Interference-Aware Power Control for Multi-Radio Multi-Channel Wireless Mesh Networks

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***Abstract*— Multi-Radio Multi-Channel (MRMC) systems are key to power control problems in WMNs. In this paper, we present a dynamic power control for MRMC WMNs. First, WMN is represented as a set of disjoint Unified Channel Graphs (UCGs). Second, each radio assigned to a unique UCG adjusts the transmission power locally using predicted interference states among different adjacent UCGs. A new power selection MRMC unification protocol (PMMUP) is proposed that coordinates local power optimizations at the radios of a node. The throughput and energy performance of the proposed method is investigated through simulations.**

***Keywords*- Interference-Aware; Multi-Radio Multi-Channel Interaction Prediction Algorithm (MMIPA); Selection Multi-Radio Multi-Channel Unification Protocol (PMMUP); Wireless Mesh Networks (WMNs).**

I. Introduction

Wireless Mesh Networks (WMNs)* have emerged as a ubiquitous part of modern broadband communication networks [1]. In WMNs, nodes are composed of wireless mesh clients, routers (e.g., mesh points) and gateways. Wireless mesh routers or mesh points (MPs) form a multi-hop wireless network which serves as a static backbone to provide Internet access to mesh clients. As a result wireless backbone nodes convey a large amount of traffic generated by wireless clients to a few nodes that act as gateways to the Internet. In order to meet high traffic demands, wireless backbone nodes (e.g., MPs) can be equipped with multiple radios and/or operate on multiple frequency channels [4]. Each radio has a single or multiple orthogonal channels. In this scenario, an MP node has each radio with its own medium access control (MAC) and physical layers [1]. This implies an independent communications in these radios. Thus, a single MP node can access mesh client network and route the backbone traffic simultaneously. This brings the advantage of a self-managing and high capacity wireless mesh networking [2]. However, utilizing multiple-radios and channels for each node simultaneously, results in striping related problems [9]. First the use of multiple radios on multiple non-overlapping channels is expensive. Furthermore, small form-factor embedded systems used for manufacturing MP nodes support a limited number of radios [3]. Limited number of radios allows for interface channel switching technique to improve channel utilization. Switching an interface from one channel to another incurs switching delays [6]. Second, timeout problems due to packet re-sequencing at the receiver node may become significant. Scalable resolutions of such problems are well known in [9], [6].

The operation of multi-radio multi-channel (MRMC) WMNs generally requires sustainable energy supply. Substantial deployments of WMNs have recently been witnessed in rural and remote communities [4]. In such applications, electric outlets are not available and nodes must rely on battery power supply for their operations. Due to the nature of topography of the remote communities, mesh networks are expected to deliver packets over long wireless distance ranges. This comes at the expense of additional transmission power consumption. Nodes transmitting with high power shorten network lifetime and as a result network connectivity fails. This phenomenon degrades the robustness of a self-configuring WMN [1]. Moreover, high power transmissions in a multi-radio system degrade channel reuse in a physical area. Consequently, severe problems of co-channel and adjacent channel interferences may occur [3].

Interference estimations using a conflict graph approach are well known in [2], [3]. Conflict graphs exploit protocol interference models (PrIM) [3]. However, the PrIM does not take into account aggregate interference as well as network scalability [5]. Furthermore, finding a global optimal throughput under the PrIM has been proved to be an *NP-hard* problem even in single radio systems [2]. To introduce a simple solution for an MRMC configuration, we investigated the impact of locally predicted interference among neighbouring multi-radio MP nodes. As a result, we arrived at an interference-aware power control protocol and a corresponding power control algorithm aimed at improving the capacity and energy efficiency of WMNs. The optimal power level is changed dynamically at each network interface card (NIC) or radio. This work is motivated by the fact that WMN system is dynamic and scalable. That is, it can autonomously adapt to nodes entering the network (i.e.,

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introducing multiple interferences) or those exiting the network due to node failures (i.e., energy depletion), poor connectivity and so forth.

The rest of this paper is organised as follows: We discuss related work in Section II. We describe the System model and the PMMUP in Section III. Section IV formulates the Problem. In Section V we present the MMIPA algorithm. Section VI presents the simulation results and Section VII concludes the paper.

