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# Distributed and Dynamic Channel Assignment Schemes for Wireless Mesh Network

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**Abstract:** Wireless mesh network (WMN) with wireless backhaul technology provides last-mile Internet connectivity to the end-users. In multi-radio multi-channel WMN (MRMC-WMN), routers provide multiple concurrent transmissions among end-users. The existence of interference among concurrent transmissions severely degrades the network performance. A well-organized channel assignment (CA) scheme significantly alleviates the interference effect. But in trying to minimize interference, the CA scheme may affect the network connectivity. So, the CA scheme has to consider both these two conflicting issues. In this paper, as part of the initial configuration of WMNs, we propose a game theory-based load-unaware CA scheme to minimize the co-channel interference and to maximize the network connectivity. To adapt to the varying network traffic, we propose a dynamic channel assignment scheme. This scheme measures the traffic-load condition of the working channels of each node. Whenever a node finds an overloaded channel, it initiates a channel switch. Channel switching based on the fixed threshold may result in a channel over/underutilization. For optimal channel utilization, we propose a fuzzy logic-based approach to compute the channel switch threshold. The contending nodes and their densities and loads dominantly affect the network capacity and hence the performance. In the context of network capacity enhancement, we have addressed these factors and focused on increasing the network capacity. The simulation results indicate that our proposed load-unaware and load-aware CA schemes outperform the other related load-unaware and load-aware CA approaches.

**Index Terms:** Wireless mesh network, Channel assignment, dynamic threshold, game theory, fuzzy logic.

## 1. Introduction

Wireless mesh backbone consisting of wireless mesh routers (WMR) provides last-mile Internet connectivity to the end-users. Gateways are the specialized WMRs with the bridge capabilities; they connect the backbone to external networks such as the Internet. WMRs manage backhaul mesh connectivity and carry out backhaul routing to discover multi-hop routes to gateways and provide Internet access to the end-users. To offer real-time services, the WMN backbone needs to provide high-quality concurrent transmissions. The interference among multiple concurrent transmissions severely degrades the network performance [1]. So, interference needs to be minimized to boost the network capacity and hence the performance. The widespread method used to improve network capacity is to make use of multiple wireless channels. The physical characteristics of the IEEE 802.11 radio interface, allow the WMRs to be equipped with multiple radio interfaces. CA scheme can take full benefits of available multiple channels. Considering the co-channel interference, the key challenge is to assign the available non-overlapping channels to multiple radio interfaces such that co-channel interference is minimized.

Because of reducing co-channel interference, as the CA scheme tries to assign different non-overlapping channels to radio interfaces of WMRs (nodes), it may fail to allocate a common channel among the pair of nodes. For every pair of nodes to communicate, they need to have a common channel between them. The lack of a common channel between them results in no communication link between them. The absence of communication links between any pair of nodes changes network topology. Such a change may partition the network into sub-networks. Whenever more nearby pairs of nodes operate on the same channel, they interfere with one other. Thus, channel diversity and network connectivity have to be balanced. While assigning channels, the number of channels assigned to the node should not be more than the number of radio interfaces of the node.

The CA scheme has to consider the following two constraints.

1. Common-channel constraint: It requires at least one radio interface of each end node of a link must be tuned to a common channel.
2. Interference constraint: It requires co-channel interference to be low.

Each of the link connectivity among the pair of nodes determines the overall network connectivity. Network connectivity maximizes the number of permissible transmissions and also tries to network reliability. Network interference degrades the performance of the wireless network. The mentioned two constraints are contradictory. CA has to minimize the co-channel interference and maximize the network connectivity..

Fig.1 shows the network topology of 6 wireless nodes, each with two radio interfaces per node with four channels available for assignment. In Fig.1, numbers associated with each node(in square box) indicate the channel number assigned to the different radio interfaces of that node, and channel number on each link between a pair of a node indicates the common channel assigned between them. In the CA solution shown in Fig.1, we have a highly connected topology with one common channel between each pair of nodes. But due to the allocation of channel C4 between pair of nodes (R1-R2), (R1-R4), and (R4-R6), CA has high co-channel interference. To mitigate interference, if we replace the channel C4 to C1 between R2 and R4, due to no extra radio interface on both R2 and R4, there will be no common channel between R2 and R4. Because of this, the network gets portioned into two connected sub-networks (R1, R2, R3) and (R4, R5, R6). Fig. 2 shows the two connected sub-networks. The corresponding CA shown in Fig. 2 has minimum co-channel interference in both sub-networks. So we have to balance both network connectivity and interference issues. We try to assign the non-overlapping channels to the routers with minimum co-channel interference and maximum network connectivity.

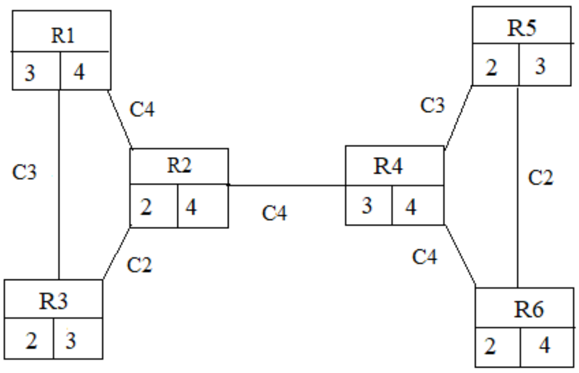


Fig.1. Connected network topology

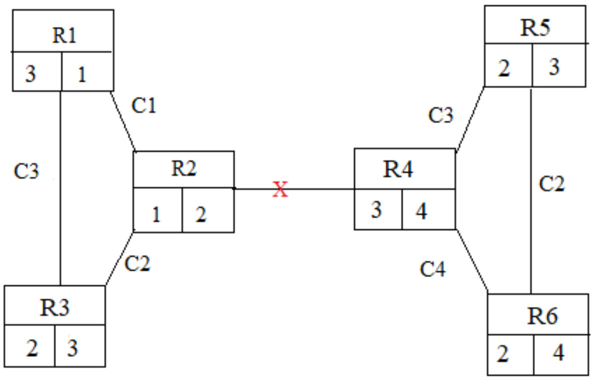


Fig.2. Disconnected network topology

In summary, the issues that motivated us to propose the channel assignment schemes are as follows.

1. Due to the self-configuring, self-organizing, and self-healing characteristics, WMNs provide quick and economical Internet access. MRMC-WMNs allow communication parallelism and try to improve the overall network connectivity. But due to the wireless medium, these networks experience interference, congestion, and capacity problems. With the above limitations, it is necessary to design a CA scheme that assigns channels with minimum interference among the routers and provides maximum connectivity. The existing CA schemes [3,4,5,6,7,8,9,10] have assigned channels to routers with minimum interference and with/without considering network connectivity. So we propose a channel assignment scheme that is dynamic, distributive, and operates with simplistic operations and ensures minimum interference with maximum connectivity.

2. To better adapt to current network traffic, we need to monitor the traffic load of channels; if required, the node

 

needs to switch/adjust channels to balance the traffic load across all the channels. If the fixed/predefined link capacity threshold is used for detecting the overloaded channels, it may result in the over/underutilization of channels. An adaptive link capacity threshold based on real-time traffic information aids in the proper utilization of wireless channels. For this, we propose a CA scheme that dynamically computes the link capacity threshold.

