Autonomous Transmission Power Adaptation 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. Previous studies have emphasized throughput maximization in such systems as the main design challenge and transmission power control treated as a secondary issue. In this paper, we present an autonomous power adaptation for MRMC WMNs. The transmit power is dynamically adapted by each network interface card (NIC) in response to the locally available energy in a node, queue load, and interference states of a channel. To achieve this, WMN is first represented as a set of Unified Channel Graphs (UCGs). Second, each NIC of a node is tuned to a UCG. Third, a power selection MRMC unification protocol (PMMUP) that coordinates Interaction variables (IV) from different UCGs and Unification variables (UV) from higher layers is proposed. PMMUP coordinates autonomous power optimization by the NICs of a node. The efficacy of the proposed method is investigated through simulations.

Key words: Multi-Radio Multi-Channel (MRMC), Power Selection Multi-Radio Multi-Channel Unification Protocol (PMMUP), Wireless Mesh Networks (WMNs).

1 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

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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]. Each radio has a single or multiple orthogonal channels [3]. In this scenario, an MP node has each radio with its own medium access control (MAC) and physical layers [1]. This results in 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 [4]. However, utilizing multiple-radios and channels for each node simultaneously, results in striping related problems [11]. First the use of multiple radios on multiple channels is expensive. In that case one assumes that the number of radios is less than the number of channels. This allows for interface channel switching technique to improve channel utilization. Switching an interface from one channel to another incurs switching delays [8]. Thus, we assume that the frequency of channel switching is low. Second, timeout problems due to packet re-sequencing at the receiver node may become significant. Scalable resolutions of such problems are well known in [11] and [8].

The operation of multi-radio multi-channel (MRMC) WMNs generally requires sustainable energy supply. Substantial deployments of WMNs have recently picked up in rural and remote communities [4]. In 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. Moreover injudicious use of transmit power decreases channel reuse in a physical area and increases co-channel interference with neighbouring hosts. This in turn causes severe reduction in network throughput. Therefore besides throughput maximizations [7], transmission power control should be prioritized in such networks [5]. Controlling transmission power would enhance topology control and routing in MRMC WMNs [6].

In this paper we study an autonomous power level adjustment mechanism for MRMC WMN. Radios of an MP adapt transmission powers based on queue arrivals, energy reserves and multiple channel conditions. The optimal power level is changed dynamically after a certain period of time (i.e., slot duration). This work is motivated by the fact that WMN system needs to be dynamic and scalable. That is, it can autonomously adapt to nodes entering the network (i.e., introducing multiple interferences) or those exiting the network due to node failures (i.e., energy depletion), poor connectivity and so forth.

We considered an MRMC system in which each radio or network interface card (NIC) has its own MAC and physical layers. However, all radios of the same MP node were assumed to share common memory, central processor and energy supply modules. 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 [8], [9]. 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 [8]. 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: energy-efficient power selection capability and the utilization of parallel radios or channels to send data traffic simultaneously. Like MUP, the PMMUP requires no additional hardware modification. Thus, the PMMUP complexity is comparative to that of the MUP. It is to be noted that the main motivation behind PMMUP concept is the need for a single MP to access mesh client network and route the backbone traffic simultaneously [1]. The routing functionality of the MP may be of multi-point to multi-point. Therefore, PMMUP manages large scale multi-radio systems with a reduced complexity [18]. In order to achieve this task, PMMUP mainly coordinates local power optimizations at the NICs. While NICs measure dynamic channel conditions. As a result, we have a simple four step power adjustment algorithm. That is, PMMUP *guesses* initial unification variables, NICs *predict* the local channel system states, PMMUP *updates* unification variables and NICs *compute* local optimal transmission power levels for each channel. We assume that each NIC has independent amount of traffic load at its queue and independent dimension of channel states to measure. Therefore each NIC dynamically selects optimal transmission power level asynchronously. We propose a PMMUP algorithm called the Multi-radio multi-channel system Unification Variables Prediction Algorithms (MRSUPA). Through simulations, PMMUP algorithm yielded significant transmission power savings over the MUP [8] and Striping models [11]. MRSUPA presented a better throughput performance than the dynamic channel assignment with power control (DCA-PC) scheme [10]. The MRSUPA algorithm is scalable and practical for multi-radio WMN compared to the single channel methods in [12] and [13].

