DISTRIBUTED DYNAMIC CHANNEL ALLOCATION USING GAME THEORY FOR BROADBAND FIXED WIRELESS ACCESS

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ABSTRACT

This paper investigates Dynamic Channel Allocation (DCA) methods for a Broadband Fixed Wireless Access (BFWA) network. Least Interfered (LI) and Random Channel Allocation (RND) are two existing DCA methods, originally used for voice traffic are implemented for a BFWA network that supports data traffic. A DCA method using a Game Theory inspired mixed strategy is proposed and the performance of this DCA method (GT) is compared with LI and RND.

I. INTRODUCTION

Broadband Fixed Wireless Access (BFWA) can be deployed rapidly and easily from scratch as compared to wireline especially in situations where cable cannot be easily or quickly installed. The spectrum allocated for a BFWA system is limited and is usually divided into channels. In order to cover a large geographical area, these channels are reused in different cells. Channel reuse causes co-channel and adjacent channel interference, which will degrade the Signal to Noise Ratio (SNR) of received packets and from Shanon's Capacity Theorem, a decrease in SNR in a fixed bandwidth will decrease the capacity of the system. These interferences are reduced by employing channel allocation. Fixed Channel Allocation (FCA) [2], [3] – where a channel is permanently allocated to a cell – can be time consuming and may need to be revised when cells are added or removed. Dynamic Channel Allocation (DCA) can reduce this task by allocating channels to cells dynamically during operation and is capable of adapting to the interference environment if new cells are added. DCA is also important if the BFWA system is operated in an unlicensed band.

The channel allocation methods can be centralised or distributed. In a centralised method, the base stations need to communicate with a central controller (e.g. base station controller or a switch) in order to allocate a channel. The higher the number of base stations required by a central controller, the greater the amount of signalling required and this may introduce delay into the network. In a centralised method, the base stations know the channel usage of their neighbours. In a distributed method, each base station selects a channel on its own and independent of the other base stations and hence the base stations are unaware of the channel usage of their neighbours. The base stations or subscriber units may take measurements (e.g. interference power, SNR) to evaluate the interference environment before making a channel allocation decision. These methods are categorised into a Channel Allocation Matrix shown in Fig. 1, with citations to each method.

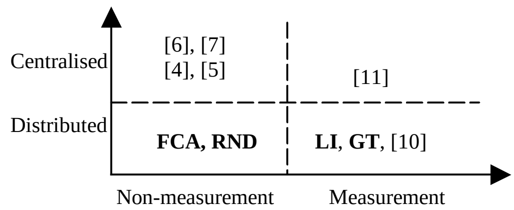

Fig. 1. Channel Allocation Matrix

Most of the proposed channel allocation methods are used for voice traffic employing circuit switching, where channel allocation is employed to reduce the probability of call blocking and call dropping. In this paper, we will look at employing DCA in a BFWA network supporting data traffic. In a voice service, if the SNR is sufficient to support a call, any increase in the SNR does not add value to the call. In contrast, an improvement in SNR for a data service increases the capacity of the system as a higher data rate can be supported. Hence, the aim of DCA in a data network is different to that for voice traffic. The DCA methods examined in this paper fall into the distributed region of the Channel Allocation Matrix.

The paper is arranged as follows: Section II gives the system description of the BFWA network used for simulation in this paper. Section III describes the application of Game Theory in DCA and introduces a payoff function. Section IV describes two existing DCA methods namely the Least Interfered (LI) and Random Channel Allocation (RND) and proposes a new method using Game Theory (GT). Section V describes the simulation and the results and Section VI gives the conclusion.

II. SYSTEM DESCRIPTION

The basic BFWA network components are the Access Point (AP), the Subscriber Unit (SU) and the Control Server. These components are illustrated in Fig. 2. The SU is mounted on the subscriber's site and uses a directional antenna to communicate with its corresponding AP. An AP uses a sectored antenna to communicate with the SUs covered by it. Several APs can be connected to a Control Server where management and authentication are provided.