II. RELATED WORK

In order to make such multi-radio systems work as a single node, we adopted a *virtual* MAC protocol on top of the legacy MAC [1]. The virtual MAC coordinates (unifies) the communication in all the radios [6], [7]. This unification protocol hides the complexity of multiple MAC and physical layers from the upper layers. The first Multi-radio unification protocol (MUP) was reported in [6]. MUP discovers neighbours, selects the NIC with the best channel quality based on the round trip time (RTT) and sends data on a pre-assigned channel. MUP then switches channels after sending the data. However, MUP assumes power unconstrained mesh network scenarios. Mesh nodes are plugged into an electric outlet. MUP utilizes only a single selected channel for data transmission.

Our power optimization protocol follows the MUP concept in spirit. Instead we propose the power selection multi-radio multi-channel unification protocol (PMMUP). PMMUP enhances functionalities of the original MUP. Such enhancements include: an energy-efficient power selection capability and the utilization of parallel radios or channels to send data traffic simultaneously. The main motivation behind PMMUP concept is the need for a single MP node to access mesh client network and route the backbone traffic simultaneously [1]. The routing functionality of the MP node may be of multi-point to multi-point. Like MUP, the PMMUP requires no additional hardware modification. Thus, the PMMUP complexity is comparative to that of the MUP. The PMMUP manages large scale multi-radio systems with a reduced complexity whereby each NIC autonomously and locally predicts interference of multiple channels. Moreover, each NIC has independent amount of traffic load at its queue and independent dimension of multiple channel states to estimate.

Numerous works have been proposed for multi-channel MAC with power control [5], [7], [8], [11]. The key idea is that data packets are transmitted with proper power control so as to exploit channel reuse. While control packets are transmitted with maximum power in order to warn the neighbouring nodes of future communication activity between the sender and the receiver. However, due to the close vicinity of NICs and neighbouring nodes, we can assume that a sender MP transmits control packets with a probe power level (i.e., a fraction of maximum power). Moreover, achieving this with beam-forming antennas reduces inter-channel interference and improves neighbour interactions with the best channel qualities [14]. Power control approaches using directional antennas are proposed in [5], [13]. This makes it possible for dynamic adjustment of the transmission power for both data and control packets to optimize energy consumption [13]. The use of beam-switched antennas permits interference-limited concurrent transmissions. It also provides a node with the appropriate tradeoffs between throughput and energy consumption. In this paper we assume that the neighbour discovery procedure is achievable via wide switched beam-width antennas and the data packets can be unicast to target receivers using directional antennas [14].

Autonomous interference estimation based power control mechanisms for single channel wireless networks are well known in [10]-[12]. These mechanisms require each node to adapt the transmission power dynamically in response to channel interference estimations. Adaptive Kalman filters are often employed to estimate channel interference conditions [10]. Using adaptive filters in a MRMC system comes with design complexity challenges [15]. However, we considered parallel optimal control of the transmission power levels by NICs of a node. The optimal controller is based on the linear quadratic methods. Optimal linear quadratic control systems are fast and robust. Parallel algorithms for optimal control of large scale linear systems are well known in [16]. Though there exist liberal applications of such methods for task assignments in distributed computer networks [17], there applications to WMN setting would be an interesting research focus. In the same spirit we proposed a local power optimization algorithm called a multi-radio multi-channel interaction variable prediction algorithm (MMIPA). The converged interference states (i.e., including states from other channels) were exploited for local power optimization. Through simulations, MMIPA yielded significant transmission power saving over the MUP [6] and Single Channel based methods [10], [13]. MMIPA presented a better throughput performance than a dynamic channel assignment with transmission power control (DCA-PC) scheme [8].

To the best of our knowledge, our paper is the first to propose a decentralised aggregate interference prediction method for power optimization in MRMC WMNs.

III. SYSTEM MODEL

A. Preliminaries

Consider a wireless MRMC multi-hop WMN in Fig. 1, operating under dynamic network conditions. Let us assume that the entire mesh network is virtually divided into L disjoint unified channel graphs (UCGs). A UCG is a set of MP PHYs (interfaces) that are interconnected to each other via a common wireless medium channel. In each UCG there are $\|V\| = N_V$, NICs that connect to each other possibly via multiple hops. This means that each multi-radio MP node can belong to at least one UCG. For simplicity it is assumed that the number of NICs, $\|T_A\|$ in each MP node is at most the number of available UCGs, $\|L_A\|$ i.e., $\|T_A\| \le \|L_A\|$. Each UCG is a subsystem with NICs as its members. Members of separate UCGs control their transmission powers in parallel

[14] through associated PMMUP as the coordinator. PMMUP controls greedy power control behaviours among individual NICs [10]. Power resources are dynamically adjusted by each NIC using intra and inter-subsystem (channel) states. Due to the decentralized nature, each MP assumes imperfect knowledge about the global network.