The rest of this paper is organised as follows. We discuss related work in Section 2. We describe the System model and the PMMUP in Section 3. Section 4 formulates the Problem. In Section 5 we present the MRSUPA algorithm. Section 6 presents simulation results and Section 7 concludes the paper.

2 Related Work

Numerous works have been proposed for multi-channel MAC with power control [5], [9], [10], [13], [15]. 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 interferences and improves neighbour reach-ability with the best channel qualities [17]. Power control approaches using directional antennas are proposed in [5], [16]. This makes it possible for dynamic adjustment of the transmission power for both data and control packets to optimize energy consumption [16]. 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 [17].

Autonomous dynamic power control mechanisms for single channel wireless networks are well known in [12]-[14]. 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 [12]. Using adaptive filters in a MRMC system comes with design complexity challenges [18]. In this work we consider parallel optimal asynchronous control of the transmission power levels by the NICs as coordinated by the PMMUP. The optimal controller is based on the linear quadratic methods [18]. Optimal linear quadratic control systems are fast and robust. Parallel algorithms for optimal control of large scale linear systems are well known in [19]. There exist liberal applications of such methods for task assignments in distributed computer networks [20]. To the best of our knowledge, our paper is the first to propose the PMMUP enabled autonomous power adjustment scheme for MRMC WMNs.

3 System Model

3.1 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 in each MP node is at most the number of available UCGs, i.e.,$\|T_A\| \leq \|L_A\|$. Each UCG is a subsystem with NICs as its members. Members of separate UCGs control their transmission powers in parallel [17] through associated PMMUP as the coordinator. PMMUP manages greedy power control behaviours among

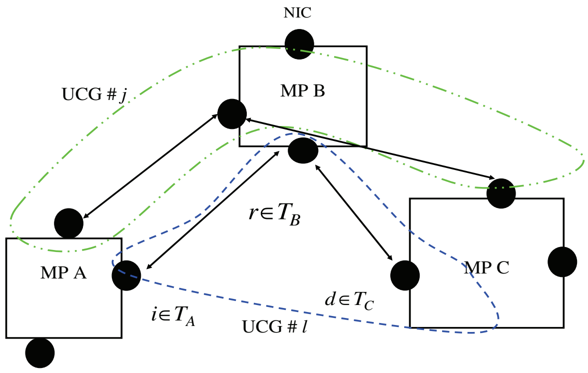

Fig. 1. Multi-Radio Multi-Channel (MRMC) and Multi-hop Wireless Mesh communication system. Two Unified Channel Graphs (UCGs) labeled UCG j and UCG l are shown.

individual NICs [12]. Power resources are dynamically adjusted by each NIC using intra and inter-subsystem (channel) states. In this sequel such states include the signal-to-interference plus noise ratio (SINR) deviation, aggregate interference and link capacity error. 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' *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 . Each asymmetrical physical link may need to be regarded as multiple logical links due to multiple channels. NICs 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 [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]. 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].

3.2 PMMUP Description

The PMMUP: V-MAC architecture is illustrated in Figure 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

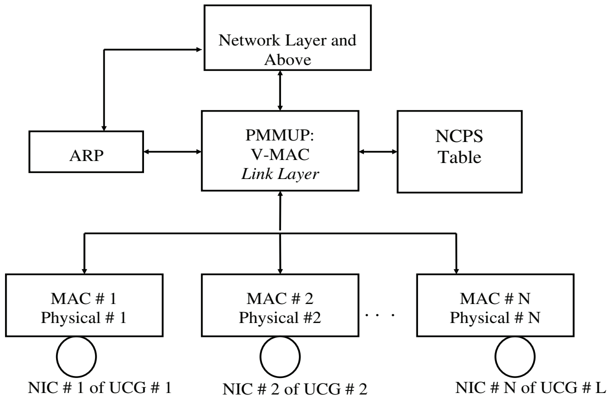

Fig. 2. PMMUP: V-MAC architecture for the WMN.

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 1. 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 [10]. PMMUP initiates communication using an address resolution protocol (ARP) message broadcast over all the interfaces [8]. Each interface sends these messages to neighbours in their corresponding UCGs with a fraction of maximum power as instructed by the PMMUP. Upon receiving the ARP requests, the destination node sends the ARP responses with the MAC addresses of the NICs on which it received the ARP requests. Once the originating host receives the ARP responses it proceeds to communicate with the interface from which it received ARP responses. The PMMUP then classifies neighbours according to the procedure highlighted in [8]. Nodes that support PMMUP are classified as PMMUP enabled nodes otherwise qualified as legacy nodes.