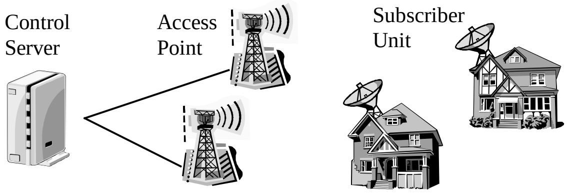

Fig. 2. BFWA components.

The BFWA network in this paper uses asymmetric time division duplexing (TDD) and the APs operate in an asynchronous manner. In this BFWA network, an AP and SU may interfere with each other. There are 15 available channels where the bandwidth of each channel is 15 MHz. Each AP occupies a channel and the SUs gain access to their AP by using a packet reservation multiple access (PRMA) protocol [1]. A single Medium Access Control (MAC) frame is shown in Fig. 3.

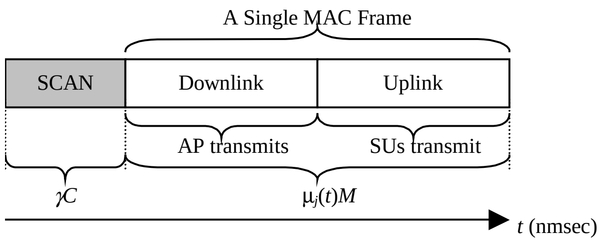

Fig. 3. A single MAC frame.

The AP broadcasts its messages to its SUs using the Downlink portion of the MAC frame and the SUs transmit to the AP using the Uplink portion of the MAC frame. The length of the transmitting (downlink and uplink) portion varies according to traffic load with a maximum frame size of M normalised seconds (nmsec). A normalised second is the time required by an AP or a SU to transmit a data packet, which is an ATM cell in this paper. The Downlink and Uplink portions of the MAC frame last for $\mu_j(t)M$ nmsec, where $\mu_j(t)$ is a measure of traffic load (both downlink and uplink) for AP j at time t as a fraction of M. The SCAN portion at the beginning of the MAC frame is used by the AP to measure the interference power of C available frequency channels with a scan time of γ nmsec per channel.

III. PAYOFF FUNCTION

In Game Theory [12], the independent choices made by every individual within a group affect the outcome of the entire group. This interdependency characteristic is present in a distributed DCA scheme where the channels selected by each AP independently of each other change the interference environment, which will in turn affect the SNR performance of each AP. Each individual (or AP) within a group will receive a payoff as a result of the choice that it has made. It is assumed that each individual is rational and hence will tend to select the strategy (or choice) that will give it the highest payoff.

The AP selects a channel based on the measured interference power during the SCAN portion and the DCA method used. The selected channel will be used for F MAC frames before executing another SCAN. The time between two SCANs is $T_j(t) = \mu_j(t)MF$ for AP j. The set of strategies $\mathbf{S}$ is defined as the number of MAC frames, F and can be represented as:

$$\mathbf{S} = \{F \in \mathbf{I} \mid 0 < F < \infty\} \tag{1}$$

Where $\mathbf{I}$ is the set of integer numbers.

For a pair of APs, the payoff function $\pi_{j,k}(t)$ for AP j at time t is defined as the number of packets transmitted (and received) that are interference free from AP k per nmsec and is expressed as:

$$\pi_{j,k}(t) = \mathrm{G}_j(t)\big((1 - \mathrm{P_I}(t))\mathrm{O}_{j,k}(t) + \mathrm{S}_{j,k}(t)\big) \tag{2}$$

Where $\mathrm{G}_j(t)$ is the packet throughput for AP j defined as the percentage of time a packet is transmitted or received. $\mathrm{G}_j(t)$ is expressed as:

$$\mathrm{G}_j(t) = \frac{\mathrm{T}_j(t)}{\gamma C + \mathrm{T}_j(t)} \tag{3}$$

$\mathrm{P_I}(t)$ is the probability that AP j and AP k use the same channel and it is dependent upon the DCA method used. $\mathrm{O}_{j,k}(t)$ is the average fraction of $\mathrm{T}_j(t)$ that would coincide with $\mathrm{T}_k(t)$ and $\mathrm{S}_{j,k}(t)$ is the average fraction of $\mathrm{T}_j(t)$ that coincides with the SCAN portion of AP k. This is illustrated in Fig. 4 where $\mathrm{O}_{j,k}(t)$ and $\mathrm{S}_{j,k}(t)$ are proportional to the averages of $\mathrm{o}_j(t)$ and $\mathrm{s}_j(t)$ respectively.

