Decentralized Power Control for Multi-Radio Multi-Channel Wireless Mesh Networks

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***Abstract*-- Multi-Radio Multi-Channel (MRMC) WMNs result in power control problems including interference, un-scalable connectivity and energy-consumption. Several previous studies have focused on the single radio wireless configurations while studying power control problems. However, such contributions can not solve the power control problems in MRMC configurations because of the architectural and structural differences amongst them. This paper presents a dynamic power control for MRMC WMNs. First, WMN is represented as a set of disjoint Unified Channel Graphs (UCGs). Second, a new power selection MRMC Unification protocol (PMMUP) is proposed that coordinates interactions among radios assigned to a unique UCG. Third, each radio-pair adjusts transmission power using the predicted Interaction State Variables (IVs) across UCGs. To ensure convergence, IVs are derived from the dynamic linear quadratic controller. Depending on the size of the queue loads and intra-and inter-channel states, each radio optimizes the transmission power locally and asynchronously. The efficacy of the proposed method is investigated through simulations.**

***Index Terms*— Asynchronous control, Multi-Radio Multi-Channel (MRMC), Power Selection Multi-Radio Multi-Channel Unification Protocol (PMMUP) and 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 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 [2], [3]. This results in independent communications among 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 with packet striping capabilities [4].

The operation of MRMC WMNs generally requires sustainable energy supply. WMNs have become a robust alternative for extending Wireless Local Area Networks (WLANs) to provide network coverage up to the furthest of far flung rural areas [5]. Electric power outlets are usually scarce especially in most of African rural areas. Mesh nodes do rely on battery power supply for their operations in such applications. Furthermore, due to the scarce skilled manpower, regular network maintenances and battery replacements in remote places are seldom. Typical topography of remote areas requires that mesh networks 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 [6]. This phenomenon degrades the robustness of a self-configuring WMN. Moreover, injudicious use of transmit power decreases channel reuse in a physical area and increases co-channel interference with neighbouring hosts. Multiple radios in MRMC configurations are practically in close vicinity, implying that significant cross-channel interference can be experienced [2]. Numerous previous contributions have relaxed this practical stand point by assuming that channels are ideally orthogonal, e.g., [7]-[9]. Effects of interference reduce network throughput and the receiver signal to interference plus noise ratio (SINR) [8,10]. Fortunately, power control minimizes interference, improves topology control and routing in WMNs [6,7].

This paper studies a decentralised dynamic power control scheme for MRMC WMN. This is to avoid single points of failures, guarantee self-configuration and self-organization, and demonstrate independency on topology configurations. Specifically, radios of an MP node adapt the transmission power based on queue arrivals, energy reserves and multiple power control dependent metrics. Such metrics include the received signal-to-interference plus noise ratio (SINR)

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deviation, aggregate co-channel interference among neighbouring nodes and transmission rate deviation. The contribution of the paper lies on how such metrics from neighbouring orthogonal channels can effectively be coordinated to yield optimal power levels for each transmitter. This scalability naturally suits the WMN applications.

The rest of this paper is organised as follows. Section II discusses related work. The System Model is described in III. Section IV formulates the Problem. In Section V, the MRSIPA algorithm is presented. Section VI presents the simulation results and Section VII concludes the paper.

II. Related Work

In order to unify the operations of independent multi-radio systems, a *virtual* MAC protocol on top of the legacy MAC is adopted [1]. The virtual MAC coordinates (unifies) the communication in all the radios [9,11]. 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 [9]. The MUP discovers neighbours, selects the network interface card (NIC) with the best channel quality based on the round trip time (RTT) and sends data on a pre-assigned channel. The MUP then switches channels after sending the data. However, the MUP assumes power unconstrained mesh network scenarios. Mesh nodes are plugged into an electric power supply socket. The 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). The PMMUP enhances functionalities of the original MUP. Such enhancements include: an energy-efficient neighbour discovery, power selection capability and the utilization of power controlled parallel radios or channels to send data traffic simultaneously. This is to increase channel diversity.