Table 1. Entry in the PMMUP (NCPS) Table

FIELD	DESCRIPTION(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": SINR, Interference, Queue status, and Energy reserves. This information is piggy-backed in the "ps-Ack" message and sent via feedback path to the originating NICs, using probing power level.
(iii) Upon receiving the ps-Ack messages, each sending NIC independently computes the SINR, 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 algorithms (See Section 5). 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

Other Advantages: PMMUP does not require a global knowledge of the network topology hence it is a scalable protocol. Contents of a neighbourhood topology set are added or subtracted one node at a time. PMMUP utilizes multiple parallel channels. Thus, it has the ability to adapt to switched antenna beams for efficient spectral reuse. That is, neighbour discovery *broadcasts* would require Omni directional beam pattern while data transmissions can be effected using directional beam pattern. PMMUP is located at the Link layer (mid-way the protocol stack) thus; cross-layer information interacts with a reduced latency. The NCPS table is assumed to have a few information to update. Neighbour discovery occurs once throughout the power optimization interval. This reduces memory and computational complexities.

4 Problem Formulation

We derive state transitional models (or, "state information") as functions of the predicted power levels for each transmitter-receiver pairs (users) in every UCG. Let us define the distributed energy-efficient power adjustment law for each user as

$$p_{i,l}\,(t+1) \;=\; \begin{cases} p_{i,\,l}\,(t) \;+\; f_l\,(\mathbf{x}) \quad \forall \mathbf{x} \in \{\mathbf{x}\} \quad \text{if Queue} \;>\; 0 \\ 0\,, \qquad \text{otherwise} \end{cases}, \tag{1}$$

where $f_l(\mathbf{x}) = f_l(\beta_l(t), I_l(t), \Gamma_l(t))$, $\beta_l(t)$, $I_l(t)$ and $\Gamma_l(t)$ as the actual SINR, aggregate network interference and scheduled transmission rate during time slot t. Using Taylor series to obtain first order linear approximations to $f_l(\mathbf{x})$ gives $f_l(\mathbf{x}) \overset{\Delta}{=} f(\gamma_l^{ss}, I_l^{ss}, \Lambda_l^{ss}) + \alpha_\beta(\beta_l(t) - \gamma_l^{ss}) + \alpha_I(I_l(t) - I_l^{ss}) + \alpha_\Gamma(\Gamma_l(t) - \Lambda_l^{ss})$ where γ_l^{ss}, I_l^{ss} and Λ_l^{ss} are steady state values of a power adaptation system[18].

Let $\frac{G_{ll}(t+1)}{I_{(i,r),\,l}(t+1)} = H(t)\frac{m(t)}{n(t)}$ be defined as the predicted effective channel gain with $m(t)$ and $n(t)$ are independent unit mean noise terms with the same variance σ_m^2. Defining the SINR as $\beta_l(t+1) = \frac{p_l(t+1)G_{ll}(t+1)}{I_{(i,r),l}(t+1)}$ and substituting $p_l(t+1)$ we get: $\beta_l(t+1) = [p_l(t) + f_l(\mathbf{x})]\,H(t)\frac{m(t)}{n(t)}$. Thus the SINR deviation is shown as

$$\begin{aligned} e_\beta(t+1) = {} & H(t)\frac{m(t)}{n(t)}\alpha_\beta(\beta_l(t) - \gamma_l^{ss})\; H(t)\frac{m(t)}{n(t)}\alpha_I(I_l(t) - I_l^{ss}) \;+ \\ & H(t)\frac{m(t)}{n(t)}\alpha_\Gamma(\Gamma_l(t) - \Lambda_l^{ss}). \end{aligned} \tag{2}$$

Here, $m(t)$ characterizes the slowly changing shadow-fading and the fast multipath-fading on top of the distance loss [12]. 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.

