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Fauna Inspired Probabilistic and Randomly Computed Channel Assignment and Multipath Routing for Multi-Channel Multi-Radio Mesh Networks

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Abstract: Nature is of course a great and immense source of inspiration for solving hard and complex problems in computer science since it exhibits extremely diverse, dynamic, robust, complex and fascinating phenomenon. It always finds the optimal solution to solve its problem maintaining perfect balance among its components. This is the thrust behind fauna-inspired computing. Fauna inspired computing technique called Monkey Tree Search (MTS) is a meta-heuristic search model. It's usage in solving complex problems in Wireless Mesh Networks (WMNs) embrace the broadcast benefits of a wireless medium in a more flexible manner. Exploiting the broadcast properties and the path diversity of wireless meshes to implement an efficient multipath routing is a challenging factor. With Multiple radios, node's capacity can be improved by transmitting simultaneously using orthogonal channels. Capitalizing and taking advantage over these properties requires efficient channel estimation and assignment to radios technique with effective route discovery mechanism. To address these challenges in this study we have proposed a Fauna inspired computing model that uses a "Probabilistic and Randomly Computed Channel Assignment Algorithm (PRC-CA)" to achieve efficient multipath routing in a multi-radio multi-channel WMN in an interference constrained topology. This approach utilizes adaptive random network coding to analyze conflict and non-conflict channels. It does a meta-heuristic search on all possible non-conflict channels and segments it with respect to the channel capacity for efficient route discovery. All possible routing path information is then processed using PRC-CA with right scheduling and fairness index maintaining Quality of Service. Proposed PRC-CA enables nodes to organize their data transmissions in different time slots with no contention. It dynamically reconfigures the channel assignment as a consequence of a change in the traffic matrix. Simulation results show that PRC-CA converges to a stable state In finite time. Each node gets fair end-to-end throughput across multiple-channels allocating distinct non-overlapping channels to each set of communicating radios increasing network connectivity. Performance evaluation results of Fauna inspired PRC-CA shows promising gains compared to other traditional and existing methods.

Key words: Wireless mesh network, multi-radio multi-channel, probabilistic and randomly computed channel assignment, routing, monkey tree search

INTRODUCTION

Wireless Mesh Networks (WMN) plays a significant role for broadband access with ubiquitous coverage. The advantage of WMN technology is multifold: can be rapidly deployed in a large-scale area so as to lower the infrastructure and deployment costs. Can combat shadowing and severe path loss to extend service coverage. Concurrently supports a variety of wireless radio and access technologies such as 802.16 (WiMAX), 802.11 (WiFi) and 802.15 (Bluetooth and Zigbee), thereby providing the flexibility to integrate different radio access networks. Can be managed in a self-organization and self-recovery fashion. The inherited advantages of self configuration, self healing and self organization along with static nature of its backhaul routers make it a prime candidate for wireless broadband provisioning. However, unlike MANETs, WMNs routers can be equipped with multiple radios due to their static nature and the existence of permanent power supplies. Since multiple channels are available in the free Industrial, Scientific and Medical (ISM) band, multiple radios can be tuned simultaneously to exploit the free non-overlapping channels and increase the overall capacity, connectivity and resilience of the

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wireless mesh backhaul. Due to these characteristics, WMNs is a prime candidate to be deployed as a broadband wireless access network in the user premises. In WMNs, backhaul routers are divided into three types: Gateways, Access Points (APs) and core backbone Routers. The Gateways have direct connection to the internet while APs provide network. Due to these advantages, WMN is believed to be a key enabling technology for 4G and future wireless systems. In order to improve the capacity of WMNs and for supporting the traffic demands raised by emerging applications for WMNs, Multi-Radio WMNs (MR-WMNs) are under intense research. Therefore, recent advances in WMNs are mainly based on a multi-radio approach. While MR-WMNs promise higher capacity compared with single-radio WMNs, they also face several challenges. For example in wireless systems channel errors can be very high compared to wired networks; therefore, graceful degradation of communication quality during high channel errors is necessary. This is particularly important when the WMN system utilizes unlicensed frequency spectrum. In order to achieve graceful quality degradation instead of full loss of connectivity, WMNs can employ frequency diversity, by using multiple radio interfaces which is difficult to achieve in a single-radio WMN system. MR-WMNs can use appropriate radio switching modules to achieve fault tolerance in communication either by switching the radios, channels or by using multiple radios simultaneously. With multiple radios, a capacity gain cannot be fully realized if the issues related to routing, link scheduling (Augusto *et al*., 2011; Lin and Lin, 2014; Jahanshahi *et al.*, 2013a) and Channel Assignment (CA) (i.e., mapping of channels to radios at each node) are not properly addressed. In fact, routing and channel assignment (Duarte *et al*., 2012; Ding *et al*., 2012; Ganesh, 2015; Lin and Lin, 2014; Jahanshahi *et al*., 2013b) are mutually dependent and normally considered jointly. While CA determines the capacity of each link in a network, routing determines the traffic rate at each link. CA (Si, 2010; Xiao *et al*., 2008) decisions thus affect routing decisions inevitably. The channel assignment problem in multi-radio WMNs (Yang and Hong, 2014) has been investigated intensively. Though many proposals aim to minimize some network-wide measure of interference they do not study the channel assignment problem in conjunction with the routing problem. Many research articles have been published in the WMN arena in terms of channel quality estimation assignment, interference mitigation, routing enhancement etc. Only few articles discuss about the issues in conjunction with channel assignment and routing in a multi-radio environment. Thus, exploiting the broadcast properties and the path diversity of wireless meshes-implementing an efficient multipath routing is a challenging. With Multiple radios, node's capacity can be improved by transmitting simultaneously using orthogonal channels. Capitalizing and taking advantage over these properties requires efficient channel estimation and assignment to radios technique with effective routing mechanism.

To address these challenges in this study we have proposed a Fauna inspired MTS computing model that uses a "Probabilistic and Randomly Computed Channel Assignment Algorithm (PRC-CA)" to achieve efficient multipath Routing in a multi-radio multi-channel Wireless Mesh Network in an interference constrained topology (Marina *et al*., 2010). The Fauna inspired computing technique called Monkey Tree Search Algorithm is a meta-heuristic search model sed in solving complex problems in Wireless Mesh Networks (WMNs). It embraces the broadcast benefits of a wireless medium in a more flexible manner. The principle of adaptive random network coding for packet envelope identification in a multi-radio WMN brings an interesting notion for our research appraisal. Initially, our algorithm analyze network for conflict and non-conflict channels using hypergraph. Next, it segments (Kumar and Ganesh, 2013; Wang *et al*., 2012) non-conflict channels in a dynamic manner through meta-heuristic search. Then by evaluating and estimating the channel conditions with respect to the channel capacity and interference, routing path information is processed with right scheduling and fairness index maintaining quality of service. In this study we specifically focus on how to choose the rate of packets on each route to maximize throughput while ensuring fairness and how to deal with retransmissions. Proposed PRC-CA ensures optimal traffic allocation across paths. It directs load to those paths that can benefit the most at any time without saturating the network or being unfair to other flows. We evaluate our proposed methodology using simulations under simple intuitive scenarios. Our simulations were conducted using MATLAB Simulink. A prototype as a proof of concept was implemented to demonstrate the practicality and flexibility of using Fauna inspired PRC-CA in wireless mesh network. Experimental results confirm that PRC-CA converges to a stable state in finite time, the possibility to direct traffic to appropriate parts of the network and achieve proportional fairness within stipulated time.

Each node gets fair end-to-end through put 0 across multiple-channels allocating distinct non-overlapping channels to each set of communicating radios increasing network connectivity and performance. Experimental results show that PRC-CA has higher efficiency compared to the state-of-art existing Mesh Routing Protocol-Hybrid (MRP-H) (Raza *et al*., 2014) and WMQR-Wireless Mesh based QoS Routing Protocolbased protocol.

