic spectrum access is a problem which spans over a very diverse area of wireless networks ranging from the cellular network, vehicular network towards the cognitive radio netwroks. Jhang et al [2] solves a problem in vehicular networks which is relevant to the communication between vehicle and RSU (road side unit). The solution is proxy based and the protocol is designed to exploit cooperative and opportunistic forwarding between any two distant RSUs and to emulate back-to-back transmissions within the coverage of an RSU. Yang et.al [3] solves the opportunistic channel access problem with new paradigm. The problem is the channel access scheme by a set of users through game theoretic manner instead of random mechanism. The solution is an iterative algorithm which converges to nash equilibrium even though user is unaware of channel state information and other users' policies.

Distributed opportunistic channel access in the relayed network has been investigated by Zhang et. al [4]. Multiple source, destination along with multiple relay nodes are considered and sources access the channel in random manner. An optimal stopping rule has been derived for the winner node in order to free the channel when its condition is worse. This leads to better multi source, multi relay in addition to better time diversity. Opportunistic spectrum access of two secondary users on two channels while the primary user's access on these channels is markov chain have been deduced in [5]. Their proposed schemes cooperative and learning based approach both show better performance than static partitioning approach. Through simulation they have justified their schemes. Dynamic spectrum access of a number of secondary networks on the presence of primary activity has been proposed in [6]. They have proposed a novel graph maximum algorithm MASPECT which uses the information from first and second hop and proved to show much better performance than traditional approach in terms of throughput and call blocking probability. Santivanez et. al. [7] have discussed some challenges, policies, architecture and protocol in terms of opportunistic spectrum access. They have shown that even a simple protocol can increase much better performance in terms of system's throughput. Liu [8] has also discussed opportunistic spectrum approach once an optimal channel has been found to access.

Since last few years, opportunistic spectrum access for the cognitive radio have been proposed a lot. There were a few situations arise for this problem. Cognitive radio can be synchronized or unsynchronized with the licensed users in the network. Licensed user's channel access scheme can be slotted or unslotted. Tackling the problem for the unsynchronized and unslotted cases is harder than the former. From the beginning of cognitive radio research, people have been giving solution for the former case. Filippi et. al. [9] have devised opportunistic channels access scheme of a slotted primary user's network. Solution is based on a model-based learning in a specific class partially observable markov decision process. In [10], [11], the authors consider a slotted system for a single SU with limited sensing, and identify the conditions under which a simple myopic policy is optimal for sensing and access, when the PUs channel occupancy can be modeled as i.i.d. Markov chains. The result is extended to the case of sensing multiple channels in [12]. In [13], the authors adopt the quickest change detection technique and establish a Bayesian formulation to decide which channel to access assuming geometrically distributed busy/idle times.

Recently, people are considering unslotted network for the cognitive radio. Such as, Sharma et.al. have studied this type of network for cognitive in a number of works. In one work [14], they determine idle/busy time distribution of primary user's access on the channel. It fits the distribution to some pre-specified distribution. Given the end time of previous cycle, from the idle time distribution SU determines remaining idle time for accessing the channel without any intervention. There is another similar kind of work is [15]. Liu et. al. [16] have also one work which assumes channel idle/busy time distribution can be general instead of only pre-specified distribution. In one measurement based paper [17], the authors also proposed an opportunistic channel access scheme for an unslotted network. Min et.al [18] have given the solution of opportunistic spectrum access for the mobile secondary user. First they model channel availability experienced by a mobile SU as a two-state continuous time markov chain. To facilitate efficient spectrum sharing, they formulate the problem of maximizing secondary network throughput within a convex optimization framework, and derive an optimal, distributed channel selection strategy. Through extensive simulation, they have justified their schemes and proved that energy efficiency while sensing can be reduced by a large percentage.

Even for the unslotted network, all of the above solutions may consider WiFi network. They have one assumption which is idle/busy time follows some distribution. However, for the WiFi network, idle time can be backoff period or really idle period which are not distinguishable to secondary user. And attempting to access backoff period causes reduced throughput to primary users. None of them proved analytically what exactly happen to a WiFi primary user when secondary user accesses the channel. We are the first one have derived an analytical model for the secondary user in order to find expected idle time and at which point or policy, the secondary user should accesses that idle time period.

III. EXPERIMENTAL RESULTS

CRC has conducted a measurement at University of Ottawa placing 16 terminals at different locations. From the previous experimental results, we have found channel 1, 6 and 11 are highly congested than the others. Therefore as the representative of preliminary results, we conducted some analysis on the data obtained from channel. In this report, we only have considered the data collected by sensor 1. In order to access a channel opportunistically at a particular time, we need to know the traffic pattern arrival pattern of that duration. While collecting the interference data, CRC records the interferer identity (Source MAC address), time instant (in microsecond granularity) when the payload captured, utilization (how long the payload occupies the channel). We can exploit these information in order to find out all flows throughout the sensing interval. In this 16-terminals data, we noticed each channel has been sensed 500 ms in a round robin fashion. Therefore, in order to sense 11 channels sensor takes around (500*11) 5.5s and in every 5 second inter sensor 1 senses channel 1. Because of these sensing limitation, we miss the channel statistics of channel in every 5s. And in our data analysis, we have assumed maximum flow duration is 500ms.

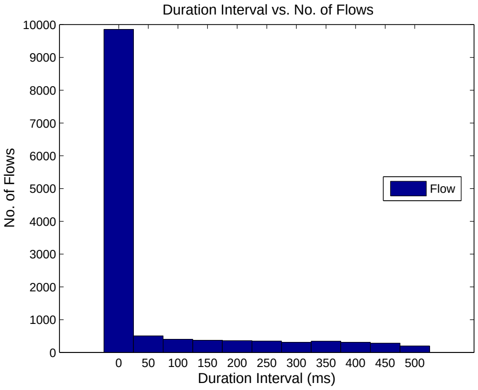


Fig. 1. Duration Interval vs. No. of Flows

In reality, flow duration can be longer, but in our case, since we miss the data after 500 ms, we consider the flow should be in between 0 and 500ms.