Further we assume that there exists an established logical topology, where some NICs belonging to a certain UCG are *sources* of transmission say $i \in T_A$ while others act as 'voluntary' *relay*s, say $r \in T_B$ to *destinations*, say $d \in T_C$. A sequence of connected *logical links* or simply channels $l \in L(i)$ forms a *route* originating from source i. Each asymmetrical physical link may need to be regarded as multiple logical links due to multiple channels. Radios can switch among different free channels at the end of a time slot so that each channel is maximally utilized all the time. Time slot durations are assumed fixed [11]. Each time slot accounts for a power control adjustment mini-slot time, a packet transmission mini-slot time and a guard time interval. For analytical convenience time slots will be normalized to integer units, $t \in \{0,1,2,...\}$ [11]. In the duration of a time slot neighbouring nodes transmitting within the same channel cause intra-channel or co-channel interference. In addition, nodes transmitting in different neighbouring channels cause inter-channel or adjacent channel interference due to spatial vicinity [5].

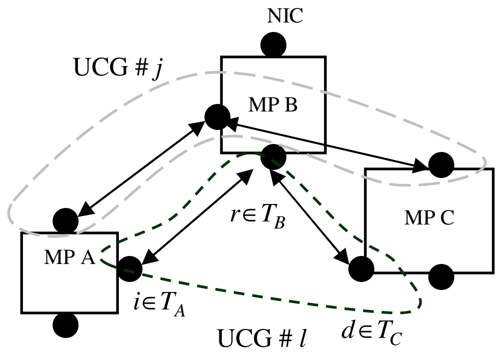

Figure 1. Multi-Radio Multi-Channel (MRMC) and Multi-hop Wireless Mesh communication system

B. *PMMUP Description*

The PMMUP: V-MAC architecture is illustrated in Fig. 2. The PMMUP performs neighbour discovery using a fraction of maximum power assigned to NIC, coordinates power selection procedure and sends data. All these activities need to happen within the same time slot duration. The coordination variables are stored at the neighbour communication power and states (NCPS) table. The NCPS table is shown in Table I. Such coordination variable includes battery energy reserves, multiple channel state conditions and higher layer unification variables.

Neighbour Discovery: At start-up, NICs of a node are tuned to orthogonal UCGs [8]. PMMUP then initiates communication using an address resolution protocol (ARP) message broadcasted over all the NICs [6]. Each NIC sends these messages to neighbours in their corresponding UCGs with a fraction of maximum power level as instructed by the PMMUP. Using this power level, neighbour MAC addresses are exchanged following procedure described in [6].

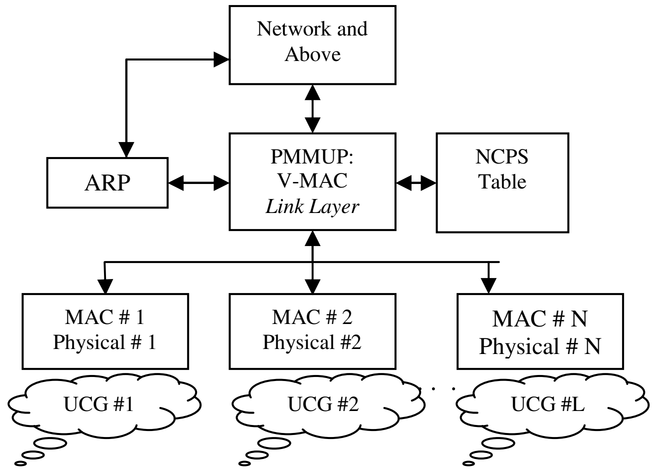

Figure 2. PMMUP: V-MAC architecture for the WMN

TABLE I. ENTRY IN THE PMMUP (NCPS) TABLE

FIELD	*DESCRIPTION (FOR EACH NEIGHBOUR NODE, NEIGH)*
Neighbour	IP address of the neighbour host
Class	Indicates whether *neigh* is PMMUP-enabled or not
MAC list	MAC address associated with *neigh* NICs
States	Recent measurements on: Channel Quality, Queue, RTT, and Energy Reserves
TPL	Recent transmit power level selected