Literature review: Promising strategy for improving network throughputs for multicast using the notion of network coding was first introduced by Ahlswede *et al*. (2000). Further to achieve maximum multicast capacity of a given network, linear coding and decoding can be done using random coefficients (Ho *et al*., 2003) rather than deterministic one was proved. By doing such random combining, it does not matter what is received or lost at a destination but it only matters that enough is received. Routing as being a special case of network coding where for each transmission there is only one packet to combine and coefficients for such combining are all ones. Extensive studies are done on non-cooperative (Wu and Vaidya, 2013) routing problem in wireless networks based on splittable and unsplittable flows. Although, they have proven the existence of flow problems; their solution is not applicable to MRMC WMNs. Due to the practical importance of WMNs, considerable research efforts have been put in the designing of an intelligent MRMC technique. Many proposals aim to minimize some network-wide measure of interference and do not study the channel assignment problem in conjunction with the routing problem. A distributed channel assignment algorithm and a distributed routing protocol are proposed for both centralized and distributed algorithms which aim to minimize the number of pairs of links that are interfering. An innovative protocol for routing in WMN called hybrid protocol (MRP-H) (Raza *et al*., 2014) is proposed. In this protocol, the new entering node broadcast the Route Discovery messages (RDISs) and waits for Route Advertisement (RADVs) reply. The received RADVs contain responses of both Route Discovery message (RDISs) and beacons. The error in communication can be identified by monitoring forward packets and missing beacons. This protocol identifies the connection failure faster but does not use flooding to maintain or establish routing. QoS routing protocol based on field routing for WMN s. The proposed protocol WMQR (Raza *et al*., 2014) is based on the problem that the more traffic load is passing through or from the gateway towards the internet. For selecting a route optimally a new routing metric is introduced that is based on total network performance and flow condition. The most commonly used reactive routing protocol is Ad-hoc on Demand distance Vector routing protocol (AODV) which is designed for ad-hoc mobile networks and it accomplished unicast and multicast routing equally and also makes the routes when required by source node. The work on routing and channel assignment (Alicherry *et al*., 2005) addressed as a combined problem. Although all of the above research works have tackled MRMC from different aspects they consider that all the nodes cooperate with each other for system wide throughput optimization ignoring node's selfish behavior and do not consider the problem how to reconfigure the WMN after a change in the traffic flows. Such a problem has been tackled in a few studys. The proposed algorithm enables nodes to organize their data transmissions in different time slots with no contention. It dynamically reconfigures the channel assignment as a consequence of a change in the traffic matrix.

MATERIALS AND METHODS

System architecture and operations: We consider a MRMC WMN as shown in Fig. 1, consisting of a static Wireless Mesh Routers (WMR) with access point functionality. Access Points (APs) provide connectivity to user devices and are collocated with mesh routers. At least one router in the mesh is designated as Wireless Mesh Gateways (WMG). The gateways provide connectivity to an external network. We assume that all wireless transmissions are in broadcast mode. Those wireless nodes that hear such transmissions may engage in packet forwarding. A majority of the traffic within the mesh is from the user devices to the routers/gateways or vice-versa. Therefore in order to improve overall network capacity, it is preferable to place WMRs close to the gateway and in regions of the mesh that are likely to experience heavy utilization. It is also assumed that our system operates synchronously in a time-slotted mode. Each wireless mesh router may be equipped with multiple wireless radios, each of which operates on an orthogonal channel. Meshrouters having multi-radio capabilities reside in multiple collision domains. We assume that there is always a chance of channel usage conflict across the mesh backbone. Each mesh router uses same transmission power as in IEEE 802.11 a/b/g/n standards. WMR serves as an ingress or egress for the aggregate traffic associated with the mobile/wireless clients.

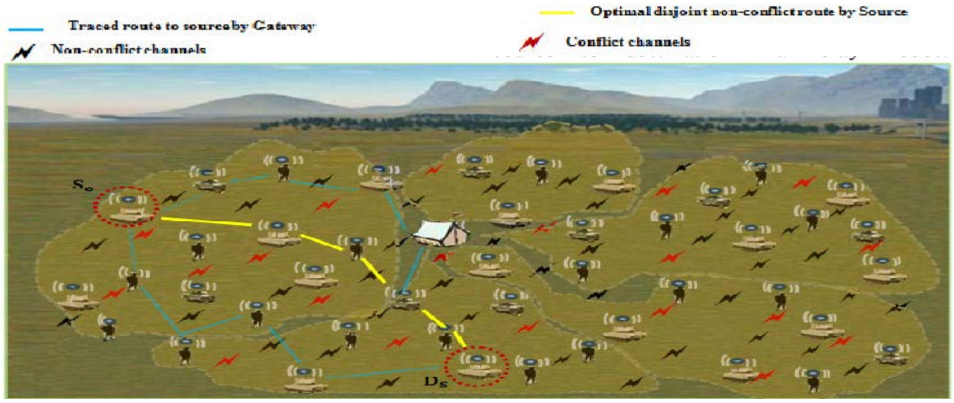

Fig. 1: System model of multi-radio WMN using monkey tree search mechanism

The role of a WMG has been extended to provide additional services such as: acting as local repository, to temporarily store information, provide local processing and bringing intelligence through interpretation techniques. Each node in our system combine incoming packets according to the adaptive random linear network coding scheme before forwarding the resulting combined packets to other nodes via its broadcast link. We employ an adaptive random network coding scheme to dynamically adjust the encoding set and constellation size to minimize the end-to-end outage probability. Next, an optimized node grouping (grouping of non-conflict channels) referred to as segmentation is performed by the destination node. i.e., WMG receives the complete update of the entire network from every WMRs. It dynamically views the compete network for non-conflict channels for linear path establishment. The WMG applies a fauna inspired computing technique called Monkey Tree Search (MTS) mechanism that performs a meta-heuristic search approach for dynamic non-conflict channel existence between the source and the destination. The destination node considering the interference constraints, the coding constraints, the number of orthogonal channels in use, channel capacity, availability of the number of radios per node and its fairness among unicast connections identifies the list of conflict and non-conflict channels. It then segments non-conflict channels by evaluating and estimating the channel conditions in a dynamic manner.

The destination node forms multiple network subgroups referred to as Network Segmentation, using non-conflict channels for end-to-end-outage. i.e., each network subgroup consists of non-conflict channels connecting source to destination via relay nodes. In the second phase, the WMG performs computation for dynamic channel assignment which is NP-Hard problem. WMG triggers the “Probabilistic and Randomly Computed Channel Assignment Algorithm (PRC-CA)” to achieve multipath routing in a multi-radio multi-channel Wireless Mesh Network in an interference constrained topology. PRC-CA identifies an unicast route through efficient channel assignment between the source and destination. This efficient channel assignment can greatly reduce interference from nearby transmitters, effective routing can potentially relieve congestion on paths to the infrastructure. All possible routing path information are then processed with right scheduling and fairness index maintaining quality of service. Summary of notations used is displayed in Table 1. The Multi-Radio WMN using PRC-CA involves two phases:

- Phase 1; fauna inspired route discovery using monkey tree search process
- Phase 2; probabilistic and randomly computed channel estimation and assignment process

Phase 1-Fauna inspired route discovery using monkey tree search process: We model the given multi-radio WMN with set of nodes and set of hyperarcs. Each hyperarc connects a starting node with any number of ending nodes. All nodes correspond to the wireless mesh routers. Each of the wireless mesh router is connected by an arc representing a wireless link. We assume that the link has an unlimited capacity. The goal of the system is to employ a unicast connection from source node to the destination node. Fauna Inspired Routing Mechanism using Monkey Tree Search is categorized into the following:

- Network Coding
- Segmentation
- Route discovery using monkey tree search

Table 1: Summary of notations

r	Number of radio nodes deployed in the network
k	Number of channels allowed for the radio nodes
G	Command control centre (OR) Gateway which has the control of all nodes
V_r	Hypergraph vertex analysis to set of 'r' nodes
V_C	Hypergraph vertex analysis said to be conflict channels
V_{NC}	Hypergraph vertex analysis said to be non-conflict channels
D	Delay: Parameter where gateway used to perform segmentation on non-conflict channels
Th_p	Throughput- parameter where gateway used to perform segmentation on non-conflict channels
P_{DR}	Packet Delivery ratio: Parameter where gateway used to perform segmentation on non-conflict channels
t_{load}	Traffic load: Parameter where gateway used to perform segmentation on non-conflict channels
V_{NC}^{i}	Grouping of vertex containing non-conflict channels
S_n	Segmented group containing set of non-conflict channels
S_{oi}	i^{th}source node
K_t	is the requested channel by the i^{th} source node
x_j	Set of all possible routes to reach the destination is given to the source by the Gateway (G)
df_{av}	Average delay of each link (L) for x_j routes by applying Chernoff upperbound
pdf_{av}	Average packet delivery ratio of each link (L) for x_j routes by applying Chernoff upperbound
tpf_{av}	Average throughput of each link (L) for x_j routes by applying Chernoff upperbound
tl_{av}	traffic load of each link (L) for x_j routes by applying Chernoff upperbound
N_{link}	Number of links
$Link_{count}$	Getting the count value for number of links
L	Link
m	Number of iterations for calculating UpperBound value for all routes x obtained from Gateway.
D_{sum}	Summation of delay value of link which is used to compute average to find fairness factor for choosing an efficient link.
PD_{sum}	Summation of packet delivery value of link
Thp_{sum}	Summation of throughput value of ith link
$t_{loadsum}$	Summation of traffic load value of ith link
D_l^i	Delay value of ith link
PD_l^i	Packet delivery ratio value of ith link
Thp_l^i	Throughput value of ith link
$tload_l^i$	Traffic load value of ith link
$L_{upperload}$	Contains list of each link's Upper bound values based on Fairness separately in a list
F	Fairness factor- helps in selection of best efficient link by source
O_{link}	Optimal link is chosen by the source
D_5	Destination reached by the source

Network coding: Adaptive random network coding is employed during this phase. Network coding provides a unifying framework for multipath and opportunistic routing in wireless mesh networks. The source node initiates packet forwarding with coding coefficients embedded in its header to all other nodes in the network. Every other node (wireless mesh routers) receives the forwarded packets and stores it in its memory. It then keeps forwarding the packets over its broadcast link until the destination node receives sufficient number of packets at which point decoding starts. Decoding is performed at the destination as new packets arrive. In the worst case, the entire generation will be decoded when retransmissions for the generation complete. Decoded packets are delivered to the upper layer according to their initial ordering. The key idea is the use of network coding at intermediate forwarders (WMR). Intermediate nodes forward random linear combinations of the packets they receive to ensure that multiple paths can be fairly and efficiently used in parallel, to deliver linearly independent information to the destination. Assume that source S broadcasts packets at a rate of 'r'. Intermediate nodes receive potentially overlapping subsets of those packets. Using network coding at each intermediate forwarding node one can achieve a rate of 'r' at the destination by simply collecting enough linearly independent combinations, produced as combinations of previously received packets and then decoding. For efficiency, relays and the destination checks for and drops linearly dependent incoming packets. To recover riginal packets, it is necessary and sufficient or the destination to receive the same number of linear combinations as the number of original packets in the generation. On a timeout, the destination unicasts a request to the source for more combinations of a given generation. By unicast we mean the 802.11 unicast mode which includes MAC-level acknowledgments and retransmissions. The request will be intercepted by any relay that has all the packets of the generation (or the source in the worst case) in that case the relay (or the source) will generate retransmissions. Relays that do not have enough packets forward the request. A pseudo end-to-end recovery scheme is employed in which the retransmissions involve generating new linear combinations of all packets that are availablein the node that produces the retransmission. As a result, the retransmitting node does not need to know which packet is missing (as in the case of not using network coding) as a result network coding simplifies the design of the retransmissionn mechanism.

Segmentation: Hyperarc analysis across network determines the availability of non-conflict channels. The hyperarc analysis is performed by the gateway to quickly identify the presence of non-conflicting radio nodes present in the network. The radio nodes which have very less interference should be selected inside the hyperarc, since the gateway performs the next hyperarc analysis and estimate the radio node successively and performs segmentation process. This hyperarc analysis continues until gateway identifies all the channels in the network. The Wireless Mesh Gateway (command control centre) designated to process additional interpretation technique performs a meta-heuristic search over the complete network for conflict and non-conflict channel analysis. i.e., Gateway checks WMR for the number of radios that interferes with other channels. Interference estimation depends on the number of interfering radios on each channel supported by each router. An interfering radio is defined as a simultaneously operating radio that is visible to a router but external to the mesh. A visible radio is one whose packet(s) pass Frame Check Sequence (FCS) checks and are therefore correctly received. WMG informs the router of radios internal to the mesh. The information could consist of an IP address range or an exhaustive list of all radio MAC addresses in the mesh. Those radios that are within an estimating router's carrier sensing range but outside its reception range, will not be accounted for in the estimation. This is because packets transmitted by such radios will fail FCS checks performed by the router.

The estimation procedure considers the number of interfering radios along with the amount of traffic generated (channel bandwidth) by the interfering radios. For instance, two channels could have the same number of interfering radios but one channel may be heavily utilized by its interfering radios compared to the other. Conflict Graphs (CG) are used extensively to model interference in cellular radio networks. The conflict graph does not correctly model routers equipped with multiple radios. Hence, the conflict graph is extended to model multi-radio routers called the Multi-radio Conflict Graph (MCG). In MCG, each radio in the mesh network is represented as a vertex. The edges are between the mesh radios instead of the mesh routers as like in conflict graph. Two vertices have an edge between each other if the edges represented by the two vertices interfere with each other. Using a vertex colouring algorithm (Rosen, 1999) to colour the MCG, we impose an important constraint: on colouring any MCG vertex, all uncoloured vertices in the conflict graph that contain any radio from the just-colored vertex be removed. The list coloring problem is NP-complete. For example, after assigning a color to vertex (v1:v3), all vertices containing either v1 or v3 should be removed from the conflict graph. This is required to ensure that only one channel is assigned to each radio in the mesh network. Upon exploring the conflict and non-conflict channels, WMG segment the set of non-conflict channels into groups. Then, WMG performs route discovery among the groups using Monkey Tree Search process to find a best linear route between the source and destination in the network.

Route discovery using monkey tree search: The monkey search algorithm is a meta-heuristic approach for improving optimization problem. It resembles the behaviour of monkey climbing trees in its search for food resources. The main assumption in this approach is that a monkey is able to survive in a jungle of trees because it is able to remember food sources previously discovered. When the monkey climbs up a new tree for the first time, it can only choose the branches of the tree in a random way, because it does not have any previous experience on that tree. Upon climbing down the tree, the monkey marks tree branches with respect to the quality of the food available in the sub tree starting at that branch. When the monkey climbs up thetree again later, using the previous marks on the branches, it tends to choose those branches that lead to the parts of the tree with better quality of food. MTS takes advantage of concepts and strategies from other metaheuristic methods like genetic algorithms, differential evolution, ant colony optimization and etc. Each cycle in MTS produces a new generation of possible solutions for a given problem. The MTS is processed by the WMG.

Algorithm 1:
Input: The number of radio nodes (r) and channels (k) allowed for the radio nodes.
Initialization: Consider set of 'r' radio nodes deployed in the network and 'k' be the number of channels allowed for the radio nodes and a command control centre (Gateway G) which has the control of all nodes.
Applying Monkey search algorithm on the Gateway (G), gateway explores 'r' radio nodes and 'k' channels in the network.
for set of 'r' nodes
Gateway (G) performs Hypergraph vertex analysis to set of 'r' nodes
if (vertex V is currently occupied) **then**
Vertex V is said to be conflict (V_C);
/* Conflict channels*/
else
Vertex V_r is said to be non-conflict (V_{NC});
/*Non-conflict channels*/
end
Gateway (G) performs Segmentation on the vertex (V_{NC}) for all radio nodes 'r'.
for set of 'r' nodes
if(vertex V_{NC}<delay D)and and (vertex V_{NC}>throughput Th_p) || (vertex V_{NC}<packet delivery ratio P_{DR})and and (vertex V_{NC}>traffic load t_{load})**then**
Grouping of non-conflict channels (V_{NC}^i) into segments (S_n);
end

When source (S_o^i) request for channel for data
transmission
Gateway (G) receives response from S_o^i and checks for channel within the
segmented groups
(S_n)
if (requested channel (K_t) is within segment
(S_n)) **then**
Trace the route to S_o^i;
Exit;
end
end//end of the for loop
Output: All possible routes (x_j)to reach the destination
is given to the source by the Gateway (G)