We have found total 20,941 data entries have been recorded for channel 1 by the sensor node 1. Data analysis of other channels follow the same mechanism as presented in this section. In the next subsection, we will show each flow statistics (not in very granular level).

A. Data Flow Analysis

We have derived the flow statistics based on the criterias, duration, average inter-arrival time, average utilization and number of payload entries.

Figure 1 represents the bar chart for flows of different duration. We have found total flows are 13294. Among them, 9856 is about zero duration. It means, these flows have only one payload. This is, we guess, for the missing data during 5s. Maybe, at the end of 500ms, on flow has started, but we could record those data after 500ms. This thing can happen in other way, for example, one flow has stated during the unrecorded 5s, and finished just when CRC has started recording data at the beginning of 500ms. These all flows are counted as of zero duration. Moreover, figures 2, 3 and 4 represent other flow statistics.

While dealing with flows, we have also found, during each flow duration how many simultaneous flows remain with the tagged flow. In order to determine, we have applied one policy. First, we have determined all flows with the statics: start time, end time and duration. Once we have the list of flows, the follow method is applied the number of concurrent flows.

- Step 1: Sort all the flows in terms their end time in ascending order.
- Step 2: Take one non-tagged flow from the sorted list. We call it as tagged flow.
- Step 3: Filter all the flows whose start time is less than the tagged flows start time.
- Step 4: Filter the flows obtained from step 3 in terms of not tagged yet,

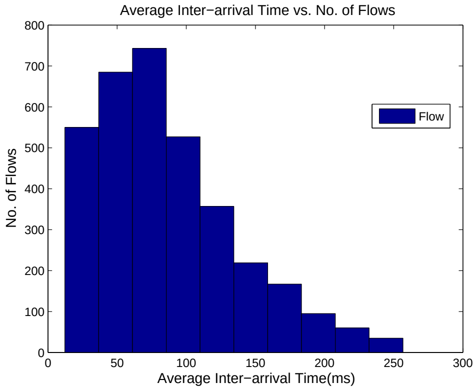


Fig. 2. Average Inter-arrival Time vs. No. of Flows

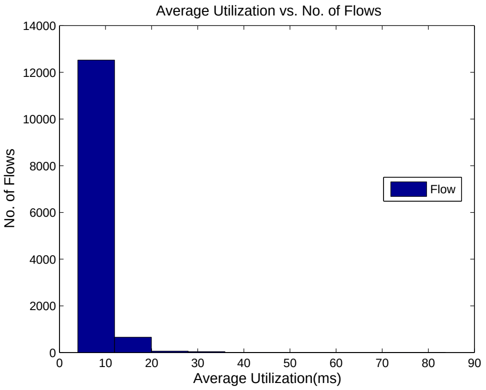


Fig. 3. Average Utilization vs. No. of Flows

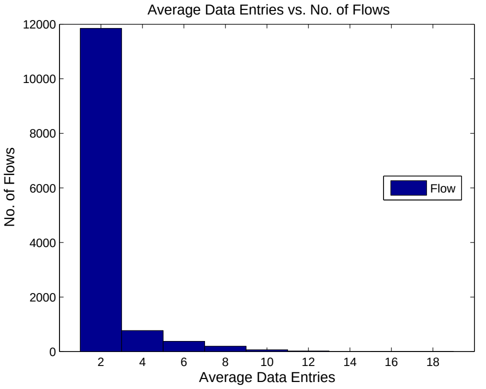


Fig. 4. Average Data Entries vs. No. of Flows

TABLE I
FLOW STATISTICS OF CHANNEL 1 FROM SENSOR NODE 1

Flow Duration (ms)/No. of Flows	50	100	150	200	250	300	350	400	450	500
1	83	107	95	100	129	154	212	244	251	192
2	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0
5	404	282	274	257	219	154	133	69	32	6
7	16	12	3	2	0	0	0	0	0	0
1	4	2	1	0	0	0	0	0	0	0

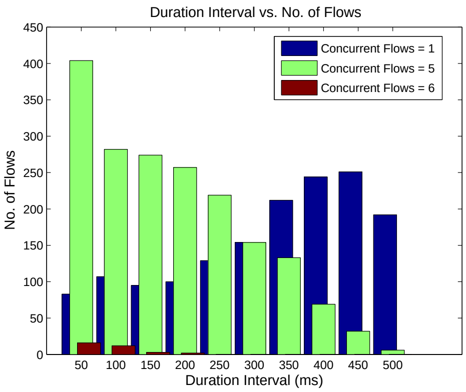


Fig. 5. Duration Interval vs. No. of Flows

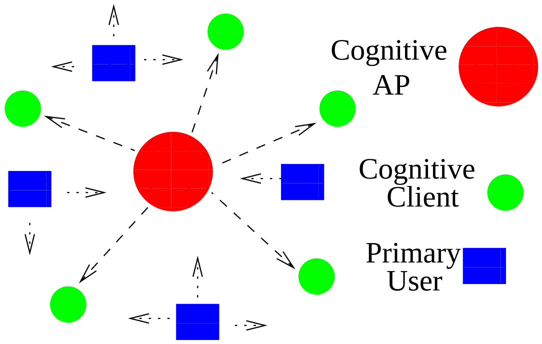


Fig. 6. System Model

- Step 5: Filter the flows obtained from step 4 whose end time is bigger than the tagged flow's end time.
- Step 6: Number of Flows obtained from step 5 is the number of concurrent flows of the tagged flow.
- Step 7: Continue step 2 until the list is empty.

Figure 5 and table I represent the detailed flow statistics obtained from the previous policy. We see, the number single flows without any concurrent flow is the highest. We also see, there are some flows which have other 4 concurrent flows.

IV. OPPORTUNISTIC CHANNEL ACCESS

As mentioned, our cognitive radio network is built on WiFi network where regular users access the channel following IEEE 802.11 DCF protocol. Following subsection is the short description of DCF protocol mechanism. In addition, we assume, one single secondary user uses the extracted spectrum hole. We have discussed a bit on the subsection how the opportunistic channel access mechnism works when there are a number of secondary users in the network.