Numerous works have been proposed for multi-channel MAC with power control techniques [10]-[14]. The key idea is that data packets are transmitted with proper power control so as to exploit channel reuse. 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, transmission power leakage across multiple channels may be significant. Thus, we advocate that a sender MP node should transmit 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 [10] and improves a node's ability to reach its neighbours which have the best channel qualities. Power control approaches using directional antennas are proposed in [10,15]. This makes it possible for dynamic adjustment of the transmission power for both data and control packets to optimize energy consumption [15]. The use of beam-switched antennas permits interference-limited concurrent transmissions. It also provides a node with the appropriate tradeoffs between the 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 connected to a unique radio interface device [16].

Autonomous dynamic power control mechanisms for single channel wireless networks are well known in [13,17,18]. These mechanisms require each node to adapt the transmission power dynamically in response to the channel interference estimations. Adaptive Kalman filters are often employed to estimate the channel interference conditions [17]. Using adaptive filters in a MRMC system comes with design complexity challenges [19]. Our work considers parallel optimal asynchronous control of the transmission power levels by a NIC-pair (a user). The optimal controller is based on the linear quadratic methods [19]. Optimal linear quadratic control systems are fast and robust. Parallel algorithms for optimal control of large scale linear systems are well known in [20]. There exist liberal applications of such methods for parallel and distributed computing [21]. Such contributions do not take into account transmission power adaptation in an MRMC wireless network. Recently, an MRMC Unification variable prediction based power control algorithm called *MRSUPA* was proposed in [22]. However, the proposed algorithm requires that the physical layer interacts with higher layers in the protocol stack [13]. Such information exchanges imply significant protocol complexities and latency [17]. Range based power control method is proposed in [16]. However, transmission ranges determine the network interference plus other power control metrics which were not considered.

In order to ensure convergence, this paper presents the PMMUP enabled asynchronous and decentralized power control method. The asynchronous attribute allows simulteneous accessing and routing of the backbone traffic. The PMMUP *guess*es initial unification variables such as energy reserves, NICs asynchronously *predict* the local states derived from a convex cost function, the PMMUP *updates* coordination variables and NICs *compute* local optimal transmission power levels. We refer to this PMMUP enabled approach as the Multi-Radio Multi-Channel System Interaction States Prediction Algorithm (MRSIPA). Through simulations, the MRSIPA yielded significant transmission power saving over the MUP [9] and Striping models [4]. The MRSIPA throughput performance outperforms that of dynamic channel assignment with transmission power control (DCA-PC) scheme [12].

III. System Model

A. Preliminary

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 has transmitter-receiver pairs its members. Members of separate UCGs control their transmission powers in parallel [21] through associated PMMUP layer as the coordinator. The PMMUP layer controls greedy power control behaviours among individual members [17] by setting a battery energy constraint. Power resources are dynamically adjusted by each user (i.e., a UCG member)

Further let 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' *relays*, 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 (See Fig.1). Each asymmetrical physical link may need to be regarded as multiple logical links due to multiple channels. Radios exploit the distributed CSMA/CA mechanism [14] to access the wireless medium. A radio holding the medium divides its access time into fixed time slot durations [13]. 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, $t \in \{0,1,2,...\}$ [13]. It is also assumed that nodes employ spread spectrum signalling techniques. Such techniques allow interference-limited simultaneous transmissions among neighbouring nodes on the same wireless channel. In addition, nodes transmitting in different neighbouring channels cause inter-channel or adjacent channel interference due to close spatial vicinity [10]. Inter-channel interference will be in this paper approximated by a quantity called a power leakage factor. This quantity will be chosen arbitral for evaluation purposes only.

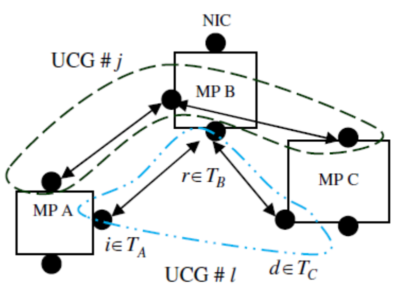

Fig. 1: Multi-Radio Multi-Channel (MRMC) and Multi-hop Wireless Mesh communication system

B. PMMUP Description

The PMMUP: V-MAC scheme is implimented at the Link Layer of the Protocol Stack [22]. The virtual MAC (V-MAC) performs three-fold functions: energy-efficient *neighbour discovery*, *power optimization* and *data transmission over power controlled parallel* wireless channels [16, 22].