The main components of the MTS are:

- Exploring process (i.e., where the gateway performs dynamic hyperarc analysis for finding non-conflict channels)
- Climb or Traversal process (Gateway provides traced routes to the source)
- Watch-Jump process (i.e., Channel switching, where the source node analyses non-conflict route based on the Fairness factor, switches to another channel until it reaches the destination)
- Somersault process (i.e. which make the source node to transfer to new route rapidly)

Monkey during its metaheuristic search depending on the availability dynamically adapts and performs various process. The WMG (command control centre) views, segments the non-conflict channel and submits the possible traced routes to the source. Monkey tree search computation is done by the WMG and applied at the source and WMR. WMG calculates upper bound (channel capacity of each link) based on the fairness factor using PRC-CA to find efficient link to traverse to the next node and this continues until the node reaches the destination. One of the main challenges faced by a multipath routing scheme is to decide how to split the rates among the multiple paths. This could create an information overflow with many linearly dependent packets flowing over the mesh across different paths. Routing mechanism should allocate network resources fairly among competing flows. A simple approach is for the source to decide the rate on each path. This is inefficient, however, since there might be a large delay in sending feedback from a broken or congested link to the source. Instead we opt for a distributed approach, where WMG using PRC-CA technique decides which next hops to send each packet to. We rely on the underlyingMTS based PRC-CA mechanism to dynamically select the actual paths to use. Ideally, our objective is to select a set of non-conflict paths that collectively give the best performance in practice we fix a limit on the number of paths and pick the best paths among them. Note, however, that we do not require disjoint paths. The paths are chosen based on their quality. Delivering packets to multiple next hops is easily achieved by exploiting the broadcast medium. The fauna inspired PRC-CA using MTS dynamically adapts to varying link qualities, congestion signals from different paths and packet losses. It prevents forwarders from producing more information than they received. Let us assume that in WMN the source node request for the channel to transfer a data to a destination. Flow model is shown in Fig. 2. Various process involved in MTS is described below.

Climb or traversal process (route tracing): During climbing or Traversal process, monkey is able to remember food sources traversed before. WMG views segmented groups connecting source through destination. Non-conflict channels among each segments are analyzed to find the fitness solution based on fairness factor. It checks for current availability of channels based on the historical statistics of channel usage (i.e., the number of channels previously used at different timeslots) and fairness factor and discovers best possible multiple paths from the source to reach the destination.

Watch-Jump process (channel switching): At each step, WMG continues its exploring mechanism for dynamic channel switching based on the current fairness factor. Channelswitching among intermediate WMR is done to find an optimal linear non-conflict route to reach the destination. Watch and Jump process checks for an optimal channel based on the fairness factor. The data is been prioritized based on channel capacity that includes packet delivery ratio, average delay, maximum throughput and load balancing at each WMR. The average delay is calculated by analyzing the delay of each channel and sorted based on the ranks. WMG then selects the best channel to traverse to next node. This process continues until the destination is identified.

Somersault process: In this method in order to explore the route to find the best non-conflict channels and avoid getting trapped at the local optima; WMR is able to somersault to another channel (route). After finding a link, with better channel capacity and satisfying fairness factor, prior to channel assignment, if WMG finds that the channel estimated for assignment degraded its fairness due tp varying link qualities, congestion signals etc., it then applies the somersault process at the forwarders. WMR somersaults to another radio/channel by dynamically switching to the next best alternate route to reach the destination. Therefore, two or more alternate routes are provided by gateway to the source/forwarder nodes.

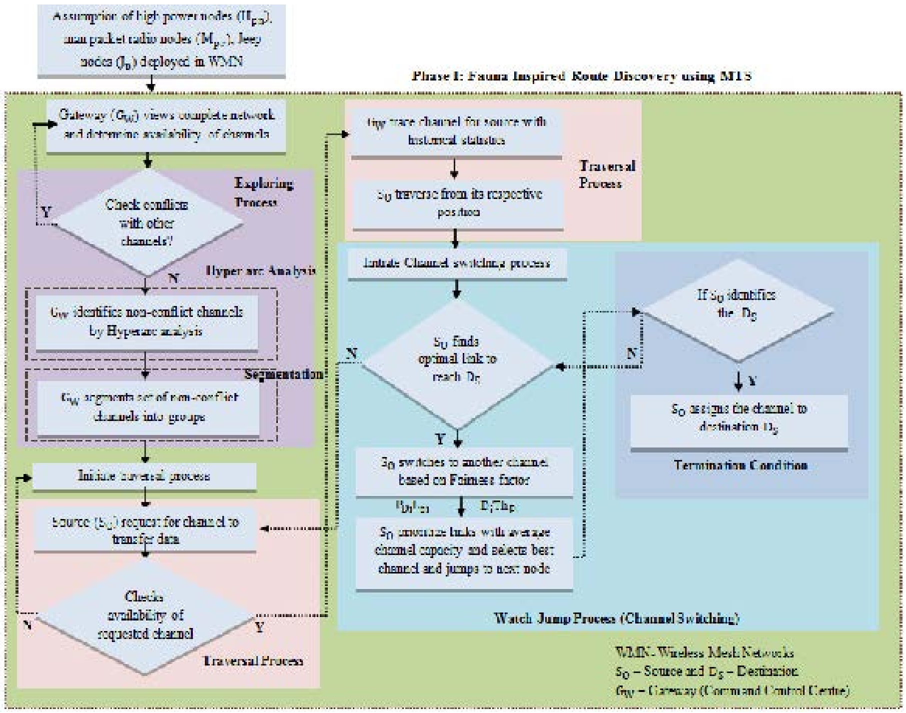

Fig. 2: Flow model of multi-radio wmn using monkey search mechanism

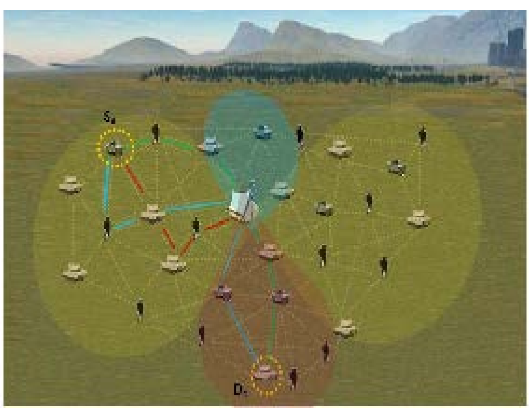

Fig. 3: Channel assignment and multipath routing using PRC-CA

Termination condition: The MTS continues execution until no improvement in the value of fairness function is obtained.

Phase II-Probabilistic and randomly computed channel estimation and assignment process: In our problem, both the number and evaluation of channels are dynamic and flexible. In such a case, the challenge is how to determine the best Channel Assignment strategies in terms of quantity and evaluation. The best strategy is decided by the fairness factor and node's utilization demand. A well-designed PRC-CA mechanism simplifies the strategy making process using MTS. It guarantees that the true value is the best strategy. In this study we propose that the true value for fairness determination should be decided according to particular scenarios. We also define the true value as the one that makes a node's utility zero given that it selects the best strategies in the later stages. Figure 3 shows sample network model of PRC-CA approach.

The goal in PRC-CA using MTS design is two-fold. First, the PRC-CA mechanism should be truthful. Therefore, Nodes request with its true values is the dominant strategy. Second, it should provide efficiency which means the channels should be allocated to those nodes which utilize them most. Therefore, overall utilization can be increased. It is computed by WMG and applied across multiple nodes (WMRs). The PRC-CA using MTS procedure consists of two parts: the winner channel determination (channel estimation and assignment) and utilization mechanism. As the channels are identical, the channel allocation result is presented in the form of the number of winning channels. The channel utilization mechanism can be flexible. The standard strategy for channel estimation and assignment is determined. Upon estimation, channels with the highest fairness values are selected as winning channel for allocation. This can be easily achieved by selecting channel with the largest fairness value from all other channels considered for evaluation. Note that the MTS does not need to sort all the channels. It only needs to know the largest fairness value to announce that channel as the determined winner. In general, uniform CA is not truthful for MRMC-WMR. To guarantee truthfulness using fairness value we introduce a PRC-CA scheme to guide the channelization decision thereby maximize utilization. During channel assignment, PRC-CA satisfies the following goals-Minimize interference between the mesh network and wireless networks co-located with the mesh. In satisfying this goal, it should periodically determine the amount of interference in the mesh due to co-located wireless networks. The interference level is estimated by individual mesh routers. The PRC-CA should then re-assign channels such that the radios operate on channels that experience the least interference from the external radios.