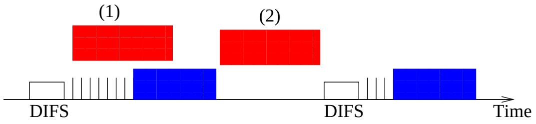


Fig. 7. Possible Transmission Opportunities for Cognitive AP

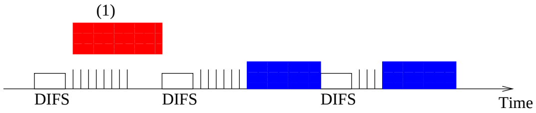


Fig. 8. Impact of First Transmission on Primary User

A. IEEE 802.11 DCF-Based MAC

The IEEE 802.11 DCF-based MAC protocol uses the CSMA/CA mechanism. A station monitors the medium before attempting transmission. If the medium is sensed busy, the station defers transmission until the medium is sensed idle for a period of time equal to a DCF interframe space (DIFS). After the DIFS medium idle time, it enters the backoff phase in which it sets a random backoff counter randomly chosen from [0,CW), where CWis the contention window size. The backoff counter decreases by one for every time slot if the medium is idle; otherwise, the counter freezes, and the decrement resumes after the medium is sensed idle again for a DIFS. When the backoff counter reaches zero, the station transmits the frame. If another station transmits a frame at the same time, a collision occurs, and both transmissions fail. CW is doubled after a collision until it reaches the maximum value (CWmax), and the sender reschedules the transmission by randomly choosing a backoff counter in [0,CW). The frame is dropped when the retransmission limit is reached. After a successful transmission, CW is reset to its minimum value (CWmin). Upon receiving a frame successfully, the receiver transmits an acknowledgment (ACK) following a short interframe space (SIFS).

B. Optimal Strategy

In our work, we assume there are N number of primary users accessing the channel following DCF protocol and there is only one secondary user which would like to opportunistically access the channel with little harm to primary users. we assume the single secondary user is the base station and it is sending traffic to its attached users whenever it gets some free slot to access. The way the primary users access channel in WiFi network is complex. It is hard for the cognitive user to know whether the primary users are in idle state or in backoff state. If the primary user is in backoff state or in idle state, secondary user finds the channel idle and therefore attempts a transmission depicted in figure 7. However, for these two transmissions, primary users will be affected only in the first case, its backoff procedure will be interrupted and the packet transmission will be delayed 8. Eventually throughput of the primary user will be reduced for this type of transmission. Same situation happens if the secondary user accesses the channel following the same mechanism as primary user. In that case, secondary user also has some protocol specific overhead and therefore idle time does not get properly utilized. However, if we somehow get to know in which period, primary user is really idle, secondary user can exploit that time duration by directly transmitting its stored packets without any kind of backoff procedure. Challenge with this strategy is to know the actual traffic arrival rate of primary user. Actually, arrival rate is also possible to learn if we observe the transmission probability of primary users. From the observed transmission probability of primary users, it is possible to derive the arrival rate and then from that we can easily derive the expected amount of time primary users being idle. Once secondary user know expected idle time, it can accesses that duration of time by sending packets just after any primary user finishes successful transmission of each packet. Following subsection is the analytical model for N users when they access channel with different packet arrival rate $\lambda_0, \lambda_1, \cdots, \lambda_{N-1}$.

C. Primary User Model

In this section, we present the analytical model for studying the performance of a set of primary users with asymmetric traffic using the DCF mode for MAC. Time is slotted with the minimal slot duration of DCF protocol. Let the traffic arrival rate and frame service rate of a particular user i are λ_i and μ_i packets per slot. Queue utilization ratio of user i is $\rho = \frac{\lambda_i}{\mu_i}$.

Digging the sensing data over a period of long duration, we can obtain the number of users N acting on the channel and transmission probability of each user. Denote the transmission probability of user i on a particular slot is given by $p_i[T]$. A user is considered as idle when it does not have packet in the queue or no packet in service. If the probability of user i not being idle is ρ_i, transmission probability of user can be represented as a function ρ_i. Therefore, we have

$$p_i[T] \;=\; p_i[T|QE](1-\rho_i) + p_i[T|QNE]\rho_i$$

$p_i[T|QE]$ and $p_i[T|QNE]$ are the conditional transmission probability of user i given that queue is empty and not empty respectively. A user never transmits if its queue is empty and thus $p_i[T|QE] = 0$. Moreover, we redefine $p_i[T|QNE]$ by τ_i. Simplifying all, transmission probability of user i is given by

$$p_i[T] = 0 * (1-\rho_i) + \tau_i * \rho_i = \rho_i\tau_i$$

Conditioning the transmission of user i in a given slot, collision happens if at least one of rest $N-1$ users transmit. If the collision probability of user i is p_i, we have

$$p_i = 1 - \prod_{j=0, j\neq i}^{N-1}(1-p_j[T]) = 1 - \prod_{j=0, j\neq i}^{N-1}(1-\frac{\lambda_j\tau_j}{\mu_j})$$

where $i = 0, 1, \cdots, N-1$.