Power Selection Process: The PMMUP chooses initial probing power and broadcasts to all interfaces. This broadcast power level is vital for neighbour discovery process. We refer to the total probing power over the interfaces as *tot-ProbPow.* The energy residing in a node is referred to as *Energy Reserves.*

If (*tot-ProbPow* > *Energy Reserves* and *load queue = 0 at the NICs)*
then do
Nothing; /* Conserve Energy*/
else do /*select the transmission power*/

(i) NICs send "ps (power selection) request" message to neighbours using a probe power level. The ps-request message probes for channel state conditions.
(ii) When the neighbouring NICs receive the "ps-request" message they compute the "state information": Interference, queue status, and energy reserves. This information is piggy-backed in the "ps-Ack" message and sent to the originating NICs using probing power level.
(iii) Upon receiving the ps-Ack messages, each sending NIC independently computes the interference, queue state, energy reserves and RTT, and copies "state information" to the

PMMUP. The PMMUP updates the NCPS table and sends the coordination updates including those from upper layers to lower level NICs for power optimization.

(iv) Each NIC runs local power optimization algorithm (See Section V). Each NIC with DATA in its queue *unicasts* pending traffics to destination neighbour (s) with optimal transmission power. The sending NIC copies the PMMUP with local optimal power information for NCPS table updates.

endif

IV. PROBLEM FORMULATION

Define the distributed power adjustment law for each user (i,r) on UCG l as

$$p_{ir}^{l}(t+1) = \begin{cases} p_{ir}^{l}(t) + f_l\left(I_g^l\right) & if \;\; queue > 0 \\ 0\,, & \text{otherwise} \end{cases} \quad , \qquad (1)$$

where $f_l\left(I_g^l\right)$ is a non-linear function of aggregate network interference among neighbours on UCG l during time slot t. Using Taylor series to obtain a first order linear approximation to $f_l\left(I_g^l\right)$ gives

$$f_l\left(I_g^l\right) \triangleq f\left(I_l^{ss}\right) + \alpha_I\left(I_g^l(t) - I_l^{ss}\right) \;, \qquad (2)$$

where I_l^{ss} is the interference steady state value and $0 \le \alpha_I \le 1$ is the coefficient of Taylor series in (2). If we assume that packets are in the queue and we substitute (2) into (1) we have

$$p_{ir}^{l}(t+1) = p_{ir}^{l}(t) + f\left(I_l^{ss}\right) + \alpha_I e_I^l(t)\,, \qquad (3)$$

where $e_I^l(t) \triangleq I_g^l(t) - I_l^{ss}$ (interference deviation).

Define the predicted aggregate interference [10] among the neighbouring network users with adjacent channel interference (ACI) as

$$I_g^l(t+1) = \left(p_{ir}^{l}(t+1) + \delta\left(p_{ir}^{l-1}(t+1) + p_{ir}^{l+1}(t+1)\right)\right)G_{ir}^{l}(t+1)$$
$$+ I_{ir}^{l}(t+1) + \delta\left(I_{ir}^{l-1}(t+1) + I_{ir}^{l+1}(t+1)\right). \qquad (4)$$

Here, δ is a fraction of transmission power p_{ir}^{l} that leaks across neighbouring adjacent UCGs. $G_{ir}^{l}(t+1)$, is the wireless channel gain. While $I_{ir}^{l}(t+1)$ is the receiver predicted interference as estimated by user (i,r) on UCG l.

Substitute (3) into (4) to get:

$$I_g^l(t+1) = \left(p_{ir}^{l}(t) + \alpha_I e_I^l(t)\right) + G_{ir}^{l}(t+1)$$
$$+\left(p_{ir}^{l-1}(t) + p_{ir}^{l+1}(t) + \alpha_I^{l-1}e_I^{l-1}(t) + \alpha_I^{l+1}e_I^{l+1}(t)\right)\delta G_{ir}^{l}(t+1)$$
$$+ I_{ir}^{l}(t+1) + \delta\left(I_{ir}^{l-1}(t+1) + I_{ir}^{l+1}(t+1)\right). \qquad (5)$$

Let $G_{ir}^{l}(t+1) = G_{ir}^{l}(t)m(t)$ and $I_{ir}^{l}(t+1) = I_{ir}^{l}(t)n(t)$ with $m(t)$ and $n(t)$ are unit mean noise terms with the same variance. Here, $m(t)$ characterizes the slowly changing shadow-fading and the fast multipath-fading on top of the distance loss [10]. The noise term $n(t)$ models the fluctuation when interfaces increase or decrease their transmission power levels or associated nodes either enter or leave the system.