Algorithm 2: Channel Estimation and Channel Assignment Process
Input: The set of routes (xj) after applying Monkey Tress Search is given as the input to the source node which requested for data transmission
Consider the subset of routes(xj) derived after applying Monkey Tree Search algorithm which is given as an input to the source node (S_o^l)
Applying monkey search algorithm, source (S_o^l) traverses from its respective position and finds an optimal channel in order to reach the destination.
Calculate average delay (df_{av}), average packet delivery ratio (pdf_{av}), average throughput (tpf_{av}) and average traffic load (tl_{av}) of each link (L) for 'xj' routes by applying chernoff upper bound.
Source S_o^i gets the count (N_{link}) of route
$Link_{count} = 0$; m = 1;
If N_{link}>1then
Repeat for each route obtained from
Gateway (G)
/* calculate Upper bound (UB) of each link
(L) to find fairness factor */
$D_{sum} = D_i$; df_{av} =avg D_{sum} ;/*Delay*/
$PD_{sum} = D_i$;
pdf_{av} = avg PD_{sum};/*Packet Delivery
Ratio*/
$Thp_{sum} = Thp_i$;
(tpf_{av} = avg Thp_{sum};/*Throughput*/
$t_{loadsum} = tload_l^i$; tl_{av} = avg $t_{loadsum}$;
/*Traffic load*/
/*Store the list of each link's Upper bound
values based on Fairness separately in a list
and increment the counter*/
Store $L_{Upperbound}$ data;
Set $Link_{count} = Link_{count}+1$;
m = m+;
Until m = N_{link};
/* continue for all routes x_j ,i.e., all routes (x_j)
from Gateway are processed */
end
Get the count ($Link_{count}$) of links L in order to
select best link to transmit the data to the
destination.
/* Effective Route selection by Source*/
ifLink$_{count}$>*1* then
Compare the each link average channel
capacity ($L_{Upperbound}$) with fairness factor (F);
else if(average delay df_{av} == F) and and (average
packet delivery ratio pdf_{av} == F) || (average
throughput tpf_{av} == F) and and (average traffic load
tl_{av} == F)
/*Store the optimal link where the source
chooses to transmit data*/

Store optimal link (O_{link});
end
Repeat step (5) until one optimal link is chosen by
the source and set route path to reach the
destination D S
Repeat step (3) using step (5) until source identifies
destination
Thus, source (S_o^l) derives best non-conflict link and
assigns channel to destination.
Output: Best optimal link is selected by the source
among the possible routes (x_j) in order to reach the
destination.

Primary functionality of the proposed algorithm is executed by WMG and applied to the source node (which has the data that to be transmitted) or WMR (forwarder). When the source/WMR requests for the channel to transfer a data, WMG checks for the current availability of channels. The computation using PRC-CA is triggered by WMG. It derives the best link to traverse to next node by considering an upper bound value (i.e., by calculating average delay, average packet delivery ratio, average throughput and average load) at each link. The link with less delay, high packet delivery ratio, maximum throughput and high load balance is selected as the intermediate link path. WMG based on the computed result provides a unicast path for the source to reach the destination. Using Chernoff bound the exponential upper bound value is applied to find best link with highest average mean-packet delivery ratio, maximum throughput, least delay and high load balance. Chernoff gives a very good bound on how much the expected value of the random variable can deviate from the mean.

Average mean calculation for delay: Let $D_1, D_2, D_3...D_n$ be the delay values of links and 'n' indicates the number of links obtained by the gateway. Below indicates the upper bound value calculation of considered 'l' link (i.e. where the number of links l = 3). ND_8 and ND_5 represents the node's current delay within the network.

Average Delay (D_i): Finding the average mean delay (D_i) in ms by combining the delay of three links ($D_1+D_2+D_3$)

$$E[e^{tZ}] = E[e^{t\, D1,\, D2,\, D3}] \quad (1)$$

where 't' is either 0 or 1.

$$= E[\prod_{i=1}^{3} e^{t(D_i)}] \quad (2)$$

Substituting $D_1=ND_5$ and D 2 =ND 8, $D_2 = ND_6$ in 1

$= E[e^{t(0.1\ 0.5\ 0.8)}]$

$= E[e^{t(1.4)}]$

$D_i = 4\ .0552$

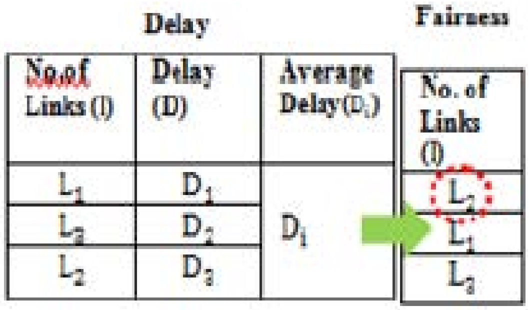

Fig. 4: Fairness on delay

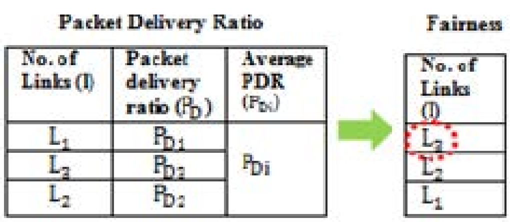

Fig. 5: Fairness on packet delivery ratio

Fairness on delay: Assume in our scenario, where traffic flows will perceive the network to be highly congested, whereas at the same time, other traffic flows will perceive it to be non-congested. Consequently, the latter traffic flows yield lower delay times, decreased packet loss and more available bandwidth in comparison with the former one, increasing the unfairness. Therefore, fairness on delay factor should maximize the minimum satisfaction ratio of reaching the link with less delay at that instance of time. Assume the number of links identified to be (L_1, L_2, L_3) and delay caused at each link to be (D_1, D_2, D_3) and the link chosen (L_2) after applying fairness based on true value is shown in Fig. 4.

Average mean calculation for packet delivery ratio: Let P_{D1}, P_{D2}, P_{D3}...P_{Dn} be the packet delivery ratio values of links and 'n' indicates the number of links obtained by the gateway. Below indicates the upper bound value calculation of considered 'l' link (i.e. where the number of links l = 3). NP_{D3} and NP_{D1} represents the node's current packet delivery ratios within the network.

Average packet delivery ratio (P_{di}): Finding the average mean packet delivery ratio (P_{di}) in percentage by combining the packet delivery ratio of three links (P_{D1}+P_{D2}+P_{D3}):

$$E\,[e^{tZ}] = E\,[e^{t\,PD1+PD2+PD3}] \tag{3}$$

where 't' is either 0 or 1.

$$= E[\prod_{i=1}^{3} e^{t(P_{Di})}] \tag{4}$$

Substituting $P_{D1} = NP_{D1}$ and $P_{D2} = NP_{D5}$,$P_{D3} = NP_{D7}$ in Eq. 3

$=E\,[e^{t\,(99.8+98.6+92.7)}]$

$=E\,[e^{t\,97.0}]$

$P_{Di} = 1.38\times10^{42}$

Fairness on packet delivery ratio: When source need to transmit the data, it needs to analyze the channel before accessing it. After analyzing the channel, it performs data transmission via the channels detected. If the sender's packet fails to reach the destination, it has to retransmit the packet. The packet that requires several retransmissions from sourceto desination will be involved in multiple channel access contentions. The number of contentions may result in increased delays oreven higher packet loss and therefore unfairness is introduced, especially for lengthier flows that require more etransmissions. Therefore the primary goal of chieving fairness is to prioritize the ransmissions on an equally shared timeslot. Assume the number of links identified is (L_1, L_2, L_3) and packet delivery ratio of each link is P_{D1}, P_{D2} and P_{D3}. The link chosen (L_3) after applying fairness is shown in Fig. 5

Average mean calculation for throughput: Let Th_{p1}, Th_{p2}, Th_{p3}...Th_{pn} be the throughput values of links and n indicates the number of links obtained by the gateway. Below indicates the upper bound value calculation of considered 'l' link (i.e. where the number of links l=3). NTh_{p8} and NTh_{p4} represents the node's current throughput within the network.