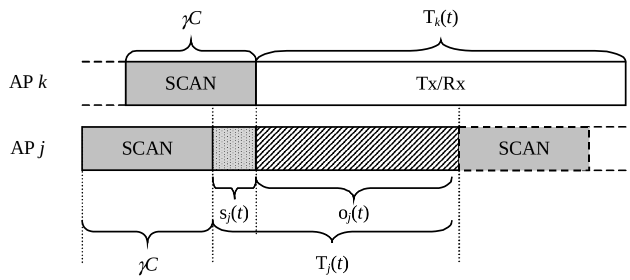

Fig. 4. Fraction of $\mathrm{T}_j(t)$ overlaps $\mathrm{T}_k(t)$ and SCAN portion of AP k.

The MAC frames for AP j and AP k can be represented as two rectangular functions $\mathrm{f}_j(t)$ and $\mathrm{f}_k(t)$ respectively as shown in Fig. 5. Since AP j and AP k are not synchronized, for constant $\mathrm{T}_j(t)$ and $\mathrm{T}_k(t)$ the value of $\mathrm{o}_j(t)$ and $\mathrm{s}_j(t)$ are a function of τ_0 as shown in Fig. 5.

The functions $o_j(\tau_0)$ and $s_j(\tau_0)$ are found by convolving $f_j(t)$ with $f_k(t)$ and the results are shown in Fig. 6.

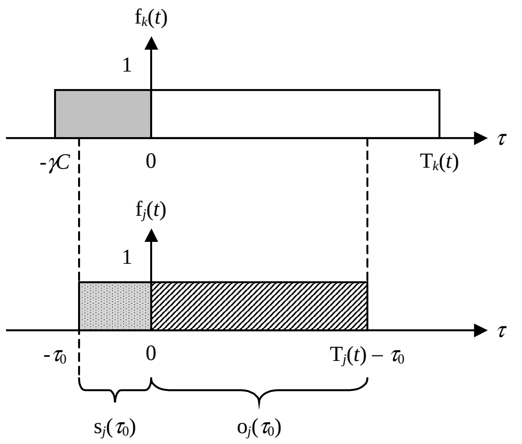

Fig. 5. Representation of MAC frames as unit step functions.

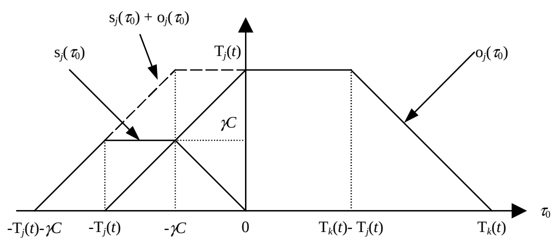

Fig. 6. Functions $o_j(\tau_0)$ and $s_j(\tau_0)$.

The average values of $o_j(\tau_0)$ and $s_j(\tau_0)$ expressed as a fraction of $T_j(t)$ gives $O_{j,k}(t)$ and $S_{j,k}(t)$ respectively and they are expressed as follows:

$$O_{j,k}(t) = \begin{cases} \dfrac{T_k(t)}{\gamma C + T_k(t) + T_j(t)} & , T_j(t) \leq \gamma C + T_k(t) \\ \dfrac{T_k(t)}{2(\gamma C + T_k(t))} & , T_j(t) > \gamma C + T_k(t) \end{cases} \quad (4)$$

$$S_{j,k}(t) = \begin{cases} \dfrac{\gamma C}{\gamma C + T_k(t) + T_j(t)} & , T_j(t) \leq \gamma C + T_k(t) \\ \dfrac{\gamma C}{2(\gamma C + T_k(t))} & , T_j(t) > \gamma C + T_k(t) \end{cases} \quad (5)$$

Where for the case when $T_j(t) > \gamma C + T_k(t)$, $T_k(t)$ is assumed to be constant for the duration of $T_j(t)$.