Here, we present a game theory-based scheme to address the CA problem for the WMN backbone. Game theory is a statistical technique that is fundamentally useful in evaluating the interactions between multiple decision-makers with conflicting interests [2]. We model the CA problem as a cooperative game and prove that the proposed game is a potential game that achieves a steady state. We model WMRs as players and channels to be assigned as the strategies. The payoff of a player is a sum of gain due to its neighbor connectivity and gain due to the co-channel interference. Each player not only tries to maximize own payoff; all players cooperate with others to maximize the overall game utility.

As part of network operation, each node needs to monitor the traffic-load conditions of its assigned channels. To better adapt to the varying network traffic-load, each node needs to switch the channel from a heavily loaded to a lightly loaded one. For this, we propose a dynamic channel assignment with an adaptive link capacity threshold.

The paper is structured as follows. The related work is discussed in section 2. Section 3 presents the proposed schemes. Through simulation results, section 4 discusses the outcome of the proposed schemes. Section 5 concludes the paper.

## 2. Related Work

Numerous research works have addressed the CA problem. We restrict ourselves to discuss only the game theory-based schemes. The solution in [3] models the CA problem as a non-cooperative game that focuses on perfect fairness and throughput under the assumption that all radio interfaces equally share the same channel bandwidth. The network is treated as a single collision domain and has addressed network connectivity. The solution is based on the central administration. The solution in [4] models the CA problem as a non-cooperative game to maximize throughput with more emphasis on minimizing interference without considering the network connectivity. For both centralized and distributed CA approaches, the explicit communication of the channel information among the routers results in more communication overhead. The solution in [5] models the CA problem as a cooperative game to assign partially overlapping channels to the routers. All players negotiate to change their interdependent strategies to reach an agreement to maximize network throughput. The solution has used a single-hop count to find the throughput, but many varying length paths exist between router and gateway. For a large network, the utility of a distant node from the gateway decreases relatively quickly to 0 value. The solution in [6] models the CA problem with heterogeneous nodes. Integer non-linear programming formulation is used to minimize co-channel interference without addressing the network connectivity. As each player has a dissimilar satisfaction level, this scheme involves a lot of complex computation. The solution in [7] models the CA problem as a semi-distributed cooperative game. Solution tries to minimize network interference. It is not consistent in mapping the radio interfaces to channels and may result in network partitions. The selection of initiator plays a very vital role in achieving good performance. The players might get trapped into the local optimum of the utility function and hence results in the degradation of system performance. Solution in [8] models the CA problem as a two-state solution. In the first stage, a non-cooperative game assigns channels to radio interfaces resulting in radio-channel pairs with minimum interference. Then in the second stage, the radio-channel pairs are assigned to the links. The game addresses link connectivity and minimizes the interference but works only with a restricted number of channels and radio interfaces. Performance very much depends on the range of selectable channels. The solution in [9] models the CA problem as a non-cooperative game to ensure link connectivity amid with impact of co-channel interference. Solution aggressively assigns more weight to link connectivity by using a constant parameter. For a reasonable number of channels, the solution reduces network interference. But interference increases with increasing numbers of channels. The performance of the scheme depends on the adjustment of the constant parameter.

All the existing game theory-based schemes have solved the CA problem to minimize interference but with/without considering network connectivity. We propose a game theory-based scheme to address the CA problem in multiple collision domains context to assign non-overlapping channels to radio interfaces of WMR with minimum co-channel interference and network-wide connectivity.

Based on various parameters, different dynamic channel assignment schemes have tried to improve network performance. We will only discuss the Adaptive Dynamic Channel Allocation (ADCA) protocol [10], which is similar to our proposed DCA. In ADCA, each router has two static interfaces and one dynamic radio interface. When a node wants to send data, it negotiates a common channel with its neighbor. In the link layer, each dynamic interface keeps one queue per neighbor. The data to be sent to each neighbor is queued in its corresponding queue. Each node negotiates a channel in two steps. In the first step, it selects neighbors based on their priority. Based on the queue length and the time spent in the queue, ADCA determines each neighbor's priority. The queue length judges whether ADCA will carry out the second step or not. If the queue length is above a predefined threshold, it considers that the traffic load has been saturated and suggests that any additional channel negotiation would be ineffective. For saturated traffic loads, it performs poorly. ADCA is particularly suitable for multi-radio WMNs with hybrid architecture. Moreover, it overlooks environmental conditions..

Based on the available radio interfaces and to better adapt to network traffic, we need to dynamically channels among the routers.

## 3. Interference-aware and Network-connective-aware Channel Assignment Cooperative Game

### *3.1. Methodology*

We formulate the CA problem as a cooperative game called Interference-aware and Network-connectivity-aware Channel Assignment Cooperative Game (INCACG) and prove that the proposed game reaches a steady state. The proposed game has two phases. First, in the negotiation phase, we model each WMR as a player and a set of channels to be assigned to each WMR as the strategies. Under a selected strategy profile and conflicting common channel constraint and interference constraint, each player computes its payoff function. To converge the game to an efficient steady-state, each player then tries to select its further strategies, such that the selected strategy not only maximizes its payoff, but also maximizes the overall game utility. Next in the assignment phase, we assign the channels to WMR.

### *3.2. Proposed Game Theory Based Load-Unaware CA Scheme*

We consider a MRMC-WMN backbone consisting of several WMRs. Each WMR has R radio interfaces. There are m non-overlapping channels and represented as $C=\{c_1,c_2,..,c_m\}$. Let $N_i$ be interfering neighbors of WMR i. The $rc_{ij}$ be the number of radio interfaces of WMR i assigned with channel j. The $in_{ij}$ is the number of neighbors of WMR i that use channel j. To avoid the self-interference, we assume $rc_{ij}=\{0, 1\}$.

In our proposed solution, INCACG is distributed CA scheme. It is a n-player game and is denoted as $P = \{P_1, P_2, P_3,..P_n\}$. INCACG is a strategic game with the strategy of each player $P_i$ represented as a channel allocation vector $S_i=\{rc_{i1},rc_{i2},., rc_{im}\}$, where $rc_{ij} = 1$ when $P_i$ assigns channel $c_j$ to one of its radio interface or $rc_{ij}=0$ otherwise. The set $SS_i$ includes all valid strategies of $P_i$ and it represents the strategy set of player $P_i$. A game profile is a Cartesian product of the player's strategy vector, $S = \times_{i\in P} S_i= S_1 x\, S_2\, x......x\, S_n$ and represents the channel configuration of the network. A game profile has one strategy per player. $S_{-i}$ denotes the selected strategies of all players except i. We use the term router and player interchangeably to represent the WMR.

Considering the common channel constraint, interference constraint and given the strategy profile S, the objective of INCACG is to formulate the payoff function of player $P_i$ that incorporates the gain due to its neighbor connectivity and the gain due to the co-channel interference.

For the player $P_i$, the gain due to its neighbor connectivity can be formulated as

$$GN_i = N_i - \sum_{p_j \in N_i} NC_{ij} \tag{1}$$

where $NC_{ij}$ is the number of common channels assigned between $P_i$ and neighboring player $P_j$. It is formulated as

$$NC_{ij} = \begin{cases} -1 & \text{if } S_i.S_j = 0 \\ 0 & otherwise \end{cases} \tag{2}$$

The $S_i.S_j$ is the dot product and it indicates the number of common channels assigned (>=1) to players $P_i$ between $P_j$ and is equal to zero if there is no common channel between the players $P_i$ and $P_j$. By selecting the appropriate strategy $S_i$, each player $P_i$ tries to maximize its gain due to neighbor connectivity and stay connected with its all neighbors.