Average throughput (Th_{pi}): Finding the average mean throughput (Th pi) in ms by combining the throughput of three links (Th_{p1}+Th_{p2}+Th_{p3})

$$E\,[e^{tZ}] = E\,[e^{t\,(Thp1+Thp2+Thp3)}] \tag{5}$$

where 't' is either 0 or 1.

$$= \left[\prod_{i=1}^{3} et^{(Th_{pi})}\right] \tag{6}$$

Substituting $Th_{p1} = NTh_{p8}$ and $Th_{p2} = NTh_{p4}$,$Th_{p3} = NTh_{p2}$ in Eq. 5

$=E\,[e^{t(0.25+0.98+0.63)}]$

$=E\,[e^{t(1.86)}[$

$Th_{pi} = 6.42$

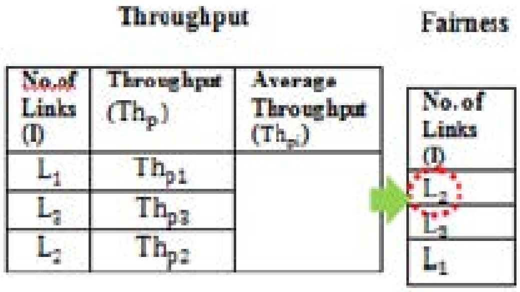

Fig. 6: Fairness on throughput

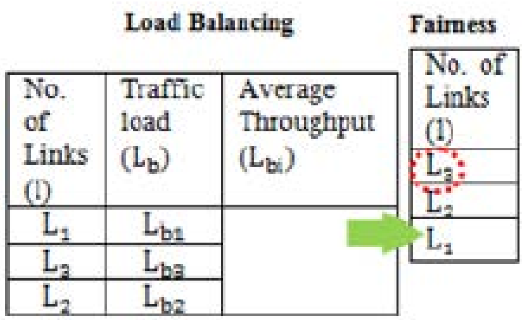

Fig. 7: Fairness based on load balancing

Fairness on throughput: Fairness is a desirable property which offers protection between the users, (i.e. prevent traffic flows of an ill-behaving user from affecting the traffic flow of another user). Our major concern is to prioritize the link (l = 3) and maximize the total throughput of all users at the same time serve each user a fair amount of throughput. With min and max fairness, all users should receive optimal throughput. Assume the number of links identified is (L_1, L_2, L_3) and throughput be (Th_{p1}, Th_{p2}, Th_{p3}). The link chosen (L_2) after applying fairness is shown in Fig. 6.

Average mean calculation for load: Let L_{b1}, L_{b2}, L_{b3} be the load values of links and n indicates the number of links obtained by the gateway. Below indicates the upper bound value calculation of considered 'l' link (i.e. where the number of links l = 3). NL_{b8} and NL_{b4} represents the node's current traffic loads within the network.

Average traffic load (L_{bi}): Finding the average mean load (L_{bi}) in kbps by combining the load of three links (L_{b1}+L_{b2}+L_{b3})

$$E\,[e^{tZ}] = E\, e^{tLb1+Lb2+Lb3} \tag{7}$$

Where 't' is either 0 or 1.

$$= E\left[\prod_{i=1}^{3} e^{t(L_{bi})}\right] \tag{8}$$

Substituting $L_{b1} = NL_{b6}$ and $L_{b2} = Nl_{b1}$, $L_{b3} = NL_{b2}$ in 7

$=E\,[e^{t(100+80+500)}]$

$=E\,[e^{t(230)}]$

$L_{bi} = 7.72 * 10^{99}$

Fairness on load: Since the nodes in our network are deployed in mesh topologyfashion, each node has to send/receive the packets to/from adjacent nodes. Other nodes also forward packets on behalf of other nodes acting as a router. Since a node has not only to transmit its own generated traffic but also the relayed one as this effect occurs consistently and frequently, it causes unfairness causing overload to other nodes in the network. In order to achieve fairness, load balancing is introduced which causes the routes to avoid congested neighbour nodes, thereby, improving the performance of the network. Assume the number of links identified to be (L_1, L_2, L_3) and load at each link to be (L_{b1}, L_{b2}, L_{b3}) and the link chosen is (L_3) after applying fairness is shown in Fig. 7.

Channel capacity: Our channels estimation and assignment is mainly based on two parameters known as channel capacity and fairness. Channel capacity is one of the primary criteria for QoS demanding application where the channel over the selected path ensures the fairness factor. The effective capacity of each channel is calculated as follows:

$$C^{i}_{ni\,nj} = W_i \log(1 + \frac{P_w}{N_0 W_i} * D_{ni\,nj}) \tag{9}$$

Where $C_{ni\,nj}$ is capacity of channel i between two nodes ni and nj. W_i is bandwidth of channel i, N_0 is spectral power density of noise and $d_{ni\,nj}$ is distance between node ni and nj with transmission power P_w.

Fairness factor: The objective of our channel estimation and channel assignment is to select best channels and radio nodes that meet the QoS requirements. Fairness is one of the key factor to evaluate the performance of wireless networks. The channel assignment (channel estimatio) works on fairness based strategy where the fairness for every available channel is based on the throughput, packet delivery ratio, delay and traffic load.

Efficient link selection by WG using fairness: Fairness must be measured over a time interval size with relevant to the nodes that are available in the network. If fairness is only measured over a time interval that is in the order of ten minutes, a task of prioritizing the links could allocate

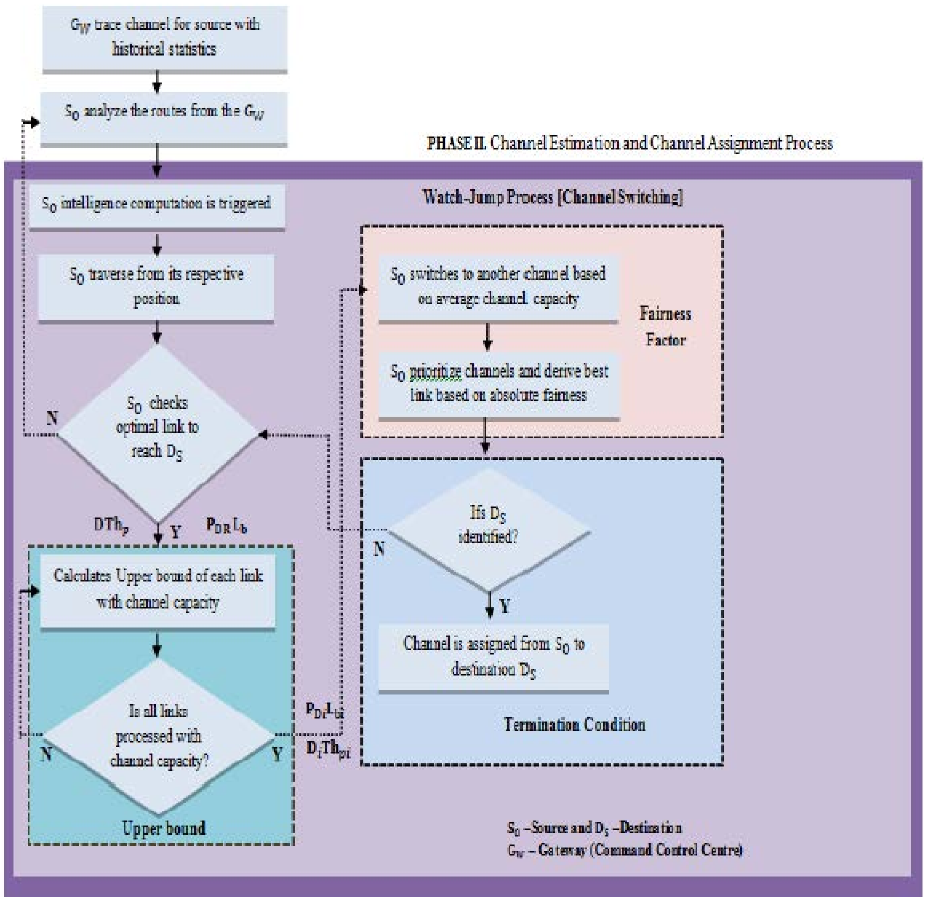

Fig. 8: Flow model of channel assignment and multipath routing using PRC-CA

Table 2: Link selection using fairness

Links (I)	Channel capacity Delay (D)	Throughput	Packet delivery ratio	Traffic load	Average Channel capacity Average delay	Average throughput	Average packet delivery ratio	Average traffic load
Link 1: $S_o \rightarrow N_{22} \rightarrow N_{28} \rightarrow D_3$	D_1	Th_{p1}	P_{D1}	L_{b1}				
Link 2: $S_o \rightarrow N_{15} \rightarrow N_{18} \rightarrow D_3$	D_2	Th_{p3}	P_{D3}	L_{b3}	D_i	Th_{pi}	P_{di}	L_{bi}
Link 3: $S_o \rightarrow N_{29} \rightarrow N_{30} \rightarrow D_3$	D_3	Th_{p2}	P_{D2}	L_{b2}				