Given that the queue is not empty, the transmission probability of user i can be approximated as

$$\tau_i \;=\; \frac{E[M_i]}{\bar{w_i}} \tag{1}$$

where $\bar{w_i}$ is the average number of backoff slots for user i to have a successful packet transmission, and $E[M_i]$ is the average number of transmission attempts user i had during $\bar{w_i}$. p_i and $1-p_i$ are the collision and success probability of a transmitted packet and the backoff counter is chosen uniformly from [0, CW], where CW is the backoff window size. Exponential increment of backoff window on a collision event can be modeled as a geometrically distributed random variable and thus the average number of backoff slots can be derived as,

$$\begin{aligned}\bar{w_i} \;&=\; (1-p_i)\frac{W}{2} + \cdots + p_i^{m'}(1-p_i)\frac{\sum_{i=0}^{m'} 2^i W}{2} + \cdots \\ &\quad + p_i^m \frac{\sum_{i=0} m'2^iW + (m-m')2^{m'}W}{2}\end{aligned} \tag{2}$$

where m' is the maximum backoff stage, m is the retransmission limit, and W is the minimum backoff window size. Similarly, transmission attempts of user i can also be modeled as geometrically distributed random variable, and the average number of transmission attempts of user i can be derived as

$$E[M_i] \;=\; (1-p_i).1 + \cdots + p_i^m.(m+1) \tag{3}$$

Following the same procedure, average number of collision slots $\bar{T_{c_i}}$ before a successful transmission of user i can be obtained. If T_{c_i} is the duration of a single collision for user i, $\bar{T_{c_i}}$ is also geometrically distributed random variable as the function of p_i. Therefore,

$$\bar{T_{c_i}} \;=\; p_i(1-p_i).T_{c_i} + \cdots + p_i^m(1-p_i).mT_{c_i} \tag{4}$$

From the observed value of $p_i[T] = \rho_i\tau_i$, collision probability of each user p_i can be obtained. Consequently, $\bar{w_i}$, $E[M_i]$ and $\bar{T_{c_i}}$ can be derived as well. Average service time $1/\mu_i$ of each packet for user i can also be approximated from the sensed data. Definition of service time is the time interval between the time instant that the frame is successfully transmitted. Service time of user i's packet can be further fine grained by the average number of slots of first backoff stage and its collision probability. In order to calculate packet arrival rate λ_i of user i, we want to fully derive the service time. During $1/\mu_i$, in addition to a successful transmission by the tagged station i, the following events may occur:

1) successful transmissions by the remaining N-1 stations;
2) collisions;
3) channel idleness when station i is in the backoff stage(s)

T_{s_i} is the successful transmission time of user i's each packet. In the steady state, during the tagged user i's service time $1/\mu_i$, on the average, the remaining stations successfully transmit $(1/\mu_i)\sum_{j=0,j\neq i}^{N-1}\lambda_j$ packets, which contribute to $(1/\mu_i)\sum_{j=0,j\neq i}^{N-1}\lambda_j T_{s_j}$ time slots. Before the stations successfully transmit the packets, the total amount of collision time that each station experiences is $(1/\mu_i)\sum_{j=0,j\neq i}^{N-1}\lambda_j \bar{T_{c_j}} + \bar{T_{c_i}}$. Because a collision is assumed to occur due to simultaneous transmission by two stations, the duration for the channel to be busy due to collision equals half of the total amount of collision time experienced by all stations, which is $(1/2)\left((1/mu_i)\sum_{j=0,j\neq i}\lambda_j \bar{T_{c_j}} + \bar{T_{c_i}}\right)$. Finally, station i spends $\bar{w_i}$ in the backoff stage before it successfully transmits the current packet. Therefore, we have

$$\begin{aligned}\frac{1}{\mu_i} &= T_{s_i} + \frac{1}{\mu_i}\sum_{j=0,j\neq i}^{N-1}\lambda_j T_{s_j} \\ &\quad \frac{1}{2}\left(\frac{1}{\mu_i}\sum_{j=0,j\neq i}^{N-1}\lambda_j \bar{T_{c_j}}\right) + \bar{w_i} \qquad (5)\end{aligned}$$

where $i = 0, 1, \cdots, N-1$

T_{s_i} and T_{c_i} can be obtained given the packet transmission duration of user i. In our results, we assume $T_{s_i} = T_{c_i}$. For N number of users, from known $1/\mu_i$, there will be N number of equations which are functions of $\lambda_0, \lambda_1, \cdots, \lambda_{N-1}$. Soving these N equations, N number of unknown variables $\lambda_0, \lambda_1, \cdots, \lambda_{N-1}$ can easily be obtained. Eventually we obtaine $\rho_0, \rho_1, \cdots, \rho_{N-1}$ for N users. Detailed derivation of all equations can be obtained in [**?**].

If the throughput of user i is denoted by ζ_i, it can be written by in terms of service time $1/\mu_i$. If the data length of primary user is L^p_{DATA} units, throughput of user i can be obtained by,

$$\zeta_p^i = L^p_{DATA}\mu_i \qquad (6)$$

D. Secondary user Model

Once we know $\rho_0, \rho_1, \cdots, \rho_{N-1}$ for N primary users, we can compute the probability that no primary user has packet in a particular slot. If this probability is denoted by p_I, we have

$$p_I = \prod_{i=0}^{N-1}(1-\rho_i)$$

Therefore, probability that at least one user is not idle is $1 - p_I$. Average number of idle slots before at least one user not being idle is geometrically distributed random variable and denoted by T_I. So we have,

$$T_I = \frac{p_I}{1-p_I}$$

As per our proposed strategy, after each primary user's successful transmission, secondary AP can use a certain number slots for its own traffic transmission. However, due to statistical unpredictability of DCF protocol, we cannot deterministically use average number of all idle slots for the secondary AP while affecting the primary user negligibly. For any duration of transmission after each primary user's successful transmission affects service time of frames transmitted by all primary users. If the transmission duration of secondary AP is χ, it contributes $(1/\mu_i)\sum_{j=0,j\neq i}^{N-1}\lambda_j\chi$ time slots to user i's service time, $1/\mu_i$. Upon the existence of secondary AP with our strategy, service time user i turns to

$$\begin{aligned}\frac{1}{\mu_i} &= T_{s_i} + \frac{1}{\mu_i}\sum_{j=0,j\neq i}^{N-1}\lambda_j T_{s_j} \\ &\quad \frac{1}{2}\left(\frac{1}{\mu_i}\sum_{j=0,j\neq i}^{N-1}\lambda_j \bar{T_{c_j}}\right) + \bar{w_i} \\ &\quad \frac{1}{\mu_i}\sum_{j=0,j\neq i}^{N-2}\lambda_j\chi \qquad (7)\end{aligned}$$

where $i = 0, 1, \cdots, N-1$

As a result, throughput of all primary users are affected as well. In order to compute secondary AP's throughput, we tag one particular user which is i. During the duration of tagged ith user's service time including χ, total number of secondary AP's transmission is N with the duration of χ. If the duration χ corresponds to L^s_{DATA} length of data, throughput of secondary AP can be written as

$$\zeta_s = L^s_{DATA}\mu_i \qquad (8)$$

Duration of secondary AP's transmission is variable and exact duration depends on each primary user i performance constraint. And, its an optimization problem. Secondary AP wants to achieve maximum throughput while affecting the primary users's performance at a certain level. If the affected throughput of user i's is $\zeta_p^{'i}$ after introducing the secondary AP in the network, optimization problem can be written as

$$\begin{aligned}&\arg\max_{\chi}\zeta_s \\ &s.t. \zeta_p^i - \zeta_p^{'i} <= \eta_i \quad i\in 0,\cdots,N-1 \qquad (9)\end{aligned}$$

