A Multiple-State Based Power Control for Multi-Radio Multi-Channel Wireless Mesh Networks

T. O. Olwal, K. Djouani, B. J. van Wyk, Y. Hamam, P. Siarry and N. Ntlatlapa

***Abstract*—Multi-Radio Multi-Channel (MRMC) systems are key to power control problems in wireless mesh networks (WMNs). In this paper, we present asynchronous multiple-state based power control for MRMC WMNs. First, WMN is represented as a set of disjoint Unified Channel Graphs (UCGs). Second, each network interface card (NIC) or radio assigned to a unique UCG adjusts transmission power using predicted multiple interaction state variables (IV) across UCGs. Depending on the size of queue loads and intra- and inter-channel states, each NIC optimizes transmission power locally and asynchronously. A new power selection MRMC unification protocol (PMMUP) is proposed that coordinates interactions among radios. The efficacy of the proposed method is investigated through simulations.**

***Keywords*—Asynchronous convergence, 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 an 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]. Each radio has a single or multiple orthogonal channels [3]. In this scenario, an MP node has each radio with its own 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 network [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. Thus, we can assume that the number of network interface cards (NICs) or radios, is less than the number of channels. This allows for radio interface- channel switching technique to improve channel utilization. Switching an interface from one channel to another incurs switching delays [8]. In such cases, we require that the frequency of channel switching should be low. Radio interfaces are allocated fixed frequency channels during every time slot period [8], [22]. Second, multiple radios multiple channel (MRMC) configurations present significant timeout problems due to packet re-sequencing at the receiver node. Scalable resolutions of such problems are well known in [8], [11].

The operation of MRMC WMNs generally requires sustainable energy supplies. Substantial deployments of WMNs have been recently witnessed in rural and remote communities [4]. In such applications, electric power outlets are hardly available and nodes must rely on battery power supply for their operations. Furthermore, regular network maintenances and battery replacements in such areas 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. 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. Radio interfaces operating on a common wireless channel need to ensure half-duplex, unicasts and collision-free communications. However, multiple radios of the same node 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 an existence of ideal orthogonal channels, e.g., [6]-[8]. The general claim is that two or more links sharing one common node can only be active for transmission if they work in different non-overlapping channels. However, in [25], it was shown that this claim is invalid considering wireless MRMC configurations. Therefore besides throughput maximizations [7], transmission

T. O. Olwal is with the Tshwane University of Technology, Paris-12 University and Meraka Institute at the CSIR, South Africa. Phone: +27 12 841 2085; +27128414829; thomas.olwal@gmail.com.

B. J. van Wyk, K. Djouani and Y. Hamam, are with Tshwane University of Technology, French South African Technical Institute in Electronics, X680, Pretoria (e-mail: vanwykb@gmail.com,djouani@univ-paris12.fr , yskandar@hamam.ws).

P. Siarry is with the University of Paris-12. (siarry@univ-paris12.fr). N. Ntlatlapa is with Meraka Institute (e-mail: Ntlatlapa@csir.co.za).

power control, antenna engineering and out-of-band signal filtering are important operations in MRMC wireless networks [5]. Controlling transmission power enhances topology control and routing in MRMC WMNs [6].

In this paper we study a decentralised power control scheme for MRMC WMN that exploits linear quadratic control theory [18]. 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). The motivation of the study is that WMN systems need 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.

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 MRSIPA 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 [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 network interface card (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 power supply socket. MUP utilizes only a single selected channel for data transmission.

Our power optimization protocol follows the MUP concept in spirit. Instead of MUP 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 neighbour discovery, power selection capability and the utilization of parallel radios or channels to send data traffic simultaneously. This makes it possible for a single MP node to access a mesh client network and route the backbone traffic simultaneously [1]. Furthermore, the routing functionality of the MP node may be of multi-point to multi-point. Therefore, PMMUP manages large scale multi-radio systems with a reduced complexity. Like MUP, the PMMUP requires no additional hardware modification. Thus, the PMMUP complexity is comparative to that of the MUP. The PMMUP mainly coordinates local power optimizations at the NICs. While NICs measure dynamic channel conditions asynchronously and autonomously.