Power Selection Process: The PMMUP layer chooses the 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*. Algorithm 1 summarizes the Power Selection Process.

Algorithm 1: PMMUP operation

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1: If (tot-ProbPow > the Energy Reserves or Load Queue = 0 at the NICs)
2: Each NIC selects transmission power to zero.
3: else
4: PMMUP unicasts and/or multicasts "ps-Request" message
5: Neighbour NICs evaluate "Link State Information" and feedback "ps-Ack"
6: Sender NICs receive "ps-Ack" and evaluate "Link State Information"
7: Each sender NIC runs local power optimization algorithm (Cf. Section V)
8: Each NIC unicasts pending DATA traffic to the Neighbour Destinations
9: Each sender NIC copies the optimal power values to the PMMUP table
10: endif
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PMMUP requests its neighbours for link state information by unicasting power selection (i.e., ps-Request) message. Up on receiving ps-Request messages, neighbouring NICs evaluate the "link state information" such as SINR, Interference, Rate, Queue status and Energy reserves (i.e., line 5). After receiving the acknowledgement (i.e., ps-Ack) message, each sender NIC evaluates additional state information such as Round trip time (RTT) (i.e., line 6). Transmission power is then optimally selected based on the link state information (i.e., line 7). Data traffics are transmitted using optimal power levels (i.e., line 8) and the PMMUP table is updated for the next time slot (i.e., line 9).

IV. PROBLEM FORMULATION

Define the distributed energy-efficient power control law for each lth transmitter-receiver pair (i.e., user) associated to the lth UCG as

$$p_l(t+1) = \begin{cases} p_l(t) + f_l(\mathbf{x}) & \text{if Queue} > 0 \\ 0 & \text{otherwise,} \end{cases} \quad (1)$$

where $f_l(\mathbf{x}) = f_l(\beta_l(t), I_l(t), \Gamma_l(t))$. Notations, $\beta_l(t)$, $I_l(t)$ and $\Gamma_l(t)$ as the actual SINR, aggregate co-channel network interference and wireless link transmission rate, respectively, during time slot t. They demonstrate the network capacity-power functions. Using Taylor series to obtain first order linear approximations to $f_l(\mathbf{x})$ gives

$$\begin{aligned} f_l(\mathbf{x}) \triangleq\ & f\left(\gamma_l^{ss}, I_l^{ss}, \Lambda_l^{ss}\right) + \alpha_\beta\left(\beta_l(t) - \gamma_l^{ss}\right) \\ & + \alpha_I\left(I_l(t) - I_l^{ss}\right) + \alpha_\Gamma\left(\Gamma_l(t) - \Lambda_l^{ss}\right) \end{aligned}, \quad (2)$$

where γ_l^{ss}, I_l^{ss} and Λ_l^{ss} are the steady state values.

Let $\mathbf{x}_l \triangleq \left(\beta_l - \gamma_l^{ss} \quad I_l - I_l^{ss} \quad \Gamma_l - \Lambda_l^{ss}\right)^T$ be the Interaction state vector (IV) of a control system for every strategy user [19]. The states' transition equation is then represented as

$$\mathbf{x}_l(t+1) = \mathbf{A}_l \mathbf{x}_l(t) + \mathbf{B}_l \mathbf{u}_l(t) + \varepsilon_l(t), \quad (3)$$

where $\mathbf{A}_l$ a 3 x 3 coefficient matrix is derived in [22] and $\mathbf{u}_l \in \{\mathbf{u}_l\}$ characterizes the input control sequence that needs to be added to $p_l(t+1)$ equation (1) in order to derive network dynamics to steady states. $\mathbf{B}_l$ is assumed to be a 3 x 1 coefficient matrix. The state stochastic shocks term $\varepsilon_l(t)$ is a 3 x 1 random vector with zero mean and unity covariance.