For the player $P_i$, the gain due to the co-channel interference can be formulated as

$$GI_i = 1 - \left( \frac{rc_{ij} * in_{ij}}{N_i * R} \right) \tag{3}$$

By selecting the appropriate strategy $S_i$, each player $P_i$ tries to maximize its gain due to co-channel interference. By combining the gain due to its neighbor connectivity and the gain due to the co-channel interference, the gain of player $P_i$ is given as

$$RG_i = GN_i + GI_i \tag{4}$$

Because INCACG is a cooperative game, each player's utility function is determined by their strategy as well as the strategies of other players. To ensure that the decision of each player is not too selfish and to guarantee that the game converges, the network utility $U_{Network}$ is formulated as the sum of the utility function of all players. The network utility $U_{Network}$ represents the network connectivity and the network interference and is computed as

$$U_{Network}(S) = U_i(S) = \sum_{i \in P} RG_i \quad (5)$$

To achieve the optimal value for the $U_{Network}$, all players have to negotiate their interdependent strategies. When players are negotiating, we have to address the following issues. First, check whether the game converges to a steady-state, i.e. whether there is a consensus among the players. Secondly, if yes, then what is the efficiency of that steady-state? The Nash equilibrium (NE) [11] concept of game theory defines a steady state. The definition of NE indicates that no player gets benefitted by deviating from its current action, if no other players deviate from their current actions. The existence of NE indicates that the negotiation among the players will eventually reach an agreement. But the existence of the NE, does not implicitly guarantee the optimal outcome. The existence of NE and its efficiency is well addressed by the potential game [12].

A finite game G is a potential game if there exists a potential function ϕ: S→R such that for all strategy profiles ∈ S, all players i ∈ N, and all strategies $S_i \in SS_i$,

$$U_i(S_i, S_{-i}) > U_i(S_i^{'}, S_i) \rightarrow \phi(S_i, S_{-i}) > \phi(S_i^{'}, S_{-i}) \quad (6)$$

There is at least one pure strategy NE in each potential game [10] and can be achieved through best-response or better-response dynamics. All NEs are either local or global maximizers of the utility function [12].

**Theorem 1.** INCACG is a potential game.
**Proof:** A potential game with potential function ϕ exists such that

$$\begin{gathered} \phi(x, S_{-i}) - \phi(y, S_{-i}) = U_i(x, S_{-i}) - U_i(y, S_{-i}) \\ \forall \text{i, x,y} \in S. \end{gathered} \quad (7)$$

where x, y are the two arbitrary strategies.

In potential games, variation in a single player's utility due to its strategy deviation will result in the equivalent amount of variation in its potential function. The utility function given by (6) and (7) shows that the INCACG is a potential game with potential function defined as

$$\phi(S) = U_{Network}(S) \quad (8)$$

To converge INCACG to a steady state, each player sequentially plays the game. In its turn, each player selects a new strategy either using the best response or better response dynamics. This strategy deviation will have related changes in the potential function. When such change improves the potential function value, then the chain of these improvements moves the game on its way to one of its equilibrium. When a game reaches equilibrium, that equilibrium stage is its utility function maximizer.

$$S_i^{t+1} = \arg\max_{s \in S_i} U_i(S) \quad (9)$$

is best response dynamics.

$$S_i^{t+1} = \begin{cases} S_i^{rand} & \text{if } U_i(S_i^{rand}, S_{-i}) > U_i(S_i^t, S_{-i}) \\ S_i^t & otherwise \end{cases} \quad (10)$$

is better response dynamics, where t is negotiation step. (9) and (10) are used to find the strategy that maximizes utility function.

With the best response dynamics, during its turn, each player has to carry out an exhaustive search over its entire strategy set to find the best strategy that provides the best value for the $U_{Network}$. This approach is fast to converge and has a higher computational cost. With the better response dynamics, every player selects a random strategy and stands by the selected strategy if it yields a better value for the $U_{Network}$ as compared to its current strategy. This approach is slow to converge and has a lower computational cost. Among these two approaches, there is a trade-off between convergence speed and computational cost. In the proposed INCACG, players select their strategy based on better response dynamics.

 

With better response dynamics even when there are many NEs, in some cases, the proposed INCACG may converge to a local optimum of utility function than the global optimum. As local optimum is a case of NE, the NE's definition indicates that no player will be able to increase its utility function and hence the network utility. Because of this reason, the game may remain in the local optimum NE network profile and may have sub-optimal performance.

To make sure that the game is not trapped in a local optimum NE, we use Smoothed Better Response (SBR) dynamics; the same is used in [5][13,14].It is given as

$$S_i^{t+1} = \begin{cases} S_i^{rand} & \textit{with probability } \omega \\ S_i^t & \textit{with probability } (1\text{-}\omega) \end{cases} \tag{11}$$

SBR introduces uncertainty to the strategy selection process and makes the game to converge to the global optimum with high probability. Using SBR dynamics expressed in (11), each player picks its strategy as per the probability w. The value of w depends on function F and is given as follows

$$F(S_i^{rand}, S_i^t) = \frac{1}{1 + e^{(U_i(S_i^{rand}, S_{-i}^t)/\zeta - (U_i(S_i^t, S_{-i}^t))/\zeta}} \tag{12}$$

Algorithm 1: Interference-aware and Network connectivity-aware Channel Assignment Cooperative Game

**Initialization:**

for each $P_i \in P$, assign $Pi=ID_i$ and $S_i = \{0\}$

**I. Negotiation phase:**

1. while t < no. of negotiations(T) do
2. for every $P_i \in P$
   a. $s_i^{rand}$ =random valid strategy { $rc_{i1}$, $rc_{i2}$ ,. ,$rc_{im}$ }
   b. as per (12). if $\omega > 0.5$ then
   c. $s_i^{t+1} \leftarrow s_i^{rand}$
   else
   d. $s_i^{t+1} \leftarrow s_i^t$
   e. end if
3. broadcast message M ($ID_i$, $S_i^{t+1}$)
4. update t
5. end while

**II: Assignment phase:**

1. for each $P_i \in P$, assign the channels of selected strategy to its radios.

Considering the two different strategies, (12) is a function of the difference of utility functions. When the difference is high ($\omega > 0.5$), a player will select a new random strategy with a high probability. When a difference is low ($\omega <= 0.5$), a player will retain strategy with high probability. The term $\varsigma$ controls the trade-off between convergence speed and performance. A higher value indicates the exhaustive strategy search and slower convergence and a smaller $\zeta$ value indicates narrower strategy search and quicker convergence. The $\zeta$=0 makes the SBR behave the same as that of a better response. As per the [11] $\zeta= 10/t^2$ based on the principle of temperature on simulated annealing.