data only to node A the first minute and only to node B the second minute and still be considered fair according to the measure. Achieving fairness does not mean that each user must consume exactly the same amount of resources (time slots). As long as the sender receives a fair throughput i.e., packets being transmitted to the node with minimal packet loss, also reaching the specified link with less delay and perform load balance against the congested routes then it is considered that the sender has been given a fair share of resources. In our considered scenario, by combining the channel capacity of each link and sorting them based on their fairness factor, absolute fairness is achieved at link 2 as shown in Table 2.

Therefore, the sender node chooses the path (which is the Link 2) as the best efficient link to reach its destination based on absolute fairness. The key distinguishing aspect in our proposed work is that we assign channels based entirely on knowledge of interference in the mesh network. The flow model of PRC-CA is shown in Fig. 8.

RESULTS AND DISCUSSION

Simulation and experimental analysis: The primary motivation in implementing a prototype is to demonstrate the practicality of our proposed Fauna inspired PRC-CA

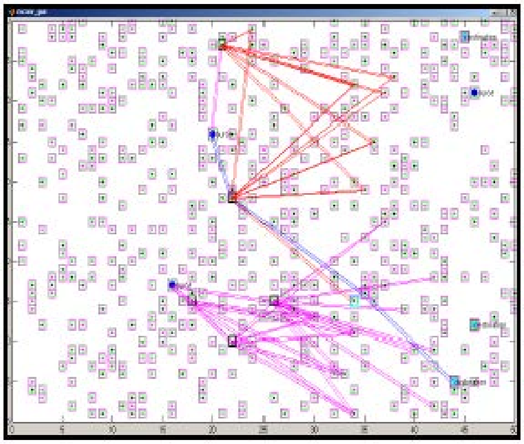

Fig. 9: Network model generated through simulation for PRC-CA scheme

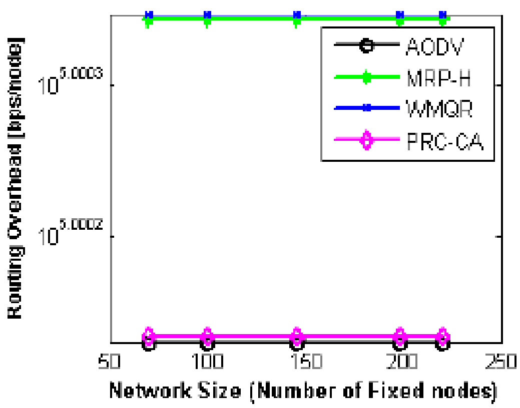

Fig. 10: Network size vs routing overhead

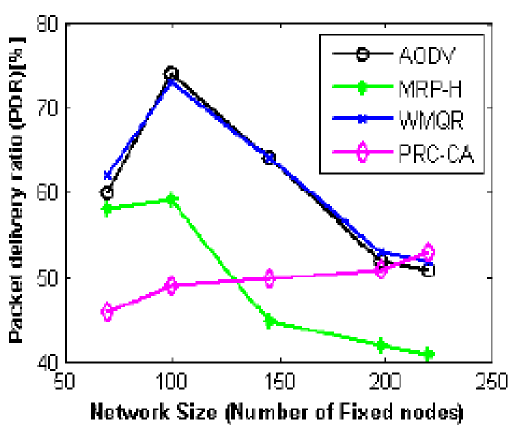

Fig. 11: Network size vs PDR

using MTS mechanism. We evaluate the implementation using self-written simulator in MATLAB Simulink. The prototype implementation consists of a MTS module and

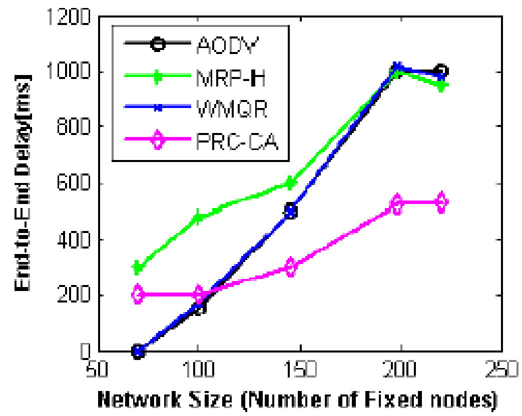

Fig. 12: Network size vs delay

a PRC-CA module installed on Wireless Mesh Gateway for evaluating channel estimation and link redirection procedures. Results indicate that the accuracy of the models has a significant impact on the simulation results for wireless mesh networks. Simulation was triggered considering randomly chosen sensor node to act as source that tends to generate message and let it send message to destination on varied time slot. Figure 9 displays sample simulation model of PRC-CA. We compared the performance of PRC-CA with other techniques such as AODV, MRP-H and WMQR in terms of routing overhead, Packet Delivery Ratio (PDR), end-to-end delay and average hop-count metrics.

Network size: The number of fixed (static) nodes is increased while keeping the network density constant. The results observed is shown in Fig. 10. Overhead of PRC-CA remains stable and constant as shown in Fig. 11 while that of other protocols overhead increases as the network size increases.

The PDR of all routing protocols decreases with the increase in network size. This is expected as the network capacity most likely decreases with the increase in network size. The ratio of the number of packets successfully delivered to the sink against the total number of packets generated. The simulation results captured during simulation are shown in Fig. 12. From the results, we can see that PRC-CA can guarantee the desired delivery rate after the network density reaches a certain level.

This is because with the increase of network density, dynamic channel assignment across forwards using PRC-CA approach becomes effective, hence message to be delivered to destination has more chances to be delivered successfully to the destination during its first transmission. Comparing the delivery rates of other routing protocols PRC-CA is better due to its optimal channel estimation and assignment technique.

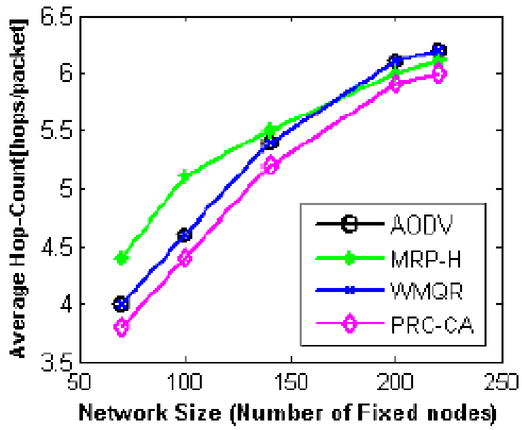

Fig. 13: Network size vs Hop count

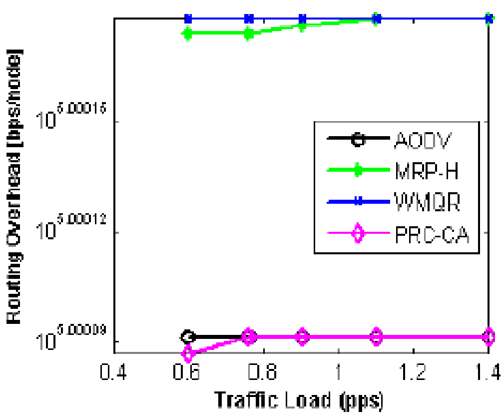

Fig. 14: Traffic load vs routing overhead

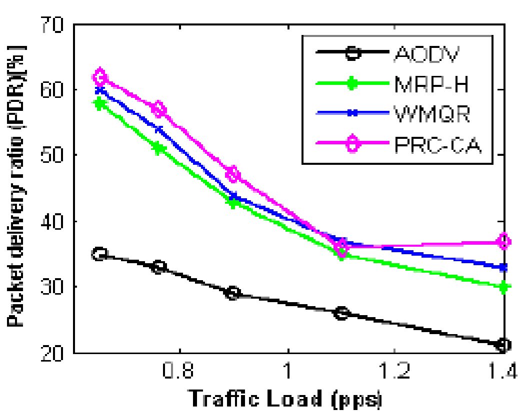

Fig. 15: Traffic flow vs PDR

The performance of the proposed PRC-CA scheme in terms of transmission delay was analyzed. The time required for the sensor node to transmit the data to the destination was evaluated for multiple iterations. From the results captured as shown in Fig. 12, it was found that the