Let us have $l \geq i$ so that the number of channels is at least the number of radio-pairs (i.e., users). The multi-radio interaction state space (MRISS) model for each user i becomes [19]:

$$\mathbf{x}_i(t+1) = \mathbf{A}_i(t)\mathbf{x}_i(t) + \mathbf{B}_i(t)\mathbf{u}_i(t) + \mathbf{C}_i(t)\mathbf{y}_i(t) + \varepsilon_i(t), \qquad (4)$$
$$\mathbf{x}_i(t_0) = \mathbf{x}_{i0}, \ \forall i,$$

where $\mathbf{y}_i(t)$, introduced in (4), is a linear combination of states (LCS) from other UCGs available to the ith user (MRMC subsystem). This LCS is defined as

$$\mathbf{y}_i(t) = \sum_{\substack{j=1 \\ j\neq i}}^{N} \mathbf{L}_{ij}(t)\mathbf{x}_j(t) + \varepsilon_i^y(t), \qquad (5)$$

where $\varepsilon_i^y(t)$ denotes the coordination process shocks with zero mean and covariance matrix $\Theta_\varepsilon = \mathrm{E}\varepsilon_i^y(t)\varepsilon_i^{yT}(t)$, $\mathbf{C}_i(t)$ is considered to be a 3 x 3 identity coefficient matrix and denotes the coupling weight among users of separate wireless channels. Matrix $\mathbf{L}_{ij}(t)$ is the higher level interconnection matrix of states between ith user on UCG i and jth user on UCG j. In order to derive the channel states to steady state values with low amount of energy, we formulate the control problem for each NIC-pair (user) as the minimization of the following stochastic quadratic cost function subject to the MRISS constraint (4) and the LCS constraint or coordination states equation (5):

$$J_i = E\left[\lim_{t\to\infty}\frac{1}{t}\sum_{\tau=0}^{t-1}\mathbf{x}_i^T(\tau)\mathbf{Q}_i\,\mathbf{x}_i(\tau) + \mathbf{u}_i^T(\tau)\mathbf{R}_i\mathbf{u}_i\right]. \qquad (6)$$

Here, $\mathbf{Q}_i \in \mathbb{R}^{3\times3} \geq \mathbf{0}$ is assumed symmetric, positive semi-definite matrix and $\mathbf{R}_i \in \mathbb{R}^{M\times M} > \mathbf{0}$ is assumed symmetric, positive definite matrix. For brevity, we choose $\mathbf{Q}_i$ to be an identity matrix and $\mathbf{R}_i$ to be a matrix of unity entries.

Thus, we seek an optimal $\mathbf{u}_i \in \{\mathbf{u}_i\}$ that solves the problem in (6). First, we introduce Lagrange multipliers $\boldsymbol{\pi}_t^i$ and a state unification (SU) vector $\boldsymbol{\varphi}_{t+1}^i$ to augment the LCS equality in (5) and the MRISS constraint (4) respectively, to the cost function. In order to attain the convergence of the control process with a reduced time cost, we invoke the dynamic programming value function

$$V(\mathbf{x}_t^i) = \min_{\{\mathbf{u}_t^i\}}\left\{\mathbf{x}_t^{iT}\mathbf{Q}_t^i\,\tilde{\mathbf{x}}_t^i + \mathbf{u}_t^{iT}\mathbf{R}_t^i\,\mathbf{u}_t^i\right\} +$$
$$\min_{\{\mathbf{u}_t^i\}}\rho E\left[V\left(-\boldsymbol{\pi}_t^T\mathbf{y}_t^i + \boldsymbol{\pi}_t^T\sum_{\substack{j=1\\ j\neq i}}\mathbf{L}_t^{ij}\mathbf{x}_t^j + \boldsymbol{\pi}_t^T\boldsymbol{\varepsilon}_t^y\right)\right] +$$
$$\min_{\{\mathbf{u}_t^i\}}\rho E\left[V\left(\boldsymbol{\varphi}_{t+1}^T\mathbf{A}_t^i\mathbf{x}_t^i + \boldsymbol{\varphi}_{t+1}^T\mathbf{B}_t^i\mathbf{u}_t^i + \boldsymbol{\varphi}_{t+1}^T\mathbf{C}_t^i\mathbf{y}_t^i + \boldsymbol{\varphi}_{t+1}^T\boldsymbol{\varepsilon}_t^x\right)\right] \qquad (7)$$