The steps used in INCACG are given in Algorithm 1. Algorithm1 has two phases namely the Negotiation phase and Assignment phase. Initially, each player is assigned with a unique identifier ID and assigned with a random strategy. In the negotiation phase, for every negotiation step, each player selects a random valid strategy and checks whether the newly selected strategy results in better value for the network utility function. If yes, then the player is assigned with that selected strategy. If no, then the player retains its current strategy. Finally, $P_i$ will broadcast a short message M ($ID_i$, $S_i^{t+1}$) to all other players of the game. The process of each player selecting its new strategy will continue till finalization criteria T is met. For the proposed game, we will use T as the maximum number of negotiations. Once the negotiation phase is over, in the assignment phase, the channels are assigned to each WMR.

Under the condition that the number of channels assigned to WMR should not be more than the number of radio interfaces, the channel assignment scheme needs to meet the common-channel and interference constraints. With network connectivity and channel diversity conflicting issues, it may not be possible to avoid co-channel interference and still have good network connectivity. The contending WMRs and their densities and loads dominantly affect the channel capacity and hence the network performance. If there is a network topology with fewer contending WMRs for each WMR, the number of channels getting overloaded can be reduced and avoid initiation of the channel adjustment. Through the proposed Interference-aware and Network-connective-aware Channel Assignment Cooperative Game, we try to get the resulting network topology which is highly connected with minimum co-channel interference. On such resulting network topology, we apply our proposed Load-Aware Dynamic Channel Assignment Scheme.

## 4. Load-Aware Dynamic Channel Assignment Scheme

Unpredictable dynamic network conditions and simultaneous transmissions of nearby nodes on the same channel lead to packet collision and reduce the network performance [15]. With the proper distribution of traffic across the network traffic we can alleviate traffic congestion and contention. For this purpose, we can use a joint design of routing that distributes the traffic over various paths and channel assignment that determines the traffic carrying capacity of links. When assigning channels to links, the load-aware channel assignment scheme has to consider the traffic load. With traffic-load, channel assignment can strengthen QoS as guaranteed by the routing. To adapt to dynamic traffic changes, we use the dynamic channel assignment (DCA) algorithm, where every node periodically measures the channel traffic-load condition of its links. If any channel is overloaded, then the channel adjustment is triggered to switch the highly loaded channel to a lightly loaded channel. By considering the traffic load of all interfering neighbors, the CA algorithm needs to adjust channels to balance the traffic load across the network.

The channel adjustment has to consider the following two requirements. To reduce the transmission of channel updating signaling traffic, the number of channel adjustments should be less. ii. The adjustment approach has to utilize local information and is supposed to have a local impact. Channel adjustment based on global information has high computational complexity. If its impact is not local, then the channel adjustment may get propagated all over the network and hence may affect the network stability.

### *4.1. Methodology*

Each router continuously monitors the traffic-load conditions of each of its working channels. Whenever a node finds its working channel is overloaded, the node tries to adjust the channel such that the number of channel adjustments is less and utilizes local information and has a local impact. Before the node selects any given candidate channel as a feasible channel to switch to, it checks the existence of the chain puzzle problem. If there is no chain puzzle problem, the node changes the current channel with a new channel. For the better utilization of channels, in each monitoring period, we dynamically compute a link capacity threshold. .

### *4.2. Proposed Dynamic Channel Assignment*

The aggregated traffic load on channel $c_m$ of node (WMR) i assigned for the link $l_{ij}$ between node i and node j (one radio of node i and j are assigned with channel $c_m$) is defined as sum of traffic load of interfering neighbors of both node i and j that use channel $c_m$ and is given as

$$ATL_i\left(c_m\right) = \sum_{j \in N_i(c_m)} \left(ITL_{ij}^{c_m}\right) + \sum_{k \in N_j(c_m)} \left(ITL_{jk}^{c_m}\right) \tag{13}$$

where $N_i(c_m)$ is the set of neighbors of node i that use channel $c_m$ and $N_j(c_m)$ is the set of neighbors of node j that use channel $c_m$. $ITL_{ij}^{c_m}$ is the traffic load on link $l_{ij}$ on channel $c_m$. j and k are the 1-hop and 2-hop neighbors of node i. For link $l_{ij}$, whenever node i finds $ATL_{ij}(c_m)$ exceeds a link capacity threshold of $l_{ij}$ it indicates that the current working channel $c_m$ of link $l_{ij}$ is being overloaded. Based on real-time traffic information, a link capacity threshold that aids channel switching can be determined dynamically.

### *A. Adaptive Link Capacity Threshold*

Most of the existing approaches detect overloaded channels using fixed/predefined link capacity threshold. Because of the varying network traffic load, it is not easy to set/define threshold values. With the saturated channel and corresponding degraded link, an over-estimated threshold does not trigger the channel switch. An under-estimated threshold value initiates frequent channel switches that may result in the underutilization of channel capacity. By taking into account the traffic load, if the link capacity threshold value is set adaptively, the channel is better utilized than the over-estimated/under-estimated thresholds. In addition, it reduces switching overhead. For a proper channel switch, the aim should be to compute a link capacity threshold appropriately.

Our proposed approach uses Fuzzy Logic based Adaptive Dynamic Channel Assignment (FLADCA) to dynamically compute the link capacity threshold (LCT) value to minimize the number of channel adjustment in an environment of varying traffic load. In our fuzzy control mechanism, the frequent switches indicate that the threshold set is too small; we will increase the threshold value. If the threshold is set too large, we will decrease the threshold value.

As interface-queue associated with the current working channel of the link $l_{ij}$ increases, the utilization of the node's working channel like $c_m$ increases. For the link $l_{ij}$, we use Channel Utilization (CU) and Interface-Queue Length (IQL) to compute the link capacity threshold. The mean forecasting model (MFM) [16] is used for forecasting the next values. For the link $l_{ij}$, the predicted channel utilization for channel $c_m$ at time t $CU_t(l_{ij})$ is computed as

$$CU_t\left(l_{ij}\right) = MFM\,(CU_{t-1}(l_{ij})) \tag{14}$$

where $CU_{t-1}(l_{ij})$ is channel utilization of $c_m$ of link $l_{ij}$ at time t-1.

The predicted interface-queue length associated with channel $c_m$ at time t $IQL_t(l_{ij})$ is computed as

$$\mathrm{IQL}_t\left(\mathrm{l}_{ij}\right) = \mathrm{MFM}(\mathrm{IQL}_{t-1}(\mathrm{l}_{ij})) \tag{15}$$

where $IQL_{t-1}(l_{ij})$ is interface-queue length associated with $c_m$ of link $l_{ij}$ at time t-1.

The fuzzy logic controller computes the link capacity threshold based on the input parameters CU and IQL. The fuzzy set for all input parameters is tabulated in Table 1 and membership functions of each input variable is shown in Fig. 3. Table 2 tabulates all the fuzzy rules for the computation of the link capacity threshold. We assign HI_DEC =-10, ME_DEC =-7, SM_DEC =-5, HI_INC =+10, SM _INC =+5.