In a similar way we define the deviation of aggregate interference among the neighbouring interfaces in a UCG as

$$\begin{aligned} e_I(t+1) = {} & G_{ll}(t)\,m(t)\,\alpha_\beta(\beta_l(t) - \gamma_l^{ss})\; G_{ll}(t)\,m(t)\,\alpha_I(I_l(t) - I_l^{ss}) \;+ \\ & G_{ll}(t)\,m(t)\,\alpha_\Gamma(\Gamma_l(t) - \Lambda_l^{ss}). \end{aligned} \tag{3}$$

Following similar procedure the deviation of transmission rate for the same link l is written as follows,

$$\begin{aligned} e_\Gamma(t+1) = {} & \frac{1}{p_l(t)}\left[\alpha_\beta(\beta_l(t) - \gamma_l^{ss})\; \alpha_I(I_l(t) - I_l^{ss})\; \alpha_\Gamma(\Gamma_l(t) - \Lambda_l^{ss})\right] \;+ \\ & \log m(t) - \log n(t). \end{aligned} \tag{4}$$

Let $\mathbf{x}_l \overset{\Delta}{=} (\beta_l - \gamma_l^{ss} \;\; I_l - I_l^{ss} \;\; \Gamma_l - \Lambda_l^{ss})^T$ be state measurements of a control system. Combining equations (2), (3) and (4) and introducing an input sequence term, we obtain $\mathbf{x}_l(t+1) = \mathbf{A}_l\mathbf{x}_l(t) + \mathbf{B}_l\mathbf{u}_l(t) + \varepsilon_l(t)$ where $\mathbf{A}_l$ is a 3 x 3 coefficient matrix given by $\mathbf{A}_l = \begin{pmatrix} \frac{m}{n}H\alpha_\beta & \frac{m}{n}H\alpha_I & \frac{m}{n}H\alpha_\Gamma \\ mG\alpha_\beta & mG\alpha_I & mG\alpha_\Gamma \\ \frac{\alpha_\beta}{p_l} & \frac{\alpha_I}{p_l} & \frac{\alpha_\Gamma}{p_l} \end{pmatrix}$, and $\mathbf{B}_l\mathbf{u}_l(t) = \begin{bmatrix} u_\beta(t) \\ u_I(t) \\ u_\Gamma(t) \end{bmatrix}$ characterizes the 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 $\varepsilon_l\left(t\right)$ is a 3 x 1 random vector with zero mean and covariance matrix, $\Theta_\varepsilon \;=\; \mathrm{E}\varepsilon_l\left(t\right)\varepsilon_l^T\left(t\right) \;=\; diag\left(\sigma_\beta^2, \sigma_I^2, \sigma_T^2\right)$. If we assume that corresponding to a UCG l is the PMMUP user i and $l = i$ then the Multi-radio interaction state space (MRISS) model representation becomes[18]

$$\mathbf{x}_i\left(t+1\right) \;=\; \mathbf{A}_i\left(t\right)\mathbf{x}_i\left(t\right) \;+\; \mathbf{B}_i\left(t\right)\mathbf{u}_i\left(t\right) \;+\; \mathbf{C}_i\left(t\right)\mathbf{y}_i\left(t\right) \;+\; \varepsilon_i\left(t\right), \qquad (5)$$

where $\mathbf{y}_i\left(t\right)$, introduced in (5), is a linear combination of states (LCS) from other UCGs available to the ith user. This LCS is defined as

$$\mathbf{y}_i\left(t\right) \;=\; \sum_{\substack{j=1\\ j\neq i}}^{N} \mathbf{L}_{ij}\left(t\right)\mathbf{x}_j\left(t\right) \;+\; \varepsilon_i^y\left(t\right), \qquad (6)$$

where $\varepsilon_i^y\left(t\right)$ denotes the coordination process shocks with zero mean and covariance matrix $\Theta_\varepsilon \;=\; \mathrm{E}\,\varepsilon_i^y\left(t\right)\varepsilon_i^{yT}\left(t\right)$, $\mathbf{C}_i\left(t\right)$ is considered to be a 3 x 3 identity coefficient matrix and $\mathbf{L}_{ij}\left(t\right)$ is the higher level interconnection matrix of states between ith user and jth user. This interconnection matrix needs to be evaluated by the PMMUP. This interconnection matrix needs to be evaluated by the PMMUP. In what follows, we formulate the control problem for each user as the minimization of the following stochastic quadratic cost function subject to the network interaction state equation (5) and coordination states in equation (6):