Performance metric can be each primary user's packet drop probability. In our analysis, we do not consider packet loss event due to buffer overflow. Packet loss only happens if and only if each transmitted packet gets collided, retransmitted and

TABLE II
IEEE 802.11A PROTOCOL PARAMETERS

Channel Rate	54Mbps	SIFS	16 μs
Slot Time	9 μs	DIFS	34 μs
CW_{min}	16	CW_{max}	1024
Retry Limit	7	PLCP Preamble	24 μs
MAC Header	5 μs	payload	(payload*8/54)μs
ACK PLCP	192 μs	ACK Frame	2.1 μs

finally dropped because of exceeding the retry limit in the MAC layer. If the packet collision probability of user i is p_i, packet drop probability can be written by p_i^m. Therefore, considering the packet drop probability as a metric, optimization problem turns to

$$\begin{aligned} &\arg\max_{\chi} \zeta_s \\ s.t. p_i^m &<= \eta_i \quad i \in 0, \cdots, N-1 \end{aligned} \tag{10}$$

V. PERFORMANCE EVALUATION OF OPPORTUNISTIC SPECTRUM ACCESS

In order to justify our proposed policy for the secondary user with the traditional scheme, we consider, WLAN has employed IEEE 802.11a operating mode. We compare the performance of secondary AP with the case when it follows regular DCF protocol for channel access. Next subsection demonstrates the parameters and scenario we follow and the following subsection is for the numerical results to compare performance.

A. System Parameters

The parameters of IEEE 802.11a protocol mode have been described in table I. we assume secondary AP has always traffic to transmit and it can fragments its traffic depending on the available time slots it obtain for transmission. All primary users have same traffic arrival statistics.

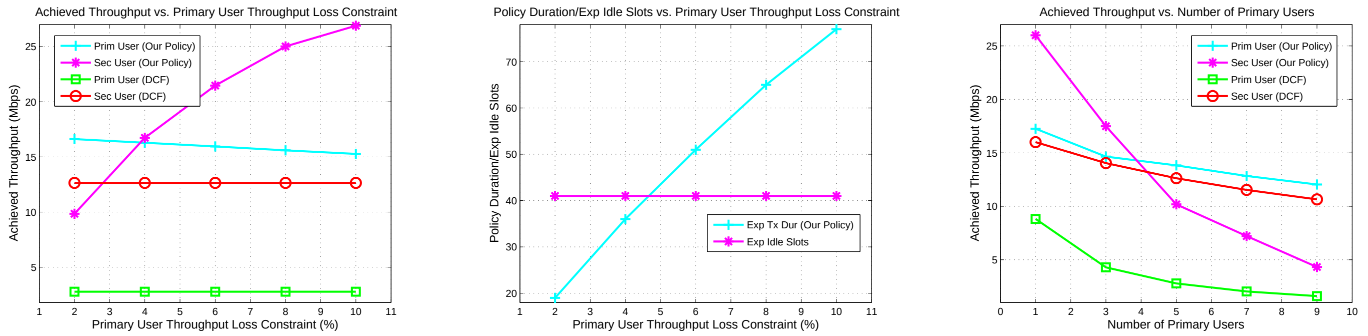
B. Numerical Results

First, we want to show results relevant to the constraint, i.e. maximum fraction of throughput loss by each primary user. In figures 9(a) and 9(b), the throughput and secondary source's transmission duration are depicted as a function of throughput loss constraint η. In the figure 9(b), we also show expected idle duration when secondary AP is silent. When the secondary AP is silent, throughput achieved by primary source is 16.94 Mbps (maximum). For the sake of clearness, we have skipped this curve. A larger throughput loss constraint allows the secondary AP transmits longer duration of time after each primary source has finished its successful transmission. Therefore, we see the increasing transmission duration (policy) with the increasing throughput loss constraint. Increasing transmission duration of secondary AP causes longer service time for each packet and thus it increases the collision probability among primary sources. Through this chain of inter-dependency, service time is increased again and throughput of each primary source is gradually decreased. Scenario we have used in these figures is pretty much unsaturated case for each primary user. Expected number of idle slots is high and shown in figure19(b). Even with this unsaturated case, when secondary AP follows DCF protocol to access channel, throughput achieved by each primary source is very low compared to our policy. With only 10% throughput loss constraint, by our policy throughput achieved by the secondary AP is higher than by traditional DCF protocol. Traditional DCF protocol has protocol overhead which occupies more than 30% of air time and also because of regular interaction with primary sources, collision probability is much higher than the case of our policy.

Figure 9(c) depicts decreasing throughput with increasing number of primary users n. Increasing number of users mean more packets occupy air time and thus secondary AP gets decreasing number idle slots for its own transmission and thus throughput is reduced as well. When number of user is 1, there is no collision (and throughput loss as well) for this user if the secondary AP follows our policy. Therefore, secondary AP uses all idle slots left by the primary user after each its transmission. By this time, if any packet comes for this user, it just waits for initiating its backoff procedure until the secondary AP finishes its transmission. While meeting each primary user's throughput loss constraint, secondary AP achieves higher throughput for $n <= 3$ than when it follows DCF protocol. With DCF protocol, primary user's performance is not protected at all, whereas our policy for secondary AP does so. All these observation have been reflected in the figure.