For notational convenience, one can drop subscripts and superscripts in (7). In all cases, variables are t-time slot dated and ith user dynamics. It should be noted that power control dependent multiple metrics are of size three, trading off complexity for the transmission power optimality. Furthermore, the recursion in (7) assumes that the network operates under conditions that are close to steady state. Thus, optimal conditions can be obtained rapidly fast. Differentiating (7) partially w. r. t. $\mathbf{u}$, and solving in terms of optimal $\mathbf{u}^*$, one gets,

$$\mathbf{u}^* = -\left(\mathbf{R} + \rho\mathbf{B}^T\boldsymbol{\varphi}\mathbf{P}\boldsymbol{\varphi}^T\mathbf{B}\right)^{-1}\rho\mathbf{B}^T\boldsymbol{\varphi}\mathbf{P}\boldsymbol{\varphi}^T\mathbf{A}\mathbf{x}. \qquad (8)$$

Let $\mathbf{P}_{\boldsymbol{\varphi}} \triangleq \mathbf{P}$ be an idempotent Riccati matrix [19] with $\boldsymbol{\varphi}$ is a unity weighting vector. Starting from an initial guess of $\mathbf{P}$ matrix in the value function, $\mathbf{P}_k$ is updated to $\mathbf{P}_{k+1}$ according to

$$\mathbf{P}_{k+1} = \mathbf{Q} + \rho\mathbf{A}^T\mathbf{P}_k\mathbf{A} - \rho^2\mathbf{A}^T\mathbf{P}_k\mathbf{B}\left(\mathbf{R} + \rho\mathbf{B}^T\mathbf{P}_k\mathbf{B}\right)^{-1}\mathbf{B}^T\mathbf{P}_k\mathbf{A} \qquad (9)$$

Hitherto, $\mathbf{y}$ signifies states from other UCGs (coordination vector), $\boldsymbol{\varphi}$ and $\boldsymbol{\pi}$ signify *unification variables* (UV) such as energy reserves and information from higher layers and $\mathbf{x}$ signifies the *interaction variables* (IVs) represented in (3) a long with those states coordinated from other UCGs. Coordination variables (CV), $\mathbf{y}$ and $\boldsymbol{\pi}$ are updated by the PMMUP. While each NIC-pair solves the local optimization problem given by the value function keeping the CV fixed. Thus, MRSIPA algorithm constitutes step 7 of the PMMUP operation discussed in Section IIIB.

V. ASYNCHRONOUS ALGORITHM: MRSIPA

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Algorithm 2: MRSIPA: Predicts MRMC Interaction
Variables Asynchronously and Optimize Transmission
Power

Input: π , y ; x_i ;
Output: u_i^*

At each virtual time-slot t and for all step
k user i performs:

1:while (k≥1) do
2:Predict: x_i(k)←x_i(k+1);
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3:if ($\mathbf{x}_i(k+1) \equiv \mathbf{x}_i^*$ **for any** $i \neq j$, $\forall j \in [1, N]$) **then do**
4:Send the converged IV to the PMMUP layer;
5:go to Step 11;
6:else /*Interaction Variables (IVs) do not convergence asynchronously***/**
7:All users update NCPS Table Contents with IVs;
8:PMMUP **Updates:** $\mathbf{y}(k) \leftarrow \mathbf{y}(k+1)$; $\boldsymbol{\pi}(k) \leftarrow \boldsymbol{\pi}(k+1)$;
9:PMMUP **Sends** these CV updates to all users for the next power iteration;
10: end if
11:if ($e(k+1) \leq \varepsilon_{rr}$, *a small positive value*) **then do**
12:Compute: $\mathbf{u}_i^*$ *from Equation (8)*;
13:Add $\mathbf{u}_i^*$ **to** Eq. (1) for optimal power level;
14:else do go to Step 1;
15:end if
16:end while