Table 1. Fuzzy set for all input parameters

| Range/ parameter | Low | Medium | High |
|---|---|---|---|
| CU | 0-35 | 25-60 | 50-(85) |
| IQL | 0-20 | 10-30 | 20-(40) |

Table 2. Fuzzy rules

| IQL/ CU | Low | Medium | High |
|---|---|---|---|
| Low | HI_INC | SM_INC | SM_INC |
| Medium | NoC | NoC | SM_DEC |
| High | SM_DEC | ME_DEC | HI_DEC |

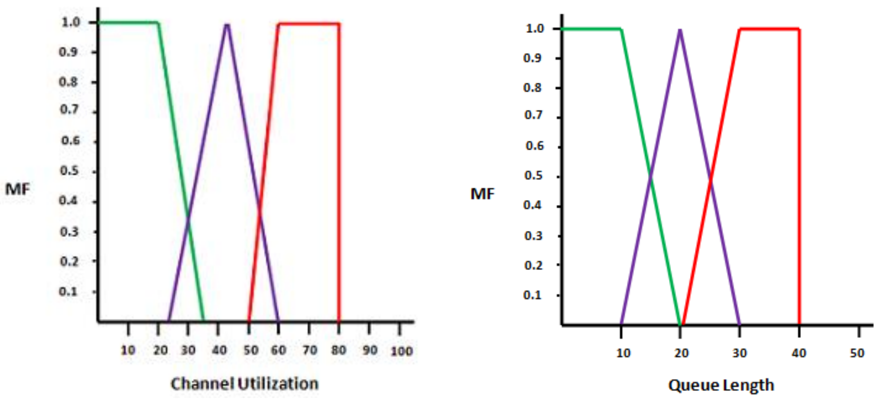


Fig.3. Membership functions for the input variables

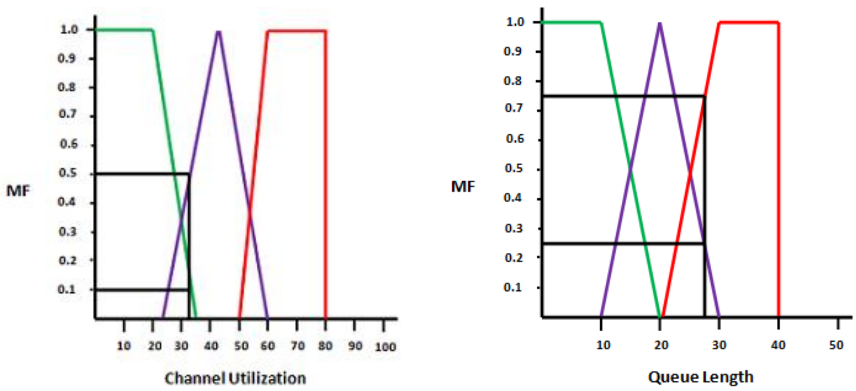


Fig.4. Illustration of DLCT-FL

**Example**

Here we illustrate the working of the proposed FLADCA scheme. Let us assume the current link threshold of link $l_{ij}$(LCT)=40%,with $CU_{t-1}(l_{ij})$=34 and $IQL_{t-1}(l_{ij})$=28. Fig.4. shows how membership function values are selected for the given values of channel utilization and interface queue length. From the Fig.4, the resulting degree of membership function of $CU_t(l_{ij})$=0.1Low and 0.5Medium and $IQL_t(l_{ij})$=0.25Medium and 0.75High. The fuzzified inputs lead to the multiple values in the rule table. The center of gravity scheme is used to aggregate all the inputs into the final output. The minimum values of the membership function are considered to compute the final output.

The tabulation of the fuzzified inputs and the selection of the minimum value are shown in the Table 3.

Table 3. Selection of minimum value of fuzzified inputs

| | IFQ | |
|---|---|---|
| CU | ~~0.25~~<br>+5<br>0.1 | ~~0.75~~<br>+5<br>0.1 |
| | 0.25<br>0<br>~~0.5~~ | ~~0.75~~<br>-5<br>0.5 |

$$\mu^{Crisp} = \frac{(0.1*5)+(0.1*5)+(0*0.25)+(-5*0.5)}{0.1+0.1+0.25+0.5} = -1.59\% \quad (16)$$

The new threshold value will be 40-1.59≅ 38.

When a node i finds that its channel $c_m$ is overloaded, it has to find the best possible channel. The new channel that the node i selects should increase network throughput and network stability, If channel $c_n$ is a candidate channel, then the condition of $c_n$ should be better as compared to the $c_m$. Node i switching to $c_n$ may overload it and result into potential network instability. To circumvent this issue, which may result in more channel switches, the following two conditions should be satisfied:

**C1.** Sum of current total traffic load of node i on $c_n$ and total traffic load of node i on $c_m$ should be less than predefined threshold LCT2.

**C2.** Sum of current total traffic load of any node j, present within interference range of node i on channel $c_n$ and total traffic load of node i on $c_m$ should be less than predefined threshold LCT2. We set

$$LCT2=0.9*LCT1 \quad (17)$$

If node i want to switch its overloaded channel $c_m$ to any candidate channel $c_n$, then both C1 and C2 conditions need to be met to avoid making being $c_n$ overloaded and in turn triggersa new channel switch.

Along with keeping the network in a stable state, the channel switching should improve the overall network performance. The gain on behalf of $ATL_{ij}(c_n)$ should be larger than Gain_Threshold.

$$\frac{Before\_TTL_i(c_m)}{After\_TTL_i(c_n)} \geq Gain\_Threshold \quad (18)$$

Channel switching results in considerable switching overhead, which includes switching delays and traffic interruptions. Such repeated channel switching may cause instability and will have a negative influence on network performance. As a result, Gain_Thershold should be determined by carefully weighing the benefits of channel switching against the switching cost. The Gain_Threshold is set to 1.2, so that the total traffic on new channel on a node i should be 20% less than the original one.

As switching of channels may partition the network into different sub-networks, channel switching should follow the connectivity invariance rule. According to the connectivity invariance rule, every node-pair that was previously connected must remain connected post-channel switching. If nodes i and j are only connected with a single channel, the channel switch may break the connectivity between them.

In Fig 5, assume that all nodes have 2 radio interfaces and operate on only 2 channels. Given the channel assignment shown in the figure, suppose R4 finds its working channel C3 on link R4-R5 is heavily loaded and wants to switch to a lightly loaded candidate, channel C7. Then this channel switch of R4 breaks the connectivity invariance rule for the node-pair R4-R6. To follow the connectivity invariance rule for the node-pair R4-R6, R4 has to switch its current channel C3 to C7. A similar channel switch needs to be done by node R5 for the node-pair R5-R8. This ripple effect further propagates to node-pair R8- R9. If node R1 switches its working channel C4 for node-pair R1-R5, a similar channel switching needs to be done for node-pairs R5-R7 and R7-R11. Because of the channel dependency problem across the node-pairs, channel switches illustrated in Fig. 5 bring out a chain of channel switches across the network. Such a scenario is called a chain puzzle problem. Chain puzzles may give rise to several problems. i. A single-channel switch chain puzzle may cover a large number of nodes, resulting in a substantial overhead. ii. As negotiations may propagate over several hops, synchronizing switching actions among all the involved nodes is challenging.

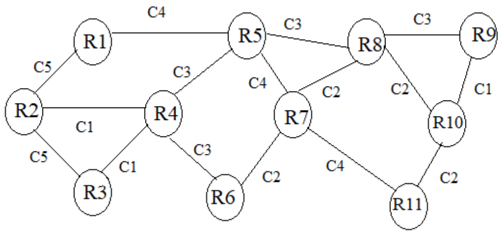


Fig.5. Chain-Puzzle Problem

Before node i selects any given candidate channel $c_n$ as a feasible channel to switch to, node has to check the existence of the chain puzzle problem. For such candidate channel $c_n$, if there exists any node j, not within 2-hop distance from node i, have to switch channel with its 1-hop neighbors to preserve the connectivity then it results in chain puzzle problem; therefore, $c_n$ is not feasible channel to switch to.