$$\begin{aligned} J_i \;&=\; E\left[\lim_{t\to\infty}\frac{1}{t}\sum\nolimits_{\tau=0}^{t-1}\mathbf{x}_i^T\left(\tau\right)\mathbf{Q}_i\,\mathbf{x}_i\left(\tau\right) \;+\; \mathbf{u}_i^T\left(\tau\right)\mathbf{R}_i\mathbf{u}_i\right] \\ &= \lim_{t\to\infty}\tfrac{1}{t}\sum\nolimits_{\tau=0}^{t-1}\sum\nolimits_{\substack{\mathbf{x}_i\in\{\mathbf{x}\}\\ \mathbf{u}_i\in\{\mathbf{u}\}}}\left[\mathbf{x}_i^T\left(\tau\right)\mathbf{Q}_i\mathbf{x}_i\left(\tau\right) \;+\; \mathbf{u}_i^T\left(\tau\right)\mathbf{R}_i\mathbf{u}_i\left(\tau\right)\right] \times \\ &\quad \rho_i\left(\mathbf{x}_i, \mathbf{u}_i\right). \end{aligned} \qquad (7)$$

Here, $\mathbf{Q}_i \in \Re^{3\times3} \geq \mathbf{0}$ is assumed symmetric, positive semi-definite matrix and $\mathbf{R}_i \in \Re^{M\times M} > \mathbf{0}$ is assumed symmetric, positive definite matrix. For brevity, choose $\mathbf{Q}_i$ to be an identity matrix and $\mathbf{R}_i$ to be a matrix of unity entries. The joint probability density function (pdf) $\rho_i\left(\mathbf{x}_i, \mathbf{u}_i\right)$ denotes the state occupation measure (SOM). The SOM is defined as
$\rho_i\left(\mathbf{x}_i, \mathbf{u}_i\right) \;=\; \Pr\left(\mathbf{u}_i|\mathbf{x}_i\right)\sum_{\mathbf{u}_i\in\{\mathbf{u}_i\}}\rho_i\left(\mathbf{x}_i, \mathbf{u}_i\right)$. It gives the steady state probability that the control system is in state $\mathbf{x}_i \in \{\mathbf{x}\}$ and the driving control parameter $\mathbf{u}_i \in \{\mathbf{u}_i\}$ is chosen. Thus, we seek an optimal $\mathbf{u}_i \in \{\mathbf{u}_i\}$ that solves the problem in (7). First, we introduce Lagrange multipliers π_t^i and a state unification (SU) vector ϕ_{t+1}^i to augment the LCS equality in (6) and the MRISS constraint (5) respectively, to the cost function. We then invoke the dynamic programming value function

$$V\left(\mathbf{x}_t^i\right) \;=\; \min_{\{\mathbf{u}_t^i\}}\left\{\mathbf{x}_t^{iT}\mathbf{Q}_t^i\,\mathbf{x}_t^i \;+\; \mathbf{u}_t^{iT}\mathbf{R}_t^i\,\mathbf{u}_t^i\right\} +$$

$$\min_{\{\mathbf{u}_t^i\}}\rho E\left[V\left(-\pi_t^T\mathbf{y}_t^i + \pi_t^T\sum_{\substack{j=1\\ j\neq i}}\mathbf{L}_t^{ij}\mathbf{x}_t^j + \pi_t^T\varepsilon_t^y\right)\right] +$$

$$\min_{\{\mathbf{u}_t^i\}} \rho\, E\left[V\left(\phi_{t+1}^T \mathbf{A}_t^i \mathbf{x}_t^i + \phi_{t+1}^T \mathbf{B}_t^i \mathbf{u}_t^i + \phi_{t+1}^T \mathbf{C}_t^i \mathbf{y}_t^i + \phi_{t+1}^T \varepsilon_t^x\right)\right]. \tag{8}$$

Differentiating w.r.t. $\mathbf{u}$ and solving in terms of $\mathbf{u}$, with subscripts and superscripts dropped for notational convinience we have,