Here,

$$e(k+1) = \left\| \mathbf{g}(k+1) - \mathbf{g}(k) \right\|,$$

$$\mathbf{g}(k) = \left[\mathbf{y}_i^T(k) \ \boldsymbol{\pi}_i^T(k) \right]^T .$$

It should be noted that the convergence of the *Step 11* is always guaranteed since the stabilizing solution **P** in (9) is obtainable under mild conditions of the channel matrix **A.**

VI. Simulation Tests And Results

In our simulations, we used MATLAB™ version 7.1. We assumed 50 stationary wireless nodes randomly located in a 1200m x 1200m region. Each node had 4 NICs each tuned to a unique frequency. 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. Direct sequence spread spectrum signalling in the IEEE 802.11 PHY layer was assumed because of its potential for multi-user access through CDMA techniques. The legacy MACs assumed CSMA/CA techniques for distributed medium acess and the Link Layer assigned NICs orthogonal codes that can overlap with little or no effect on each other. Other simulation specifications used are illustrated in Table I. The model matrices discussed in Sections IV and V were computed from one hop node interaction with its neighbours using specified parameters from Table I. It should be noted that each simulation was performed long enough for the output statistics to stabilize (i.e., sixty seconds simulation time).

TABLE I: SIMULATION SPECIFICATIONS

Parameter	*Specifics*	*Parameter*	*Specification*
Bandwidth	10 *MHz*	Maximum Txt. & Interf. Ranges	**240 m and 480 m**
Basic Rate	2 *Mbps*	Probe power	**Variable[Pmin,Pmax]**
Max. Link Capacity	54 *Mbps*	MAC Scheme	**CSMA/CA**
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. 2 shows the simulation when packets were generated from each node and the transmission power needed to reach the neighbouring nodes was measured. Related power control approaches were simulated under the same channel conditions as those of the MRSIPA approach. During the transmission time, 4 non-overlapping UCGs with adjacent power leakage factor of 0.5 were used. Leakage factor depicts the amount of interference coupling between non-overlapping channels which are co-located. Simulation results reveal that increasing the amount of generated traffic increases the amount of needed power. This suggests that high data volume implies high transmission energy consumption. At 20 packets per slot, the MRSIPA requires 28.57% more power than dynamic channel assignment with power control (DCA-PC) [12], 22.22%, 88.89%, and 66.67% less power than load-based concurrent access protocol (LCAP) with directional antennas [15], Load Sensitive (LS) Striping [4] and the MUP without power control [8], respectively. This is because the PMMUP enabled the MRSIPA is based on the awareness of the battery power supply and queue load. The MRSIPA predicts cross-channel states asynchronously. Asynchronous prediction boosts convergence rate resulting in a low computational and transmit power. The MRSIPA recorded more power consumption than the DCA-PC because the MRSIPA assumes that all NICs have static channel assignments within the complete duration of the transmission (i.e., a time slot). However, channels are switched after the elapse of one time slot. The DCA-PC allows for channel switching over a few optimally selected NICs leading to a reduction in transmission power level [12].

Fig. 3 illustrates throughput performance with 95% confidence interval when offered loads were varied. The MRSIPA recorded the most superior throughput performance at various loads compared to the related methods. Specifically, at 90 packets/s of load: the MRSIPA yielded 72.73% more throughput performance measured in terms of packets per time slot duration than the MUP algorithm. This is because the MRSIPA stripes packets using all the Interfaces and at a judicious power level. The MUP selects only one Channel with a good round trip time (RTT). The MUP transmits packets without transmit power control. This results in adverse network intra-channel interference and a degraded throughput per node. The MRSIPA provided 66.67%, 48.15% and 22.22% more throughput than LS-striping, LCAP with directional antennas and the DCA-PC methods, respectively. The MRSIPA converges asynchronously while the LS-striping is a synchronous. Thus, the former saves more computational time, and hence relatively lower delay than the latter. Short execution periods yield an improved throughput performance under the same packet transmission rate. The MRSIPA exploits all power-controlled channels simultenously while the DCA-PC utilizes only assigned channels for transmission. The MRSIPA method selects transmission power based on the knowledge of the neighbourhood conditions while the LCAP is based on only the traffic load. Thus, our approach demonstrates dominant throughput performance as multiple channels are used in parallel for communication. Finally, it is worth noting that asynchronous convergence and autonomous transmissions among radios resolve the problems of retransmissions within a UCG. Users experiencing very poor channel conditions can power-down temporarily until the channel regains good conditions. Though, this might result in significant energy gain at the expense of traffic delay. Delay effects are limited by exploiting other active users to relay traffic on behalf of inactive users.