As each node autonomously initiates the channel switch and sends a request message for the channel switch. At any given time, a node may receive more than one such message. It results in request message collisions/inconsistent requests. To decrease the likelihood of such situations, before requesting node is allowed to send a request message, we make the node wait for some time. To set this waiting period appropriately, we associate the channel switch timer to each link. Based on the aggregate traffic of that link, we set the timer using the following equation.

$$T_{ij(c_m)} = \frac{1}{ATL_{ij}\left(c_m\right)} \tag{19}$$

When a node finds any of its channels with a higher load, it will set the timer with a smaller value and thus gets an early opportunity to adjust its overloaded channel.

After the channel adjustment, path adaption is done locally so to make traffic flows switch to new path segments.

## 5. Performance Evaluation

### *5.1. INCACG Performance Evaluation*

Through the simulation results, we compare our proposed distributed CA scheme INCACG with two CA schemes called Interference-aware Game-based CA (IGCA) [7] and link-preserving interference-minimization (LPIM) [9]. LPIM has modeled the CA problem as a non-cooperative game. IGCA has modeled the CA problem as a cooperative game. ns-3 [17] is used for all simulations. Table 4 tabulates the simulation parameters. We simulate grid topology of size 3*3, 4*4, 5*5, 6*6. For each topology, we run the game in two phases. In the negotiation phase, to overcome the deafness problem, all the nodes communicate using the common control channel. Initially, each node initialized with a null strategy. For each negotiation step, based on node (player) ID, each node is allowed to play the game. Once the game converges, then in the assignment phase, the channels are assigned to the different nodes.

Table 4. Simulation parameters

| Parameter | Value |
|---|---|
| Topology | Grid topology of size 3*3, 4*4, 5*5, 6*6 |
| No. of nodes | 9,16,25,36 |
| No. of channels (m) | 4,6 |
| No. of radio interfaces(R) | 2,3 |
| No. of negotiations (T) | 1000 |
| Max. Data Rate | 11Mbps |
| Queue Type and Size | Drop Tail and 50 |
| Monitoring Period | 100ms |

Since the utility functions of all three schemes are of different ranges, we evaluate the performance of INCACG, LPIM, and IGCA in terms of convergence time and channel distribution among the WMRs. The convergence time indicates the time it takes for the game to end i.e. to provide proper channel assignment. It indicates the amount of time the game has taken to reach the NE through the negotiations in INCGCA and IGCA and in LPIM, it indicates the time at which none of the players can increase its utility unilaterally. The channel distribution indicates how channels are distributed among the WMRs. For good network performance, channels are to be distributed equally among the WMRs to avoid the over or underutilization of channels. The standard deviation (SD) is taken as a method of variation to measure how the channels are distributed among the WMRs. The lower value of SD indicates that all the channels are distributed equally among the WMRs.

Fig. 6 and Fig. 7 show the performance of the three schemes for the WMN backbone, where each WMR has 2 radio interfaces. There are 4 non-overlapping channels. Fig. 6 indicates that as compared to the other two schemes INCACG scheme takes less time to converge. The convergence time of INCACG is 47% and 6% better than both LPIM and IGCA schemes, respectively. In IGCA, for every negation step, the game checks whether the randomly selected strategy yields a better value for the network utility and an entire network is connected, so it takes more time to converge. In LPIM, randomly, each player is allowed to select its strategy. At the end of each player's turn, the game checks the game convergence condition, which means none of the players can increase its utility unilaterally with all links preserved, so it takes more time to converge. In INCACG, for every negation step, considering only their neighbors, each player randomly selects strategy and checks whether it yields a better value for the network utility, and at the end, the game checks network connectivity; it takes less time to converge.

Fig. 7 indicates the channel distribution of all the schemes. As the SD of the INCACG is less, it shows that the INCACG distributes the channel equally among the WMRs. INCAG checks both common channel assignment and channel interference of nearby links, it assigns the channels equally. Even though the LPIM also assigns channels based on both common channel assignment and channel interference, it stresses more aggressively on link connectivity than interference. To increase interference gain, ICGA tries to assign different channels on nearby links.

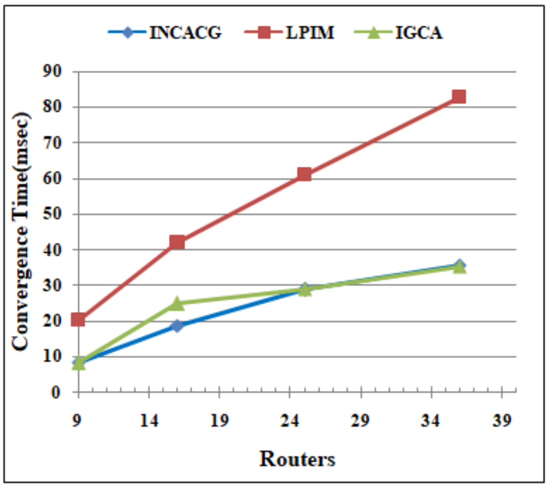


Fig.6. Convergence Time (R=2 and m=4)

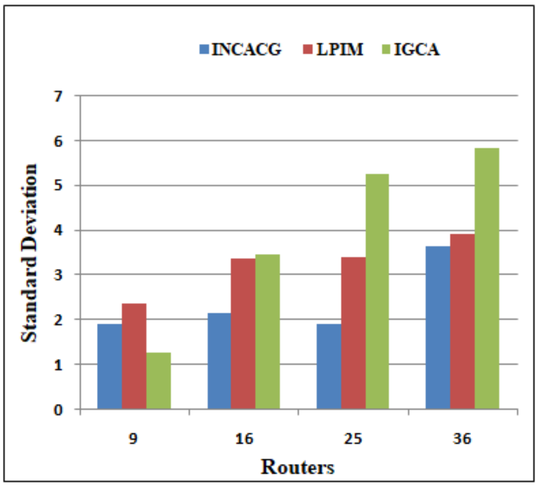


Fig.7. Channel Distribution (R=2 and m=4)

Fig. 8 and Fig. 9 show the performance of the three schemes for the WMN backbone, where each WMR has three radio interfaces. There are six non-overlapping channels. Fig. 8 indicates that as compared to the other two schemes INCACG scheme takes less time to converge. The convergence time of INCACG is 48% and 21% better than both

LPIM and IGCA schemes, respectively. Before assigning any channel, IGCA checks whether the same channel is being assigned to the interfering WMRs. As we increase the number of channels, IGCA has to compare more numbers of the channel assignment, so it takes more time for IGCA to converge. As with Fig 7, Fig 9 also indicates that INCACG distributes the channel equally among the WMRs. In IGCA, each player follows better response dynamics to select its strategy; in some cases, IGCA reaches local optimum of utility function than the global optimum.