A larger λ means primary source is accessing the channel more often. Therefore, the number of slots in which the secondary source can transmit while meeting the constraint on throughput loss of the primary sources decreases. Because of space limit, we have not shown expected idle period when secondary AP is not in action however throughput for this scenario has been demonstrated in figure 9(d). Decreased idle slots lead to less number transmission slots used by secondary AP and thus throughput is gradually decreased with increasing λ. We also see decreasing throughput for secondary AP/primary user when they all are in DCF mode. However, the decrementing behavior is not that acute. This is because of the unsaturated traffic of primary users. Even the highest $lambda$ is unsaturated for each primary user and number of primary users acting in the network is also less. Therefore, even though ρ gets increased with increasing λ, collision probability remain almost same as the secondary AP has always traffic to send and thus service time of each packet for primary users/secondary AP does not vary that much and so does the throughput. However, when secondary APfollows our policy, with $<= 0.000608$ λ, it achieves higher throughput than the former. And each primary user's throughput is much better than the other one because of having less collision throughout each packet's service time.

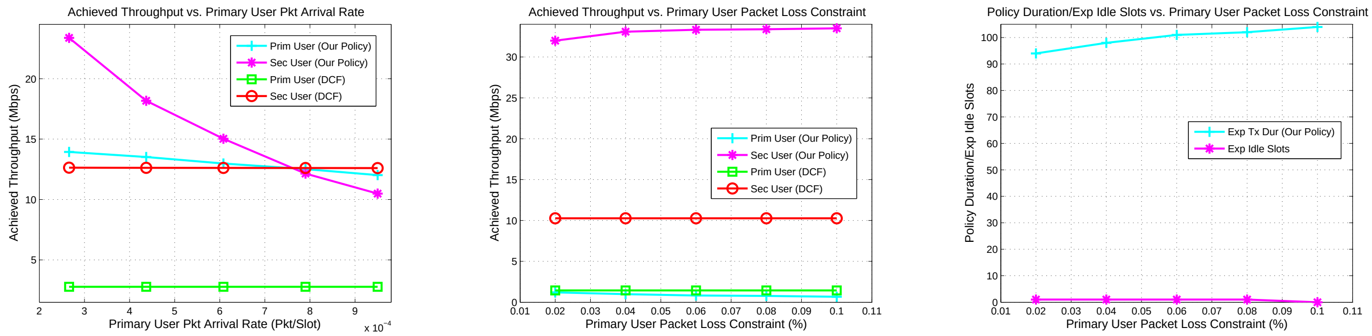
All the scenarios, we have described above is mostly unsaturated network for primary users. Now we would like to discuss a bit about more congested primary user network having some packet loss constraint. Figure 9(e) depicts throughput achieved by both kind of users with the increasing packet



(a) Achieved Throughput (Mbps) vs. Primary User's Throughput Loss Constraint (%) for $\lambda = 0.000095$ and $n = 5$

(b) Policy Duration/Exp Idle Slots vs. Primary User's Throughput Loss Constraint (%) for $\lambda = 0.000095$ and $n = 5$

(c) Achieved Throughput (Mbps) vs. Number of Primary Users (n) for $\lambda = 0.000608$ and $\gamma = 0.1$



(d) Achieved Throughput (Mbps) vs. Primary User's Packet Arrival Rate (Pkts/Slot) for $n = 5$ and $\eta = 0.15$

(e) Secondary User Throughput (Mbps) vs. Primary User's Packet Loss Constraint (%) for $\lambda = 0.000608$ and $n = 10$

(f) Policy Duration/Exp Idle Slots vs. Primary User's Packet Loss Constraint (%) for $\lambda = 0.000608$ and $n = 10$

Fig. 9. Comparison Between Our Policy and DCF Protocol used by Secondary AP

loss constraint. Policy for this scenario is in the figure 9(f). Packet loss happens on the ISM band when the retransmitted packet exceeds its retry limit and its very harmful for QoS aware multimedia traffic. Expected number of idle slots is close to zero when secondary AP keeps silent. Meeting the packet loss constraint, with our policy, secondary AP can use larger number of time slots, has slightly incresing trend with incresing packet loss constraint. Thus throughput achieved by secondary AP following our policy is much higher in all cases than DCF protocol being followed. However, because of larger number of slots being used for its transmission, service time of each primary user's packet is much larger and primary user's throughput is degraded much more badly than the other case (DCF).

C. *Comparison with Experimental Results*

In order to fit the experimental results with our analytical model, we have taken one particular flow statistic is below in table II. This flow does not have any concurrent flow. Actually the average inter-arrival time is the representative of $\frac{1}{\rho_i \tau_i}$ and average utilization is $T_{s_i} = T_{c_i}$ in our analytical model. Given these value, from the set of equations derived in above subsection, we can easily derive payload arrival rate λ_i, probability that one payload is in queue or in service ρ_i etc. Once we know ρ_i, we can easily get average idle time p_I and cognitive radio can access the channel $\frac{1}{p_I} 20\mu s$ duration of time just after the interferer finishes its successful each payload transmission. Since, in our results, the flow length is not that big, statistics obtained from one single flow is not that meaningful and may not be actual statistics. However, this is the way, a single CORAL terminal can opportunistically accesses one channel.

TABLE III
FLOW STATISTICS OF ONE SINGLE FLOWS HAVING NO CONCURRENT FLOW

Start Time	1314977101 sec, 592920 μs
End Time	1314977101 sec, 993788 μs
Duration	400868 ms
Avg Inter-arrival Time	20063 μs
Avg Utilization	2888

Figure 10 is probability distribution comparison between one actual flow's (e) exact payload inter-arrival time and model extracted inter-arrival time. Model is developed based on average inter-arrival which is the mean $\frac{1}{\rho_i \tau_i}$ of all inter-arrival times for that particular flow. Due to data insuffiency, we see a huge difference between these two distribution.