IV. DCA METHODS

DCA methods described in this section are RND, LI and GT.

A. Random Channel Assignment (RND)

In RND [10] each AP randomly selects a channel at the start of every MAC frame (i.e. F=1) without any interference measurements (i.e. γ= 0). The channels are selected based on a uniform distribution and hence each of the C channels has an equal probability of being selected. The probability $P_I(t)$ for RND namely, $P_{I\_RND}(t)$ is:

$$P_{I\_RND}(t) = \frac{1}{C} \quad (6)$$

B. Least Interfered Method (LI)

In LI [8], the AP scans all available channels and selects the channel with the lowest interference power. If more than one channel shares the same lowest interference power, the channel used previously will be selected and if none were used previously, the channel with the lowest number is selected. The selected channel is used for F frames before the next scan and channel selection.

For a pair of AP (e.g. AP j and AP k) the probability $D(t)$ of either one or both APs detect the channel usage of the other AP is:

$$D(t) = \frac{\gamma C (T_j(t) + T_k(t))}{(\gamma C + T_j(t))(\gamma C + T_k(t))} \quad (7)$$

Hence, the probability $P_I(t)$ for LI namely $P_{I\_LI}(t)$) is:

$$P_{I\_LI}(t) = \frac{(1 - D(t))}{C} + \frac{D(t)}{C^2} \quad (8)$$

In (8), when an AP fails to detect the channel usage of the other AP, both APs have a probability of $1/C$ of using the same channel. Similarly, if one of the APs detects the channel usage of the other AP, they both have a probability of approximately $1/C^2$ of using the same channel, which is also the lowest interfered channel.

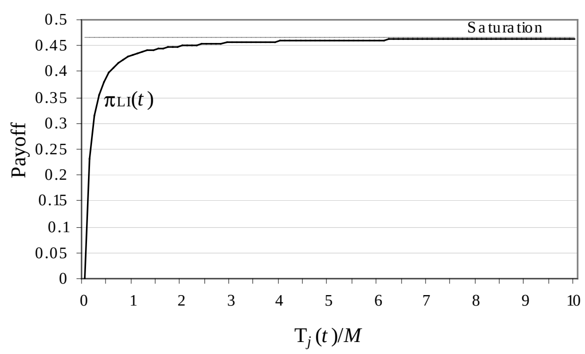

Fig. 7. Payoff for LI.

Fig. 7 shows that the payoff for LI saturates when $T_j(t)/M > 2$. Higher $T_j(t)/M$ ratios cause the system to react slowly to changes and the gain in payoff is not significant.

The probability $Q_X(t)$ of exactly X APs out of A APs in the network using the same channel is (assuming $T_j(t)$ and $T_k(t)$ are the same):

$$Q_X(t) = \frac{A!}{X!(A-X)!} P_{I\_LI}(t)^X \left(1 - P_{I\_LI}(t)\right)^{A-X} \qquad (9)$$

The probability $P_X(t)$ of X or less APs using the same channel as AP j is:

$$P_X(t) = \sum_{k=1}^{X} Q_k(t) \qquad (10)$$

Fig. 8 shows that (1 - $P_X(t)$) saturates for $T_j(t)/M > 2$. The interference is minimised for small ratios of $T_j(t)/M$ but will give a smaller payoff as shown in Fig. 7. In LI, the AP will select $F \in \mathbf{S}$ such that $T_j(t)/M = 2$.

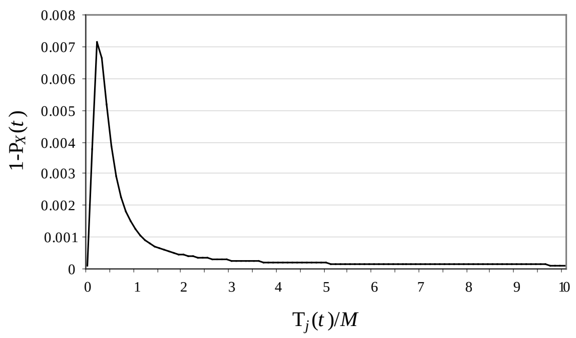

Fig. 8. Plot of (1-$P_X(t)$) against $T_j(t)/M$ for X=100 and A=136.