$$\mathbf{u}^* = -\mathbf{F}\mathbf{x}, \tag{9}$$

where $\mathbf{F} = \left(\mathbf{R} + \rho \mathbf{B}^T \phi \mathbf{P} \phi^T \mathbf{B}\right)^{-1} \rho \mathbf{B}^T \phi \mathbf{P} \phi^T \mathbf{A}$. 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 $\mathbf{P}_{k+1} = \mathbf{Q} + \rho \mathbf{A}^T \mathbf{P}_k \mathbf{A} - \rho^2 \mathbf{A}^T \mathbf{P}_k \mathbf{B} \left(\mathbf{R} + \rho \mathbf{B}^T \mathbf{P}_k \mathbf{B}\right)^{-1} \mathbf{B}^T \mathbf{P}_k \mathbf{A}$.
Hitherto, $\mathbf{y}$ signifies states from other UCGs. ϕ signifies *unification variables* (UV) such as energy reserves and higher layers' information and $\mathbf{x}$ signifies the *interaction variable* (IV) including those states coordinated from other UCGs. Using MRSUPA, each NIC-pair predicts $\mathbf{x}_i$ and ϕ_i locally and autonomously keeping $\mathbf{y}$ fixed [14]. PMMUP assigns NICs the updated $\mathbf{y}$ according to algorithm 1 in Section 5.

5 MRSUPA Algorithm

Table 2. (Algorithm 1: MRSUPA:**)***Asynchronous Unification Variables Prediction*