D. *Model Extension*

As mentioned, we have shown results for the secondary network on ISM band when there is only one secondary user.

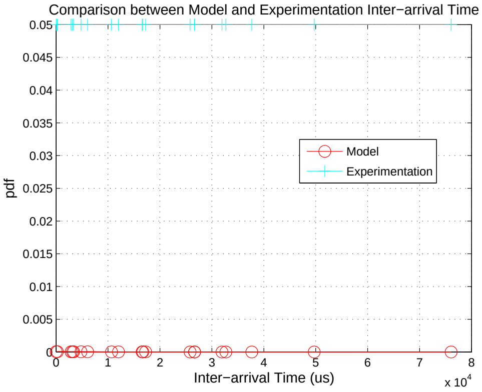


Fig. 10. Comparison between Model and Experimentation Inter-arrival Time

On having a number of secondary users, there are two options to divide the extracted spectrum hole among them. One is TDMA which needs a control channel for coordinating all secondary users to access the channel. Another one is, after obtaining the spectrum hole, all secondary users use that time duration through low overhead DCF protocol. This does not need any control channel. Simulation model for this design is almost ready and we will show results in the next version of report.

VI. PREDICTION USING NEURAL NETWORK

We employ Multi-layer Feedforward Neural Networks (MFNNs) for designing traffic prediction models as multiple layers of neurons with non-linear transfer functions allow us to learn the linear and non-linear relationships between inputs and outputs. Specifically, we used 2/5-layers feedforward back-propagation networks with multiple hidden layer and one output layer. In order to make the predictions accurate, ideally we should take more inputs in order to find out traffic statistics in one particular interval. Input should be:

1) DayofWeek: ranging from 1 (Monday) to 7 (Sunday).
2) HourOfDay: ranging from 1 to 24.
3) MinuteofHour: ranging from 0 to 59
4) Traffic statistics of previous minute (Data rate or payload inter-arrival time)

Input could be more granular (second of minute, previous second's statistics), however neural network may not get any patter from the data, if the input becomes so granular. Variations in channel availability continue at finer time scales, meaning cognitive radio cannot simply improve performance by working at finer time scales. Our data is not complete either because of the reasons discussed above. Also, we have only one day data of duration around 5 hours. Therefore we cannot first use two inputs in our neural network model. We have only used last two inputs for the prediction model. We use inputs to predict mean value of future traffic load (Data rate and payload inter-arrival time) over next one minute interval. We made use of MATLAB neural network toolbox to implement traffic prediction. The training is done by using Levenberg-Marquardt algorithm and the maximum number of epochs is set at 11. Predictions have been discussed in the following two subsections.

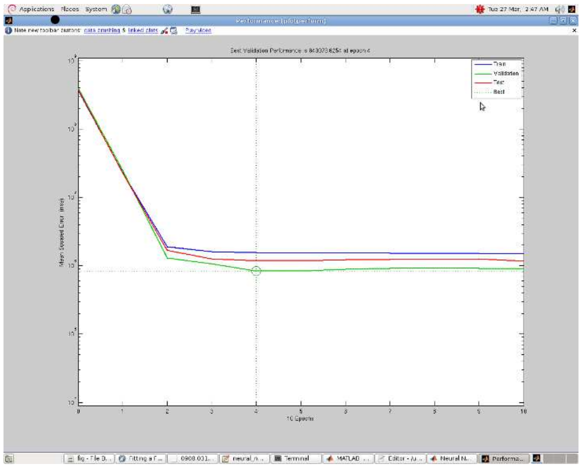


Fig. 11. Mean Square Error vs. Epoch

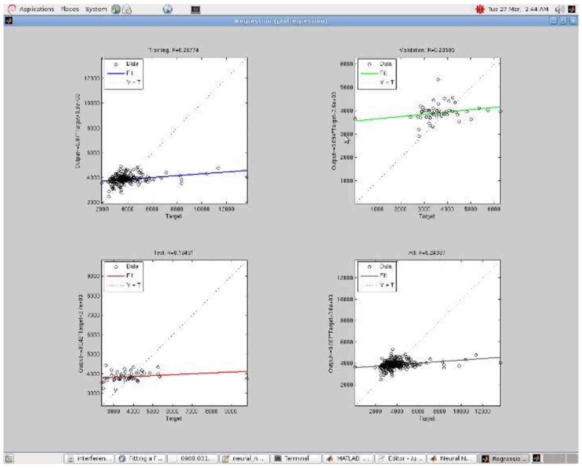


Fig. 12. Output vs. Target

1) Data Rate prediction: In the first experiment, we have used 2-layers feed-forward neural network considering input as minute and previous minute's data rate. Figure 11 shows peformance plot (mean square error) with the increasing epoch. We see training, test and validation error all go really down at 2nd epoch. we have used 70% data for training, 15% for validation and 15% for test. We also have plot regression plot 12 for training, validation and test data. Regression is the correlation between fitted output and target data. It ranges between 0 and 1. The higher the regression value, the better model is more fitted.

With the same experimentaion setup, figure 13 compares fitted model output with the actual data. we see a big gap. This might be the lack of data or missing data.

As described, we do not obtain actual flow statistics from the 16-terminal data and collected data is very limited, only

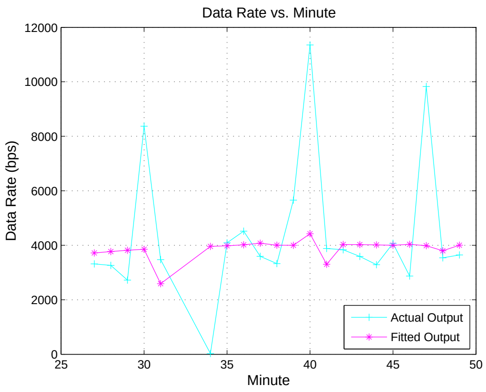


Fig. 13. Data Rate vs. Minute

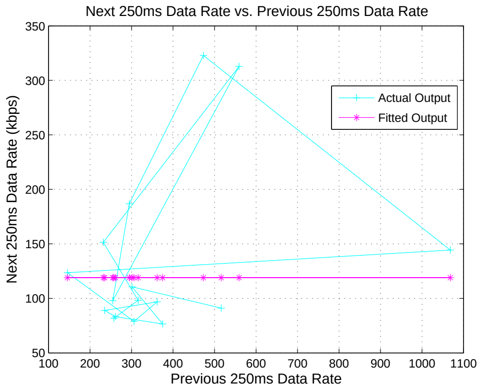


Fig. 14. Next 250ms Data Rate vs. Previous 250ms Data Rate using Multi-layer Neural Network