C. DCA using Game Theory (GT)

In GT the AP scans all available channels during the SCAN portion and selects the channel with the lowest interference power. The channel selection method is similar to LI and hence the probability $P_I(t)$ for GT namely $P_{I\_GT}(t)$ is the same as $P_{I\_LI}(t)$ as given in equation (8). However, in GT, the AP aims to achieve a high payoff – defined in (2) – whereas in LI, the AP aims to achieve a low interference. The channels in GT are randomly ordered to encourage usage of different channels. In GT, the selected channel is used for F MAC frames such that $T_j(t)$ has a value of T_{XL} nmsec with probability p and a value T_{XT} nmsec with probability (1-p) where $T_{XT} > T_{XL}$. The derivation for p, T_{XL} and T_{XT} are described in this section.

Fig. 9 is a plot of payoff functions $\pi_{j,k}(t)$ and $\pi_{k,j}(t)$ for AP j and AP k respectively where $T_k(t)$ is constant. The payoff for both APs is the same (i.e. $\pi_{j,k}(t)$ and $\pi_{k,j}(t) = \pi^*(t)$) when $T_j(t) = T_k(t)$. There is a peak payoff $\pi_{j,k}(t)=\pi_{Pj}(t)$ for AP j when $T_j(t) < T_k(t)$. Hence, if $T_k(t)$ is constant, AP j will tend to have $T_j(t) < T_k(t)$ to obtain the peak payoff $\pi_{Pj}(t)$. This peak payoff is reached at the expense of AP k's payoff (i.e. AP k has a lower payoff – less than $\pi^*(t)$). For every fixed value of $T_k(t)=T_{XT}$, the value of $T_j(t)=T_{XL}$ such that $\pi_{j,k}(t)=\pi_{Pj}(t)$ can be found by optimising (2), where $\pi_{k,j}(t) < \pi^*(t) < \pi_{Pj}(t)$. However, both APs will try to obtain a higher payoff and neither will want to stay at the point where its payoff is small.

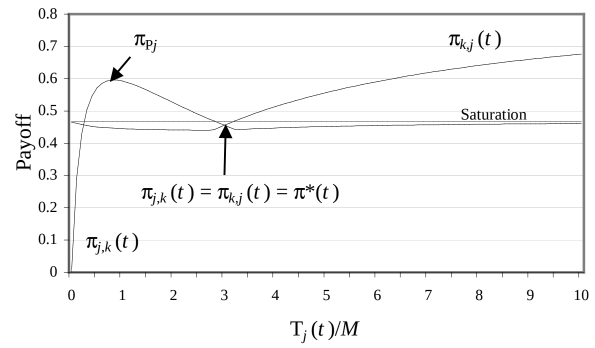

Fig. 9. Payoff function for constant $T_k(t)/M = 3$.

A mixed strategy [12] is used so that both APs take turns to reap the peak payoff. For one set of T_{XL} and T_{XT}, each AP can play two strategies s_1 and s_2, where in strategy s_1 an AP will select $F \in \mathbf{S}$ such that its $T_j(t)$ (or $T_k(t)$) is T_{XL} and in strategy s_2 an AP will select $F \in \mathbf{S}$ such that $T_j(t)$ (or $T_k(t)$) is T_{XT}.

In strategy s_1 an AP would measure the interference power *exploring* the possible usage of different channels. While in s_2, an AP would spend more time *exploiting* the channel that it has selected. The amount of channel exploration and exploitation is determined by the probability p.

The combination of strategies and the respective payoffs for each AP are summarised in the strategic form of the game shown in TABLE I.