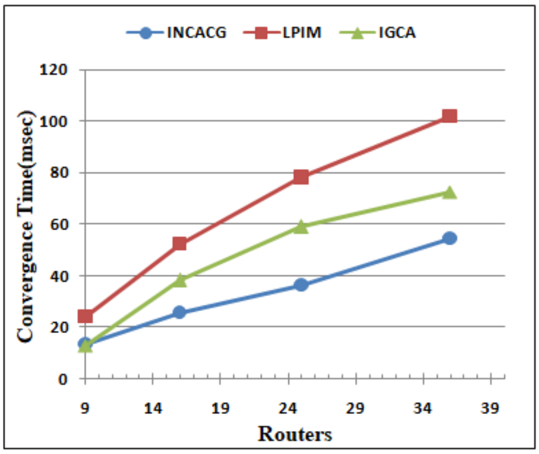


Fig.8. Convergence Time (R=3 and m=6)

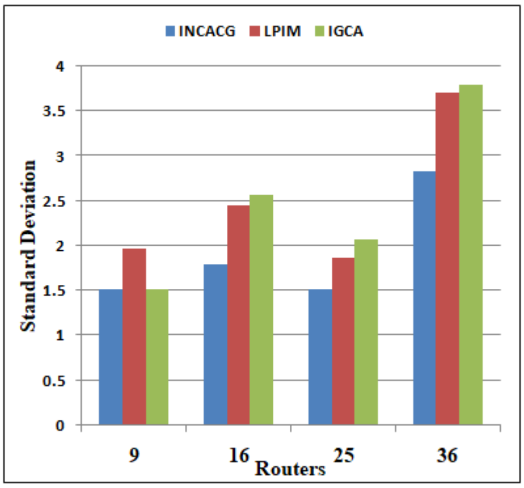


Fig.9. Channel Distribution (R=32 and m=6)

We consider network connectivity as one indicator of CA scheme performance. For grid WMN backbone of size 5*5 and 6*6 with m=4 and R=2, IGCA fails to provide the network connectivity. LPIM gives more preference to the link connectivity, at the end the game checks whether the network is connected or not. INCACG follows the SBR dynamics, it brings uncertainty to the strategy selection process and makes the game convergence to the global optimum of network utility, and provides the network connectivity. From Fig.7 and Fig. 9, it is clear that INCACG shows unwavering fairness in channel assignment. So, INCACG avoids under and overutilization of channels in the network. From a strategy selection dynamics point of view, INCACG follows the SBR dynamics, LPIM follows best response dynamics, and ICGA follows better response dynamics. As IGCA follows better response dynamics, players may get trapped at local optimum states; because of this, no player will be able to raise its utility function. In this circumstance, system performance may get caught in a sub-optimal state rather than the global optimum. As LPIM follows best response dynamics, each player carries carry-out an exhaustive search to find the best strategy, so it needs intensive computation. As INCACG follows the SBR dynamics, due to uncertainty to the strategy selection, the game avoids players getting trapped into local optimum states and hence convergences game to the global-optimum state. Considering both network connectivity and co-channel interference, compared to both LPIM and IGCA schemes, INCACG has better performance. Even with an increasing number of channels and radio interfaces, the convergence time of INCACG is better than both LPIM and IGCA schemes.

### *5.2. FLADCA Performance Evaluation*

Through the simulation results, we compare the performance of the proposed dynamic channel assignment FLADCA with ADCA [10]. The ns-3 simulation is carried out 49 nodes on 7*7 grid topology in 1000*1000m area.

Each node has 3 radio interfaces and minimum of 2 and maximum of 8 neighbors for ADCA, we configure the simulation environment with queue threshold QT is set to 30 and control interval=20ms and data interval=80ms. For FLADCA initial link capacity threshold LCT is set to 60. There are 10 different UDP flows, each transmitting the data at different data rates. Source nodes are selected randomly. The simulation time is 100 seconds. At different simulation times, each UDP flow starts sending data. As FLADCA runs on top of topology (highly connected with minimum co-channel interference) that resulted of our proposed INCACG scheme, the FLADCA performs better than the ADCA.