STEP: CONTROL ACTION TAKEN BY EACH PMMUP USER

```
Input: $\phi$, $\mathbf{y}$, $\mathbf{x}_i$, A,B,C,Q and R
Output: $\mathbf{u}_i^*$
1:while ($k \geq 1$) do
2: for each (user $i \in [1, N]$) do
3:   Predict: $\mathbf{x}_i(k) \leftarrow \mathbf{x}_i(k+1)$; $\phi_i(k) \leftarrow \phi_i(k+1)$;/*from min of Eq. (8)*/
4:  if ($\mathbf{x}_i(k+1) \equiv \mathbf{x}_i^*$ && $\phi_i(k+1) \equiv \phi_i^*$ for any $i \neq j, \forall j \in [1, N]$ ) then
5:  Send converged states to PMMUP;
6:  PMMUP Updates: $\mathbf{y}(k) \leftarrow \mathbf{y}(k+1)$ ;
7:  PMMUP Sends Updates to all NICs belonging to the same mesh point;
8:  else /*UV do not converge Asynchronously*/ do go to Step 2;
9: end for each.
10:  if ($e(k+1) \leq \varepsilon_{rr}$ a small positive value) then
11:  Compute: $\mathbf{u}_i^* = -\mathbf{F}_{\phi^*} \mathbf{x}_i^*$ /* Local Optimization using Eq.(9)*/
12:  Add: $\mathbf{u}_i^*$ to Equation(1) of Section 4;
13:  else do go to Step 1;
14:  end if
15:end while
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Here, $e(k+1) = \|\mathbf{g}(k+1) - \mathbf{g}(k)\|$, $\mathbf{g}(t) = \left[\mathbf{y}_i^T(k)\ \ \phi_i^T(k)\right]^T$, and $\mathbf{g}(k+1) = \left[\mathbf{y}_i^T(k+1)\ \ \phi_i^T(k+1)\right]^T$.

Table 3. Simulation Specifications

Parameter	*Specs.*	*Parameter*	*Specification*
Bandwidth:	10 MHz	Trx and Interf. Ranges:	240 m and 480 m
Basic rate:	2 Mbps	Probe Power:	Variable[Pmin,Pmax]
Max Link Rate:	54 Mbps	MAC scheme:	Time-Slotted CDMA
Min Trx Power:	10 mW	Slot time:	100 msec
SINR Threshold:	4-10 dB	Offered Load:	12.8,51.2,89.6,128 packets/s
Thermal Noise:	90 dB	Packet and FEC sizes:	1000 bytes and 50 bytes
Max Trx Power:	500 mW	Simulation Time:	60 seconds

6 Simulation Tests and Results

In our simulations, we used MATLAB version 7.1[21] to implement state information interactions between Link and Physical layers. 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. Other simulation specifications were used as illustrated in Table 3 from which design matrices were evaluated.

Fig. 3 shows the simulation when packets were generated by each node and the consumed energy per the transmitted amount of packets were recorded. Time slots of 0.1667% of Simulation time were allowed for at least 60 Monte Carlo Simulation runs for random network configurations. Four non-overlapping UCGs with adjacent power leakage factor of 0.5 were assumed. The results reveal that increasing the amount of generated traffic increases the amount of power needed. At 20 packets per slot, MRSUPA required 28.57% more power than a dynamic channel assignment with power control (DCA-PC) [10], 22.22%, and 66.67% less power than a load sensitive concurrent access protocol (LCAP) based method [16], and MUP without power control [8], respectively. This is due to the autonomy among the NICs, MRSUPA converges fast resulting in a low computational and transmission energy. However, MRSUPA is based on static channel assignments in contrast to the DCA-PC. Switching channels can resolve interference problems [9][10].

For a specific deployment area, the density of users was varied and the average throughput in a UCG was noted as shown in Fig. 4. We calibrated confidence intervals of about 95% plotted along the throughput performance results. When the network density was 2x10-5 , MRSUPA presented superior throughput of 79.17%, 54.17% and 33.33% more over the autonomous interference estimation (AIDPC) based method [12], MUP without power control [8] and DCA-PC [10], respectively. This is because, MRSUPA probes neighbours with a controlled power level and unicasts data packets directionally. This results in a good spatial reuse for throughput enhancement. Fig. 5 illustrates throughput performance

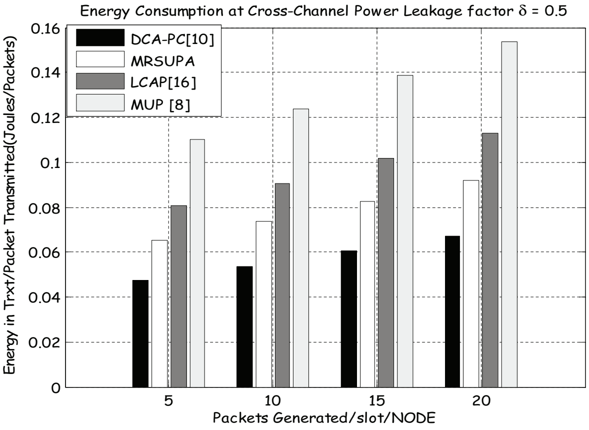

Fig. 3. Energy per transmitted data versus packets generation rate.

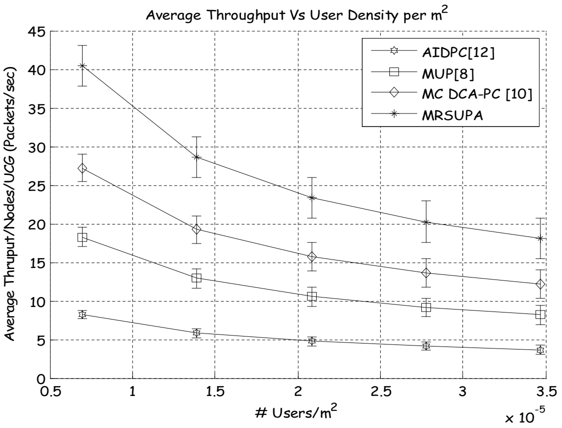

Fig. 4. Average Throughput per UCG versus Users' density.

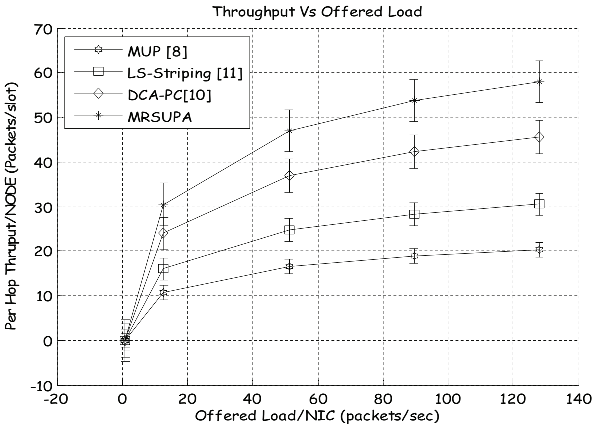

Fig. 5. Per Hop Throughput for every Multi-radio Node versus Offered Load.