Also, let $e_I^l \triangleq e_I^{l-1} \triangleq e_I^{l+1}$ since with a large time slot duration the interference state deviation goes to zero. Substituting these facts in (5), expanding and simplifying the result, we have a state transition equation [15]:

$$e_I^l(t+1) = mG\left(\alpha_I^l + \delta\alpha_I^{l-1} + \delta\alpha_I^{l+1}\right)e_I^l(t)\,. \qquad (6)$$

Or, more succinctly, $e_I(t+1) = A_I e_I(t)$. Introducing an input control sequence and noise terms to (6) we have

$$e_I(t+1) = A_I\, e_I(t) + B_I\, u_I(t) + \varepsilon_I(t)\,, \qquad (7)$$

where $B_I u_I(t) \triangleq u_I(t)$ characterizes the control sequence that needs to be added to $p_{ir}^{l}(t+1)$ equation (1) in order to derive network dynamics to steady states. B_I is assumed to be a unity coefficient matrix. The state stochastic shocks term $\varepsilon_I(t)$ is a random variable with zero mean and variance, σ_ε^2.

Assume that corresponding to a UCG l is the user (NIC-pair) i. Then, the multi-radio multi-channel state interaction (MRSI) model representation becomes [15]

$$e_i(t+1) = A_i\, e_i(t) + B_i(t)u_i(t) + C_i(t)\, y_i(t) + \varepsilon_i(t)\,, \qquad (8)$$

where $y_i(t)$, introduced in (8), is a linear combination of states (LCS) from other UCGs available to the ith user. This LCS is defined as [17]

$$y_i(t) = \sum_{\substack{j=1 \\ j\ne i}}^{N} L_{ij}(t)e_j(t) + \varepsilon_i^y(t)\,, \qquad (9)$$

where $\varepsilon_i^y(t)$ denotes the coordination process shocks with zero mean and covariance σ_ε^y. $C_i(t)$ is a unity coefficient matrix and $L_{ij}(t)$ is the inter-channels state coupling matrix available between ith user and jth user. In what follows, we formulate the control problem for each user as the minimization of the following stochastic quadratic cost function subject to the cross-channels interaction state equation (8) and coordination states in equation (9):

$$J_i = E\left[\lim_{t\to\infty}\frac{1}{t}\sum_{\tau=0}^{t-1} e_i^T(\tau)Q_i\, e_i(\tau) + u_i^T(\tau)R_i u_i(\tau)\right]$$
$$= \lim_{t\to\infty}\frac{1}{t}\sum_{\tau=0}^{t-1}\sum_{\substack{e_i\in\{e\}\\ u_i\in\{u\}}}\left[e_i^T(\tau)Q_i e_i(\tau) + e_i^T(\tau)R_i e_i(\tau)\right]\times \rho_i\left(e_i,u_i\right) \;,$$

Such that

$$e_i(t+1) = A_i e_i(t) + B_i u_i(t) + C_i y_i(t) + \varepsilon_i^x(t),$$
$$y_i(t) = \sum_{\substack{j=1 \\ j\neq i}}^{N} L_{ij}(t) e_j(t) + \varepsilon_i^y(t). \quad (10)$$

Here, $Q_i \in \mathbb{R} \geq \mathbf{0}$ is assumed symmetric, positive semi-definite matrix and $R_i \in \mathbb{R} > \mathbf{0}$ is assumed symmetric, positive definite matrix. For brevity, we choose Q_i to be an identity matrix and R_i to be a matrix of unity entries. The joint probability density function (pdf) $\rho_i(e_i, u_i)$ denotes the state occupation measure (SOM). The SOM is defined as $\rho_i(e_i, u_i) = \Pr(u_i \mid e_i) \sum_{u_i \in \{u_i\}} \rho_i(e_i, u_i)$. It gives the steady state probability that the control system is in state $e_i \in \{e\}$ and the driving control parameter $u_i \in \{u_i\}$ is chosen. Thus, we seek an optimal $u_i \in \{u_i\}$ that solves the problem in (10). First, we introduce a Lagrange multiplier π_t^i and a state unification (SU) weight φ_{t+1}^i to augment the LCS equality in (9) and the MRSI constraint (8) respectively, to the cost function. We invoke the dynamic programming value function to (10)