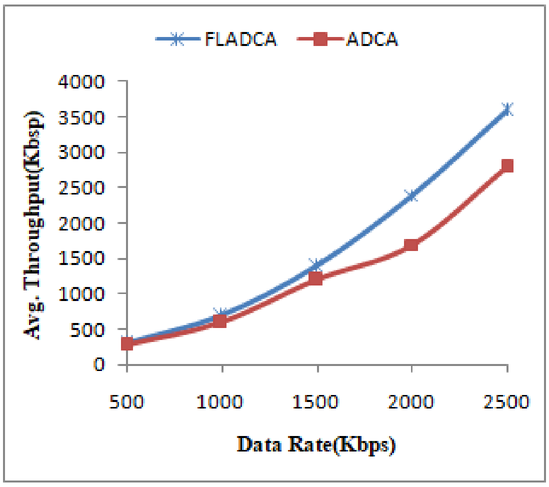


Fig.10. Average Throughput

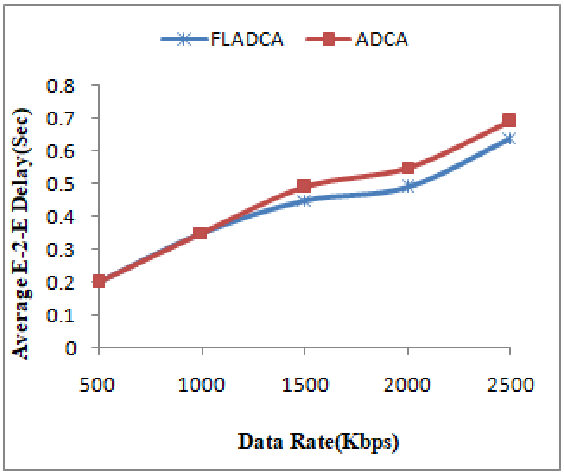


Fig.11. Average End-to-End Delay

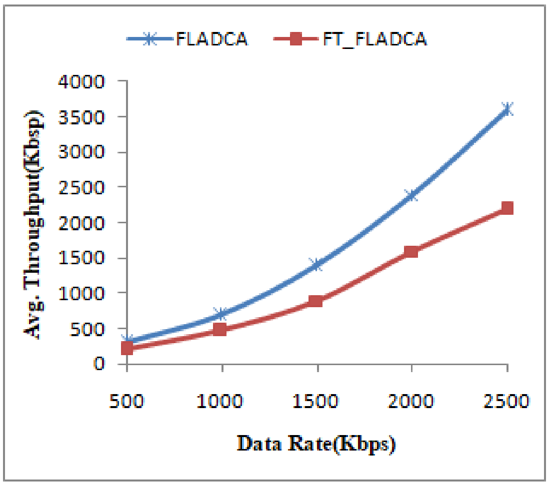


Fig.12. Average Throughput

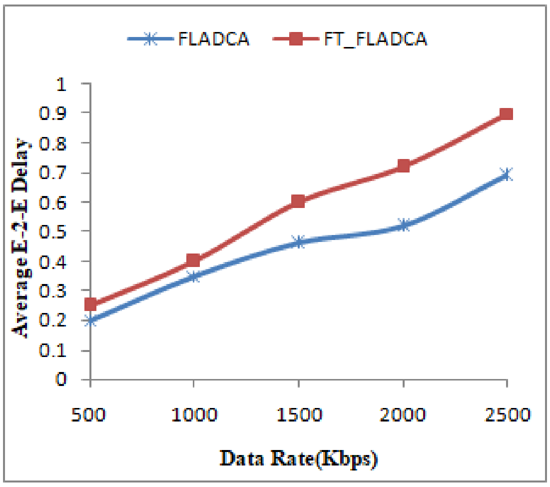


Fig.13. Average End-to-End Delay

Fig. 10 and Fig. 11 show the performance of both schemes for the WMN backbone with three non-overlapping channels. Fig. 10 indicates the average throughput of ADCA and FLADCA. As the data rate increases, there is a decrease in the average throughput of the ADCA. Based on the queue length only, ADCA measures the traffic and selects one of the available channels without considering its current utilization. As FLADCA is based on both queue length and channel utilization of each candidate channel, it has better average throughput. The average throughput of FLADCA is 17.3% more than the ADCA. Fig. 11 shows an average end-to-end delay of both schemes. As the data rate increases, there is an increase in the average end-to-end delay of the FLDCA. In FLADCA, based on the aggregated traffic load, every node has to check the existence of the chain-puzzle problem and then carries the local path adjustment; each node takes time to adjust the channels. In ADCA, before handling the current sender's channel switch request, the receiving node needs to respond to all the pending node's channel switch requests. Because of this, the sending node takes more time to negotiate its channel with a receiver and hence makes the packet wait for more time in the sender's queue, thus increasing the average end-to-end delay. The average end-to-end delay of FLADCA is 5.2% less than the ADCA.

Fig. 12 and Fig. 13 show the performance of FLADCA and its modified version with a fixed threshold (FT_FLADCA). For FT_FLADCA, we set the channel utilization threshold=75%. With the link capacity threshold value driven by traffic load, as measured using channel utilization and queue length, the FLADCA performs better than the FT_FLADCA. The average throughput of FLADCA is 34% more as compared to FT_FLADCA. An average end-to-end delay of FLADCA is 27% less as compared to the FT_FLADCA.

## 6. Conclusion

First, we model the CA problem as a cooperative game. The proposed INCACG scheme attempts to assign the available non-overlapping channels to the WMN backbone routers with minimum interference and proper network connectivity. Compared to existing LPIM and IGCA CA schemes, the simulation results demonstrate that the INCACG scheme converges quickly and fairly distributes the channels among the routers. By utilizing only the local information and having only a local impact, the proposed FLADCA attempts to balance the traffic load across all channels. Since FLADCA considers both channel utilization and interfaces queue length and dynamically sets the threshold, its performance is better than ADCA. In FLADCA with adaptive link capacity threshold, channels are better utilized than the over-estimated/under-estimated thresholds. In future work, we would like to check the performance of both proposed schemes for the different topologies and different types of traffic.

## References

[1] Ravindra S, Siddesh G K, "Interference Mitigation and Mobility Management for D2D Communication in LTE-A Networks", International Journal of Wireless and Microwave Technologies(IJWMT), Vol.9, No.2, pp. 20-31, 2019.DOI: 10.5815/ijwmt.2019.02.03

[2] Emoghene Ogidiaka, Francisca Nonyelum Ogwueleka, Martins Ekata Irhebhude, " Game-Theoretic Resource Allocation Algorithms for Device-to-Device Communications in Fifth Generation Cellular Networks: A Review", International Journal of Information Engineering and Electronic Business(IJIEEB), Vol.13, No.1, pp. 44-51, 2021. DOI: 10.5815/ijieeb.2021.01.05

[3] T. Chen and S. Zhong, "Perfectly fair channel assignment in non-cooperative multi-radio multi-channel wireless networks," Computer Communications, vol. 32, no. 6, pp. 1058–1061, Apr. 2009, doi: 10.1016/j.comcom.2008.12.030

[4] R. D. Vallam, A. A. Kanagasabapathy, and C. S. R. Murthy, "A non-cooperative game-theoretic approach to channel assignment in multi-channel multi-radio wireless networks," Wireless Netw, vol. 17, no. 2, pp. 411–435, Feb. 2011, doi:

10.1007/s11276-010-0288-5
[5] P. B. F. Duarte, Z. Md. Fadlullah, A. V. Vasilakos, and N. Kato, “On the Partially Overlapped Channel Assignment on Wireless Mesh Network Backbone: A Game Theoretic Approach,” IEEE J. Select. Areas Commun., vol. 30, no. 1, pp. 119–127, Jan. 2012, doi: 10.1109/JSAC.2012.120111
[6] X. Chen, J. Xu, W. Yuan, W. Liu, and W. Cheng, “Channel assignment in heterogeneous multi-radio multi-channel wireless networks: A game theoretic approach,” Computer Networks, vol. 57, no. 17, pp. 3291–3299, Dec. 2013, doi: 10.1016/j.comnet.2013.07.017
[7] A. Bezzina, M. Ayari, R. Langar, G. Pujolle, and L. Saidane, “Interference-aware Game-based Channel Assignment algorithm for MR-MC WMNs,” in 2014 IFIP Wireless Days (WD), Rio de Janeiro, Brazil, Nov. 2014, pp. 1–6, doi: 10.1109/WD.2014.7020816
[8] L.-H. Yen and Y.-K. Dai, “A two-stage game for allocating channels and radios to links in wireless backhaul networks,” Wireless Network, vol. 21, no. 8, pp. 2531–2544, Nov. 2015, doi: 10.1007/s11276-015-0928-x
[9] L. H. Yen and B. R. Ye, “Link-preserving channel assignment game for wireless mesh networks,” IJAHUC, vol. 31, no. 1, 2019, doi: 10.1504/IJAHUC.2019.099635
[10] Y. Ding, K. Pongaliur, and L. Xiao, Channel allocation and routing in hybrid multichannel multiradio wireless mesh networks, IEEE Transactions on Mobile Computing, vol. 12, no. 2, pp. 206-218, 2013. doi: 10.1109/TMC.2011.261
[11] A. B. MacKenzie and L. A. DaSilva, “Game Theory for Wireless Engineers,” Synthesis Lectures on Communications, vol. 1, no. 1, pp. 1–86, Jan. 2006, doi: 10.2200/S00014ED1V01Y200508COM001
[12] D. Monderer and L. S. Shapley, “Potential Games,” Games and Economic Behavior, vol. 14, no. 1, pp. 124–143, May 1996, doi: 10.1006/game.1996.0044
[13] G. Arslan, M. Demirkol, and Y. Song, “Equilibrium Efficiency Improvement in MIMO Interference Systems: A Decentralized Stream Control Approach,” IEEE Trans. Wireless Commun., vol. 6, no. 8, pp. 2984–2993, Aug. 2007, doi: 10.1109/TWC.2007.051043
[14] Y. Song, C. Zhang, and Y. Fang, “Joint Channel and Power Allocation in Wireless Mesh Networks: A Game Theoretical Perspective,” IEEE J. Select. Areas Commun., vol. 26, no. 7, pp. 1149–1159, Sep. 2008, doi: 10.1109/JSAC.2008.080912
[15] Sharad Sharma, Shakti Kumar, Brahmjit Singh,"Hybrid Intelligent Routing in Wireless Mesh Networks: Soft Computing Based Approaches", International Journal of Intelligent Systems and Applications(IJISA), vol.6, no.1, pp.45-57, 2014. DOI: 10.5815/ijisa.2014.01.06
[16] Review of basic statistics and the simplest forecasting model: the sample mean. Robert Nau. Fuqua School of Business, Duke University. August 2014
[17] ns3-official website. http://www.nsnam.org.

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