with offered loads using a similar experiment as for Fig. 4. MRSUPA recorded the most superior throughput performance at various loads compared to the related methods. Specifically, at a load of 80 packets/s, MRSUPA yielded 65.38%, 48.08% and 19.23% more throughput than MUP [8], load sensitive striping (LS-striping) [11] and DCA-PC [10], respectively. This is because MRSUPA stripes arriving packets over all the Interfaces resulting in decongested queues. MUP makes use of only one channel and does not take transmission power into account. The LS striping does not consider power control. Moreover, MRSUPA autonomously predicts channel state and queue conditions.

7 Conclusions

This paper has demonstrated effectively how to autonomously adapt transmission power in an MRMC WMN. Simulation results showed that using the PMMUP algorithm we can significantly achieve power conservation and throughput improvement for a multi-radio system. However, a scalable joint power control and routing problem with delay constraints in a MRMC WMN forms the basis of our future work.

References

1. Akylidiz, I. F., Wang, X., Wang, W.: Wireless Mesh Networks: a survey. J. Computer Networks. 47, 445–487 (2005).
2. O'Hara, B., and Petrick, A.: The IEEE 802.11 Handbook: A designer's Companion. IEEE; 1st Ed, 188 pages, (1999).

3. Engim Inc.: Multiple Channel 802.11 Chipset. Available from: `http://www.engim.com/`.
4. Ishmael, J., Bury, S., Pezaros, D., Race, N.: Rural community wireless mesh networks. J. IEEE Internet Computing. 22–29 (2008).
5. Ramamurthi, V., Reaz, A., Dixit, S., Mukherjee, B.: Link scheduling and power control in Wireless Mesh Networks with Directional Antennas. In: Proc. ICC '08, 19-23 May 2008, pp.4835–4839 (2008).
6. Chen, L., Zhang, Q., Li, M., Jia, W.: Joint topology control and routing in IEEE 802.11 based multiradio multichannel mesh networks. IEEE Transactions on Vehicular Technology. 56 (5), 3123–3136 (2007).
7. Tang, J., G. Xue, G., Zhang, W.: End-to-end rate allocation in multi-radio wireless networks: cross-layer schemes. In: Proc. 3rd Intl. conf. QShine'06, 191(5), Waterloo, Aug. 7-9 (2006).
8. Adya, A., Bahl, P., Padhye, J.,Wolman, A., Zhou, L.: A Multi-Radio Unification Protocol for IEEE 802.11 Wireless Networks. In: Proc. 1st international conf. Broadband Networks (Broadnets'04), (2004).
9. So, J., Vaidya, N. H.: 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), 222–233 (2004).
10. Tseng, Y.-C., Wu, S.-L., Lin, C.-Y., Shen, J.-P.: A multi-channel MAC protocol with power control for multi-hop ad hoc networks. In: Proc. Distributed Computing Systems Workshop, 419–424 (2001).
11. Adiseshu, H., Parulkar, G., Varghes, G.: A Reliable and Scalable striping protocol. In: Proc. SIGCOMM, Aug. (1996).
12. Sorooshyari, S., Z. Gajic, Z.: Autonomous dynamic power control for wireless networks: user-centric and network-centric consideration. IEEE Trans. Wireless Commun. 7 (3), 1004–1015 (2008).
13. Wang, K., Chiasserini, C. F., Proakis, J. G., Rao, R. R.: Joint scheduling and power control supporting multicasting in wireless ad hoc networks. J. Ad Hoc Networks. 4, 532–546 (2006).
14. Koskie, S., Gajic, Z.: Optimal SIR-based power control strategies for wireless CDMA networks. J. Inform. And Syst. Sciences. 1 (1), 1–18 (2007).
15. Poojary, N., Krishnamurthy, S. V., Dao, S.: Medium access control in ad hoc mobile nodes with heterogeneous power capabilities. In: Proc. IEEE ICC, 872–877 (2001).
16. Arora, A., M. Krunz, M.: Power controlled MAC for ad hoc networks with directional antennas. Elsevier Ad Hoc Networks. 5, 145–161 (2007).
17. Winters, J. H., Martin, C. C., N. R. Sollenberger, N. R.: Forward Link smart antennas and power control for IS-136. In: Proc. IEEE 48th Vehicle Tech. Conf. 1998, 1,601–605 (1998).
18. Mahmoud, M. S., Hassan, M. F., Darwish, M. G.: Large Scale Control Systems Theories and Techniques, Dekkar, New York, (1985).
19. Gajic, Z., Shen, X.: Parallel algorithms for optimal control of large scale linear systems, Springer-Verlag, London. (1993).
20. Abdelwahed, S. S., Hassan, M. F., Sultan, M. A.: Parallel asynchronous algorithms for optimal control of large scale dynamic systems. J. Optimal Control applications and methods. 18, (1997).
21. MathWorks Inc.: `http://www.mathworks.com/`