$$V(e_t^i) = \min_{\{u_t^i\}} \left\{ e_t^{iT} Q_t^i e_t^i + u_t^{iT} R_t^i u_t^i \right\} +$$
$$\min_{\{u_t^i\}} \rho E \left[V \left(-\pi_t^T y_t^i + \pi_t^T \sum_{\substack{j=1 \\ j\neq i}} L_t^{ij} e_t^j + \pi_t^T \varepsilon_t^y \right) \right] +$$
$$\min_{\{u_t^i\}} \rho E \left[V \left(\varphi_{t+1}^T A_t^i e_t^i + \varphi_{t+1}^T B_t^i u_t^i + \varphi_{t+1}^T C_t^i y_t^i + \varphi_{t+1}^T \varepsilon_t^x \right) \right]. \quad (11)$$

We drop superscripts i and subscripts t for notation convenience. Differentiating w.r.t. u and solving in terms of u implies $u^* = -\left(R + \rho B^T \varphi P \varphi^T B\right)^{-1} \rho B^T \varphi P \varphi^T A e$. Or more succinctly

$$u^* = -Fe, \quad (12)$$

with $$F = \left(R + \rho B^T P_\varphi B\right)^{-1} \rho B^T P_\varphi A . \quad (13)$$

Let $P_\varphi \triangleq P$ be a Riccati matrix [15] with φ is a unity scalar. Starting from an initial guess of P matrix in the value function, P_k is updated to P_{k+1} according to

$$P_{k+1} = Q + \rho A^T P_k A - \rho^2 A^T P_k B \left(R + \rho B^T P_k B\right)^{-1} B^T P_k A . \quad (14)$$

Hitherto, y_i signifies Interference states from other UCGs. φ_i and π_i signify *unification variables* (UV) such as energy reserves in a node and weighting information from upper layers of the protocol stack. e_i signifies *interaction state variable (IV)* among different UCGs. Each transmitting user solves the local optimization problem according algorithm 1 in Section V.

V. MMIPA ALGORITHM

Algorithm 1: MMIPA: Predicts MRMC Interaction Variables
*/*NICs Predict Interference States and Compute optimal power signal*/*

Input: π_i , y_i ; */*Coordination Variables*/*
e_i ; */*ith System Interaction Variable*/*
*A, B, C,Q and R; /*Control System Matrices*/*
Output: u_i^* */*ith NIC system optimal power control signal*/*
1: **while** $(k \geq 1)$ **do**
2: **for each** *(NIC-pair* $i \in [1, N]$ *)* **do**
3: Predict: $e_i(k) \leftarrow e_i(k+1)$; */*from function (11)*/*
4: **end for each**
5: **if(** $\Delta(k+1) \leq \varepsilon_{rr}$ *, a small positive value)* **then**
6: Compute: $u_i^* = -Fe_i^*$;*/* Local Optimization (12)*/*
7: **Add** u_i^* **to** Equation (1) ;
8: **else do go** to Step 1;
9: **endif**
10: **end while**
Here,
$$\Delta(k+1) = \left\| e_i(k+1) - e_i(k) \right\| .$$

VI. SIMULATION TESTS AND RESULTS

In our simulations, we used MATLAB™ version 7.1[18]. We assumed 50 stationary wireless nodes randomly located in a 1200 m x 1200 m region. Each node had 4 NICs each tuned to a unique UCG. Thus, each UCG had 50 NICs assumed fully interconnected over a wireless medium. For evaluation purposes, we considered the frequency spectrum of 2412 MHz-2472 MHz. So that in each UCG, frequency carriers are: 2427 MHz, 2442 MHz, 2457 MHz and 2472 MHz. To evaluate design matrices in Sections IV and V, other simulation specifications were used as illustrated in Table II.