TABLE I
STRATEGIC FORM OF THE GAME

		AP k			
		s_1		s_2	
AP j	s_1	$U_{j,k}(s_1,s_1)$	$U_{k,j}(s_1,s_1)$	$U_{j,k}(s_1,s_2)$	$U_{k,j}(s_2,s_1)$
	s_2	$U_{j,k}(s_2,s_1)$	$U_{k,j}(s_1,s_2)$	$U_{j,k}(s_2,s_2)$	$U_{k,j}(s_2,s_2)$

The function $U_{j,k}(x, y)$ is the payoff for AP j when AP j plays strategy x and AP k plays strategy y (x, $y \in \{s_1, s_2\}$). Similarly the function $U_{k,j}(x, y)$ is the payoff for AP k when AP k plays strategy x and AP j plays strategy y. The payoff assumes the APs select their strategies simultaneously and independent of each other.

In a mixed strategy, an AP plays strategy s_1 with probability p and plays strategy s_2 with probability (1-

p). If both APs follow this rule, the payoff π_{MIX} obtained by both APs playing the mixed strategy is thus:

$$\pi_{\text{MIX}} = p^2\,\mathrm{U}(s_1,s_1) + p(1-p)\mathrm{U}(s_1,s_2) + (1-p)p\,\mathrm{U}(s_2,s_1) + (1-p)^2\,\mathrm{U}(s_2,s_2) \tag{11}$$

Where, $\mathrm{U}(s_1, s_1) = \mathrm{U}_{j,k}(s_1, s_1) = \mathrm{U}_{k,j}(s_1, s_1)$, $\mathrm{U}(s_2, s_2) = \mathrm{U}_{j,k}(s_2, s_2) = \mathrm{U}_{k,j}(s_2, s_2)$, $\mathrm{U}(s_1, s_2) = \mathrm{U}_{j,k}(s_1, s_2) = \mathrm{U}_{k,j}(s_1, s_2)$ and $\mathrm{U}(s_2, s_1) = \mathrm{U}_{j,k}(s_2, s_1) = \mathrm{U}_{k,j}(s_2, s_1)$. Optimising (11) to find the probability p that maximises π_{MIX} leads to:

$$p = \frac{2\,\mathrm{U}(s_2,s_2) - \mathrm{U}(s_1,s_2) - \mathrm{U}(s_2,s_1)}{2(\mathrm{U}(s_1,s_1) + \mathrm{U}(s_2,s_2) - \mathrm{U}(s_1,s_2) - \mathrm{U}(s_2,s_1))} \tag{12}$$

V. SIMULATION AND RESULTS

The three DCA methods (RND, LI and GT) are simulated using OPNET Modeler. A scenario with 37 cells is used with the layout shown in Fig. 10, where each cell has a radius of 0.5 km. The simulation has 136 APs where each cell has from 2 to 12 APs giving a non-uniform traffic distribution. Boundary effects are reduced using this layout and measurements taken from the indexed cells shown shaded in Fig. 10. A total of 669 SUs are distributed randomly in the layout.

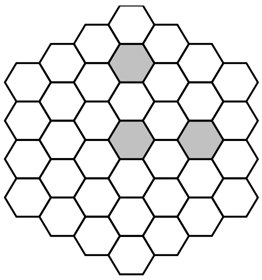

Fig. 10. Simulation layout

An ON-OFF model using a Pareto distribution is used to generate self-similar traffic typical of a packet data networks in both the AP and SU [13]. Pareto's probability distribution function is given by,

$$p(t \mid t > \beta) = \frac{\alpha\beta^{\alpha}}{t^{\alpha+1}} \tag{13}$$

With mean,

$$E[t] = \frac{\alpha\beta}{\alpha - 1} \tag{14}$$

Where β is the minimum OFF (or ON) period and $1 < \alpha < 2$. The values for α are 1.7 for ON-periods and 1.2 for the OFF-periods [13]. The value of β depends upon the data rate and average file size, which is assumed to be 13.9 kbytes for web browsing applications [10].

The radio propagation is assumed to follow the Random Height path loss model [14], which has a path-loss exponent of 2 for distances up to 1km and an exponent of 3.8 thereafter. The lognormal shadow standard deviation is 3.5 dB. Only co-channel interference and thermal noise are assumed in the simulation.

Fig. 11 is the received SNR in the downlink direction (the uplink yielding similar results). It can be seen that GT gives the best SNR performance followed by LI and lastly RND.