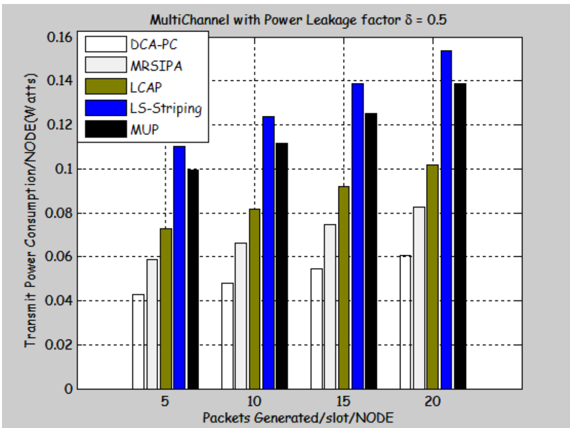

Figure 2: Transmission power needed to transmit packets from a sender node to receiver nodes

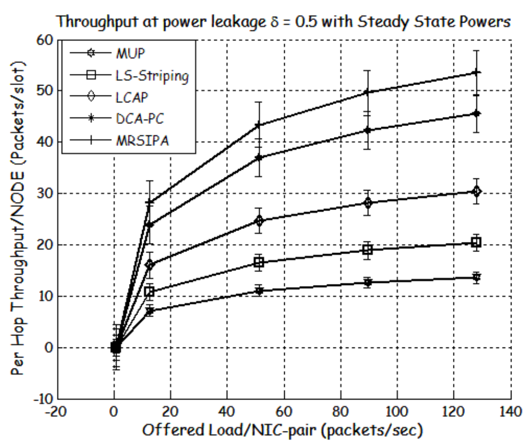

Figure 3: Average Throughput due to the transmission of each node measured at 95 % Confidence Interval versus Offered Load Traffic

VII. CONCLUSION

This paper has demonstrated effectively how transmission power can be controlled in an MRMC WMN. Simulation results showed that using an asynchronous dynamic power control yields significant power conservations and throughput improvement and better trade-off for a multi-radio multi-channel (MRMC) wireless system. A scalable and energy-efficient routing and asynchronous power control under other topologies forms the basis of our future work. The implimentation of the new protocol in outdoor field tests remains an open issue.

REFERENCES

[1] I. F. Akyildiz, X. Wang, and W. Wang, "Wireless mesh networks: A survey," *Computer Networks Journal (Elsevier),* vol. 47 (4), 2005, pp. 445-487.

[2] B. O'Hara and A. Petrick, *The IEEE 802.11 Handbook: A designer's Companion.* IEEE; 1st Ed (December 1999), 188 pages.

[3] Engim Inc., Multiple Channel 802.11 Chipset. Available from: http://www.engim.com/products_en3000.html.

[4] H. Adiseshu, G. Parulkar, and G. Varghes, "A Reliable and Scalable striping protocol," in Proc. *SIGCOMM*, Aug. 1996.

[5] J. Ishmael, S. Bury, D. Pezaros and N. Race, "Rural community wireless mesh networks," *IEEE Internet Computing Journal,* July/August 2008, pp. 22-29.

[6] H. Zhu, K. Lu and M. Li, "Distributed Topology Control in Multi-Channel Multi-Radio Mesh Networks," In *Proc. ICC 2008*, pp. 2958-2962.