TABLE II. SIMULATION SPECIFICATIONS

Parameter	*Specification*	*Parameter*	*Specification*
Bandwidth	10 *MHz*	Txt. & Interf. Ranges	240 m and 480 m
Basic Rate	2 *Mbps*	Probe power	Variable[Pmin,Pmax]
Max. Link Capacity	54 *Mbps*	MAC Scheme	Time-Slotted CDMA
Min.Txt. Power	10 *mW*	Slot & Power update Period	100 msec, 80 msec
SINR threshold	4-10 *dB*	Offered Load and Queue Length	12.8,51.2,89.6,128 *packets/s and* 50 *packets*
Thermal Noise	90 *dBm*	Packet sizes and FEC sizes	1000 *bytes and 50 bytes*
Max.Txt Power	500 *mW*	Simulation Time	60 *seconds*

Fig. 3 shows the simulation when packets were generated from each node and the transmission power needed to reach the neighbouring nodes was measured. During the transmission time 4 non-overlapping UCGs with adjacent power leakage factor of 0.5 were used. The results reveal that increasing the amount of generated traffic increases the amount of needed power. At 20 packets per slot, MMIPA requires 29.41% more power than DCA-PC [8], 20%, 78.82%, and 62.35% less power than LCAP with directional antennas [13], MUP without power control [6] and AIDPC with a common base station receiver [10], respectively. This is because MMIPA predicts interference interaction states autonomously and locally. Autonomous prediction boosts convergence rate resulting in a low computational and transmit power. MMIPA recorded more power consumption than DCA-PC because MMIPA assumes static channel assignments with all NICs all the time. The DCA-PC allows for switching the channels over a few NICs leading to a reduction in transmission power [8].

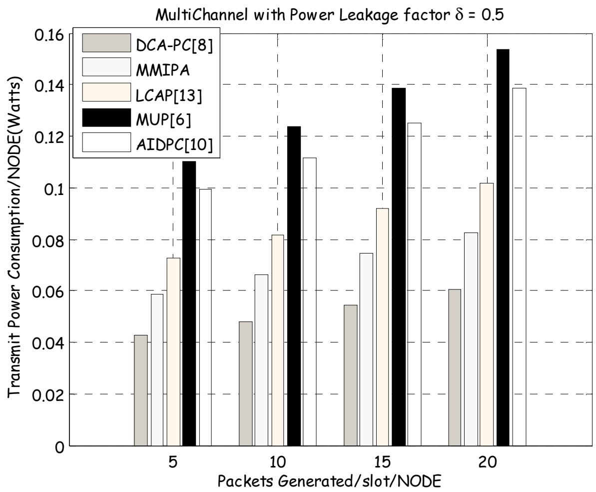

Figure 3. Transmission power needed for a NODE

Fig. 4 illustrates throughput performance when offered loads were varied. MMIPA recorded the most superior throughput performance at various loads compared to the related methods. Specifically, at 90 packets/s of load, MMIPA yielded 64% more throughput than MUP algorithm. This is because MMIPA stripes packets using all the Interfaces and at a judicious power level. While MUP selects only one Channel with a good round trip time (RTT). MUP transmits packets without transmit power control. This results in adverse network intra-channel interference and a degraded throughput.

VII. CONCLUSION

This paper has demonstrated effectively how transmission power can be controlled in an MRMC WMN. Simulation results showed that using an autonomous interference-aware power control yields significant power conservations and throughput improvement for a multi-radio system.

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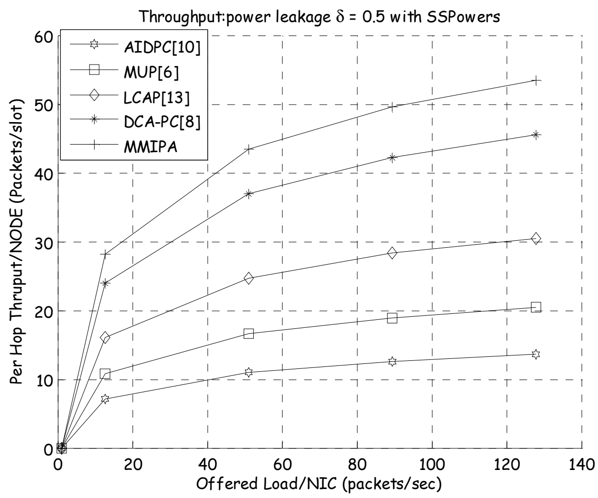

Figure 4. Average Throughput per NODE Vs Offered Load