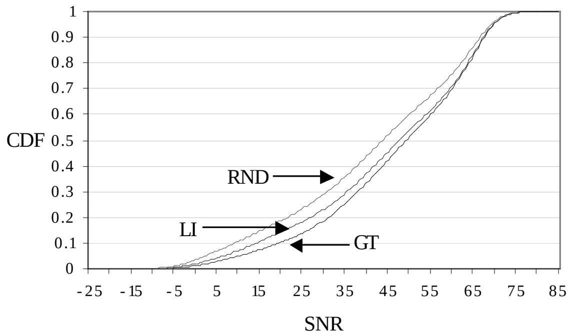

Fig. 11. CDF of received SNR in downlink.

The average payoff π_{AVG} is defined as the number of packets received successfully per nmsec. A packet is received (by an AP or SU) successfully if its received SNR is above 21 dB.

TABLE II
PAYOFF FOR AN AVERAGE AP

DCA	$P_{>21\text{dB}}$	G_{AVG}	π_{AVG}
RND	0.729	1.0	0.729
LI	0.836	0.931	0.778
GT	0.857	0.982	0.841

TABLE II lists the average payoff obtained by each DCA method. G_{AVG} is the average throughput for all the APs in the indexed cells and $P_{>21\text{dB}}$ is the average probability of a packet received in the indexed cell having a SNR above 21 dB. GT has the highest payoff compared to the other two DCA methods. RND falls in the non-measurement quadrant of the channel allocation matrix (Fig. 1) and hence it has the highest throughput. However, due to its poor SNR performance, its overall payoff is smaller than LI and GT.

Fig. 12 shows the channel usage as the average number of APs per channel. Since RND selects a channel randomly from a uniform distribution, the channels are efficiently utilised as the APs are spread evenly among the channels. GT with the use of an ordered list also utilises the channel efficiently. However, in LI, the lower numbered channels are used more often because all APs have the same channel order.

Fig. 13 is the standard deviation of the number of APs per channel. With a value of 2.9, RND has the highest average standard deviation (for all channels). The average standard deviation for GT is 1.7 while LI has an average standard deviation of 1.8. In RND the average standard deviation is almost twice that of the other two methods. Hence, in LI and GT channel usage is more stable and does not fluctuate as much as in RND.

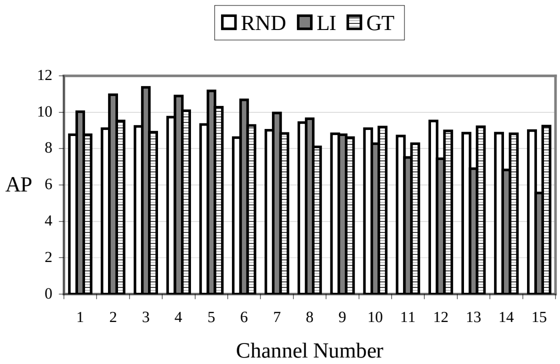

Fig. 12. Average AP per channel.

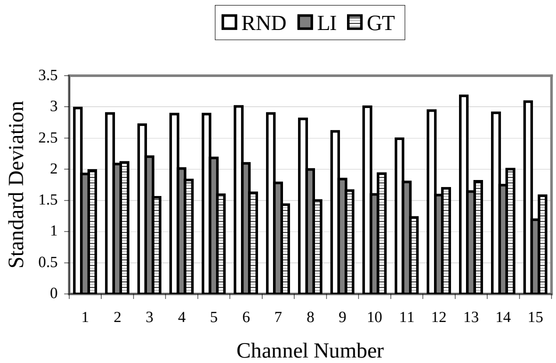

Fig. 13. Standard deviation.

VI. CONCLUSIONS

DCA using RND and LI, originally used in voice networks, are implemented and analysed for a data network. A payoff function used in Game Theory is defined for a BFWA network and a DCA (GT) employing a mixed strategy is derived from the LI method. RND, LI and GT methods are simulated under typical Internet traffic and their performances are compared. GT gives the best SNR performance and highest payoff compared to the other two methods. The GT method also utilises the channels efficiently compared to LI and its channel usage is more stable compared to RND.

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