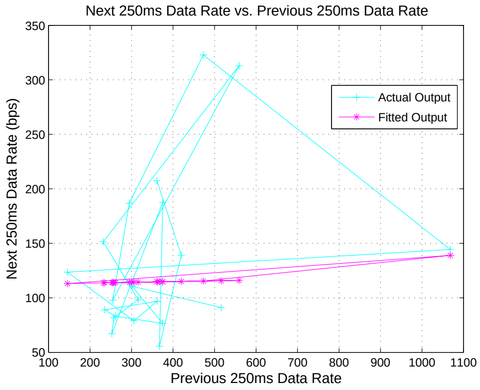


Fig. 15. Next 250ms Data Rate vs. Previous 250ms Data Rate using 2 Layer Neural Network

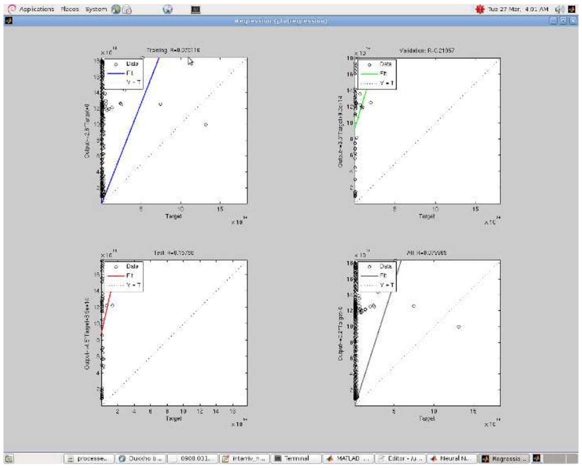


Fig. 16. Output vs. Target

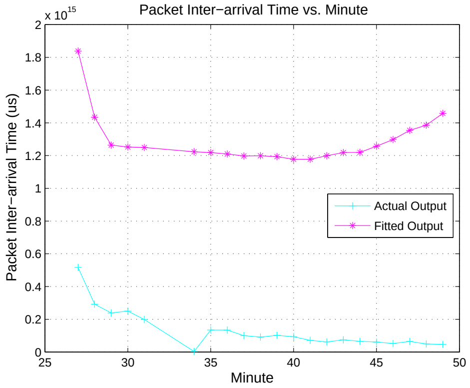


Fig. 17. Payload Inter-arrival Time vs. Minute

for around 5 hours. In order to make the neural network work for proper prediction, we need constant traffic statistics for a few weeks. Also, we have only meaningful consecutive data for 500ms, after that there is a silent period for around 4.5s on each channel. Considering this, our second experimentation's input is previous 250ms data statistics, whereas the output is just next 250ms statistics. Figures 14 and 15 are the prediction results in terms of bitrate when there are 5 and 2 layers respectively. These results are even more worse than the minute level prediction.

2) *Payload Inter-arrival Time Prediction:* In order to predict payload average inter-arrival time of the next the minute from the previous minute's average inter-arrival time, we plot figure 17. Prediction is not that accurate again for missing data. Figure 16 is the regression plot for this prediction.

Similar to bitrate prediction, we also have prediction results in terms of payload inter-arrival time for next 250ms interval based on previous 250ms interval. Figures 18 and 19 are reflections of these results when there are 5 and 2 layers in the network. In this case, inter-arrival time prediction is much more improved than bitrate prediction.

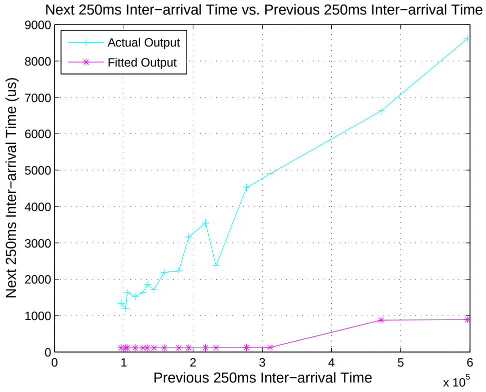


Fig. 18. Next 250ms Inter-arrival Time vs. Previous 250ms Inter-arrival Time using Multi-layer Neural Network

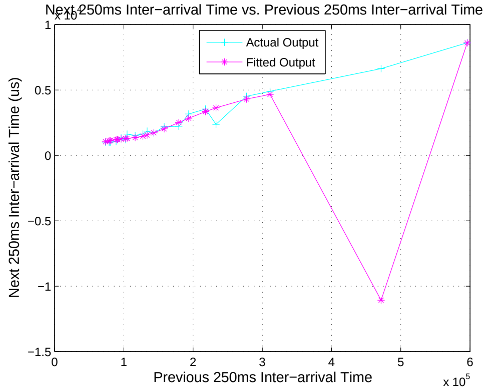


Fig. 19. Next 250ms Inter-arrival Time vs. Previous 250ms Inter-arrival Time using 2 Layer Neural Network

VII. CONCLUSION

In this work, we have done analysis on the data set collected by CORAL platform. In order to make use of this data for the purpose of cognition, in the second part of the paper, we have proposed a novel opportunistic channels access scheme. By using some fictious data, we have justified the validity of this model. Later on, we have proved that model is workable for real data collected by CORAL platform. As neural network is very effective tool for finding the non-linear relationship between inputs and output, in the last part of this paper, we have done prediction in terms of bitrate and payload inter-arrival time using multi-layer feedforward neural network. Results obtained by this tool is not that promising and we hope to work on this further for better prediction.

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