[7] L. Chen, Q. Zhang, M. Li, and W. Jia, "Joint topology control and routing in IEEE 802.11 based multiradio multichannel mesh networks," *IEEE Transactions on Vehicular Technology*, vol. 56, no. 5, September 2007, pp. 3123-3136.

[8] J. Tang, G. Xue and W. Zhang, "End-to-end rate allocation in multi-radio wireless networks: cross-layer schemes," in Proc. *3rd Intl. conf. QShine'06,* Aug. 7-9 2006, Waterloo, vol. 191, issue 5.

[9] A. Adya, P. Bahl, J. Padhye, A. Wolman, and L. Zhou, "A Multi-Radio Unification Protocol for IEEE 802.11 Wireless Networks," In *Proc. Of the first international conference on Broadband Networks (Broadnets'04),* 2004.

[10] V. Ramamurthi, A. Reaz, S. Dixit, and B. Mukherjee, "Link scheduling and power control in Wireless Mesh Networks with Directional Antennas," *Communications, 2008. ICC '08. IEEE International Conference,* 19-23 May 2008*,* pp.4835-4839.

[11] J. So and N. H. Vaidya, "Multi-channel MAC for ad hoc networks: handling multi-channel hidden terminals using a single transceiver", in *Proc. ACM Intl. Symposium on Mobil. Ad Hoc Netw. Comp. (MOBIHOC),* May 2004, pp. 222-233.

[12] Y.-C. Tseng, S.-L. Wu, C. –Y. Lin and J. –P. Shen, "A multi-channel MAC protocol with power control for multi-hop ad hoc networks," in Proc. *Distributed Computing Systems Workshop, 2001 intl. conf.,* April 2001, pp. 419-424.

[13] K. Wang, C. F. Chiasserini, J. G. Proakis and R. R. Rao, "Joint scheduling and power control supporting multicasting in wireless ad hoc networks," *Elsevier Ad Hoc Networks*, vol. 4, 2006, pp. 532-546

[14] N. Poojary, S. V. Krishnamurthy and S. Dao, "Medium access control in ad hoc mobile nodes with heterogeneous power capabilities," in Proc. *IEEE ICC*, 2001, pp. 872-877.

[15] A. Arora and M. Krunz, "Power controlled MAC for ad hoc networks with directional antennas," *Elsevier Ad Hoc Networks*, vol. 5 (2007), pp. 145-161.

[16] T. O. Olwal, B. J. Van Wyk, K. Djouani, Y. Hamam, P. Siarry and N. Ntlatlapa, "Range Based Power Control for MRMC Wireless Mesh Networks," in Proc. *SATNAC 2009*, pp. 49-54, Swazi Land, Aug. 2009.

[17] S. Sorooshyari and Z. Gajic, "Autonomous dynamic power control for wireless networks: User-centric and Network-Centric Consideration," *IEEE Trans. Wireless Commun.,* vol. 7 (3), 2008, pp. 1004-1015.

[18] S. Koskie and Z. Gajic, "Optimal SIR-based power control strategies for wireless CDMA networks," *Intl. Journal of Inform. And Syst. Sciences,* vol. 1 (1), 2007, pp. 1-18.

[19] M. S. Mahmoud, M. F. Hassan and M. G. Darwish, *Large Scale Control Systems Theories and Techniques,* Dekkar, New York, 1985.

[20] Z. Gajic and X. Shen, *Parallel algorithms for optimal control of large scale linear systems,* Springer-Verlag, London, 1993.

[21] S. S. Abdelwahed, M. F. Hassan and M. A. Sultan, "Parallel asynchronous algorithms for optimal control of large scale dynamic systems," *Journ. of Optimal Contr. Applicat. and methods*, vol. 18, 1997.

[22] T. Olwal, B. J. van Wyk, K. Djouani, Y. Hamam, P. Siarry and N. Ntlatlapa, "Autonomous Transmission Power Adaptation for Multi-Radio Multi-Channel Wireless Mesh Networks" in *Ad Hoc-Now 2009*, LNCS 5793, pp. 284-297.

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