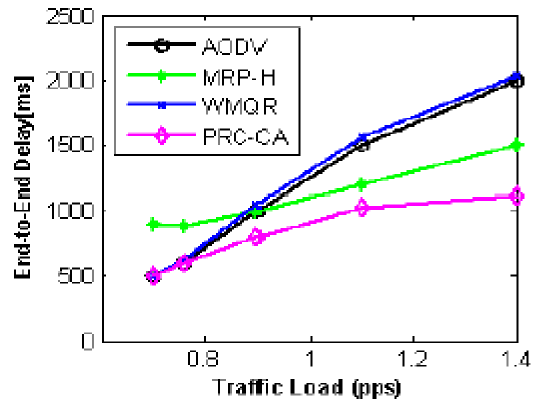

Fig. 16: Traffic flow vs delay

time taken for data propagation from sensor node to the destination via the WMR was less. Therefore, PRC-CA shows good delay for scaled network size compared to AODV, MRP-H and WMQR that shows high delay as network size increases.

The hop-count shown in Fig. 13, directly reflects the increase in network size. The AODV and WMQR show hop-counts close to the ideal hop-count. MRP-H shows longer than ideal routes indicating suboptimal routes, while PRC-CA only route successfully to/from nodes closer to the WMG and thus show shorter hop-counts.

Traffic load: In this scenario we vary the relative traffic load by changing the number of active users. We increase the Traffic load by reducing the mean packet inter-arrival time from 1s-0.5 s (i.e., from 0.5-1 packets per second). The user traffic flows are both originated and terminated within the mesh network. Figure 14 and 15 depicts the simulation results for the routing overhead. The curves for various routing protocols (including PRC-CA) are plotted as the offered load increases.

Figure 14 shows that the routing overhead of AODV rises as traffic load is increased. The main reason behind this increase is the corresponding increase in lost packets (that triggers the route discovery process). In contrast, MRP-H and WMQR protocols show overhead immunity to the traffic load. MRP-H has a low overhead, due to the larger beacon period. PRC-CA shows very low overhead.

Figure 15 shows that as the offered traffic load intensifies, the PDR of AODV, MRP-H, WMQR drops faster than PRC-CA. Although PRC-CA shows smaller PDR in certain points it still outperforms the other protocols. The drop in PDR is due to the packet loss in the WMR as well as lost routes due to the routing protocols' attempt to restore failed routes (or what are considered to be failed routes due to packet drops).

The delay increase in almost all of the protocols as the traffic load increases as shown in Fig. 16. It is due to

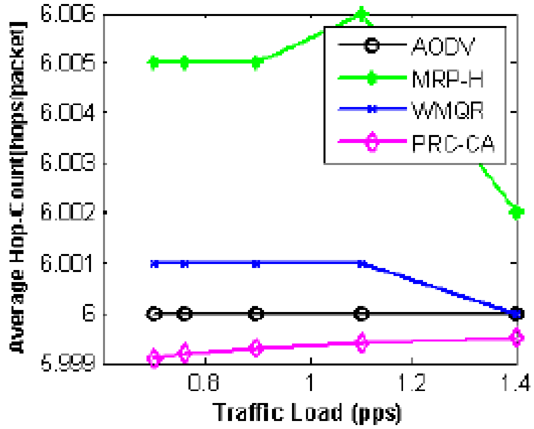

Fig. 17: Traffic flow vs hop count

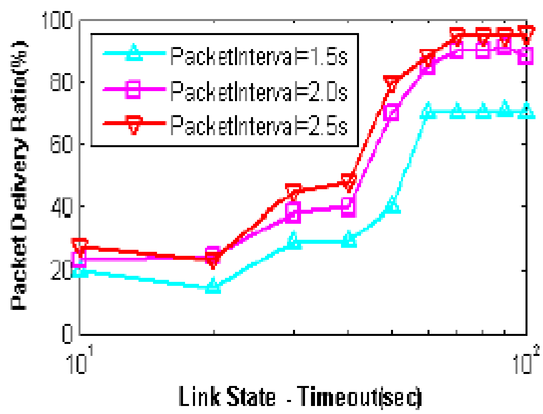

Fig. 18: Link state vs PDR

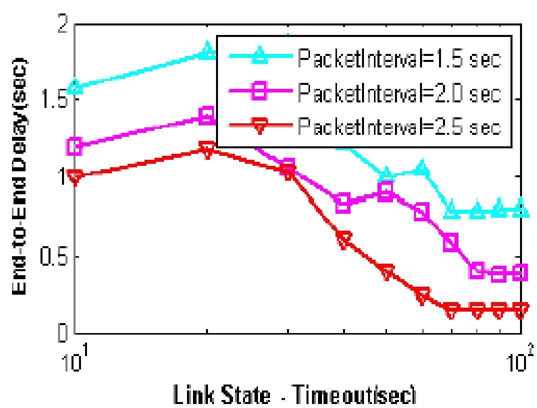

Fig. 19: Link state vs delay

the larger queuing delays at WMR resulting from the increase in offered load. AODV has a higher delay than MRP-H and WMQR due to the delay caused in discovering broken routes later than the other two. The delay statistics consider only the few packets that reach their destinatio s. PRC-CA outperforms other protocols in terms of delay as the number of packet drops and broken routes thereby reducing routing overhead in this approach. Aim of PRC-CA is to reduce end-to-end delay in order to reduce packet loss and consequent under-utilization.

Figure 17 shows that the hop-count of each packet is almost insensitive to an increase in traffic load. From the results MRP-H and WMQR shows increase in hop-count compared to on-demand protocol AODV that shows a slight increase in the hop-count. As expected, among the other protocols PRC-CA exhibits the best overall performance as it implements the fauna inspired MTS technique for route discovery.

Link state analysis: The efficiency of the link state is verified for efficient channel assignment/switching. The behaviour of PRC-CA through simulation experiments was analyzed and the results are displayed in Fig. 18 and 19. Fauna inspired MTS based PRC-CA route discovery through dynamic channel estimation and assignment approach makes the PRC-CA resistant to transient periods of high packet loss.

MTS sends route error message to appropriate WMR as soon as it detects fairness index drop across route traversed. This makes MWR to switch to different route with high fairness factor. WMR makes its routing decision only based on the fairness index evaluated through PRC-CA. The effect of link state with different average packet intervals was evaluated using PRC-CA approach and the results are shown in Fig. 18 and 19.

CONCLUSION

In this study, we presented a Fauna inspired MTS computing model that uses PRC-CA approach. The proposed approach takes the current channel assignment and the new set of flow rates into account and attempts to minimize the maximum total utilization over all the collision domains while constraining the number of radios that can be assigned a new channel. With respect to Fauna inspired MTS based scheme, PRC-CA leverages the possibility to adjust the link transmission rates and presents enhancements such as an improved definition of the link priorities. We performed extensive simulation studies that confirmed that PRC-CA meets the constraint on the maximum allowed number of radio changes and outperforms both other existing routing and channel assignment approaches such as MRP-H and WMQR in terms of maximum channel utilization and improved network performance. The simulation studies also confirmed the strong correlation between the maximum channel utilization and the improved delivery rate thus supporting our objective of PRC-CA implementation. We believe that investigating similar impact across Cognitive Radio based MANET constitutes an interesting subject for future work.

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