The problem of cross-layer resource optimization in multi-hop wireless networks has recently received much research attention [5], [7], [10], [22], [26], [27]. Ramamurthy *et al.* [5] studied the problem of link scheduling and power control in a Time-Division Multiple Access (TDMA) WMN where nodes use directional antennas. The authors developed a generalised interference model applicable to directional antennas and formulate a mixed integer linear programming problem solvable by sub-optimal heuristics. However, TDMA based power control approaches are centralised schemes. Tang *et al.* [7] and Merlin *et al*. [26] developed an end-to-end cross-layer rate allocation with power control considerations in MRMC wireless networks. However, due to the *NP*-hard nature of joint cross-layer resource optimization in multi-hop wireless networks, sub-optimal solutions usually arise [6]. WMN with MRMC configurations are expected to be fully distributive [3]. A realistic joint power and multi-channel medium access control was proposed in [10]. The developed dynamic channel assignment using the power control (DCA-PC) method has the advantage of being independent of dynamic topology and node degree [22]. Though, the DCA-PC is an energy-efficient and "on demand" approach, it is agnostic to effects of multi-dimensional channel states [27]. Kawaidia and Kumar [27] presented principles and protocols of multi-dimensional effects of power control in wireless Ad Hoc networks. However, the suggested principles are suited to single channel-single radio wireless networks with dominant co-channel interference.

Numerous works have been proposed for multi-channel MAC with power control techniques [9], [13], [15]. The basic idea is that data packets are transmitted with proper power control so as to exploit channel reuse. On the other hand 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, transmission power leakage may be significant. Thus, we advocate that a sender MP 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 [5] and improves a node's ability to reach its neighbours 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 connected to a unique radio interface device [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 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 asynchronous multiple-state based power control for MRMC WMNs. PMMUP *guess*es initial unification variables such as energy reserves, NICs asynchronously *predict* the local channel and inter-channel states, PMMUP *updates* unification variables and NICs *compute* local optimal transmission power levels as a function of multi-channel states. We refer to this PMMUP enabled approach as the Multi-Radio Multi-Channel System Interaction States Prediction Algorithm (MRSIPA). Through simulations, MRSIPA yielded significant transmission power saving over the MUP [8] and Striping models [11]. MRSIPA presented a better throughput performance than a dynamic channel assignment with transmission power control (DCA-PC) scheme [10].

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 is a subsystem with *sender-receiver NIC pairs* as its members. Members of separate UCGs control their transmission powers in parallel [20] through an associated PMMUP as the coordinator. PMMUP controls greedy power control behaviours among individual NICs [12] by setting a battery energy constraint. Power resources are dynamically adjusted by each sender NIC using intra and inter-subsystem (channel) states. In this sequel such states include the received signal-to-interference plus noise ratio (SINR) deviation, aggregate interference among neighbouring nodes, transmission rate and connectivity range deviations. 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 [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, $t \in \{0, 1, 2, \ldots\}$ [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 close spatial vicinity [5].

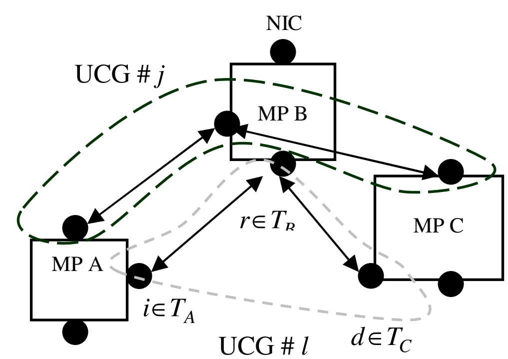

Fig. 1: Multi-Radio Multi-Channel (MRMC) and Multi-hop Wireless Mesh communication system

B. PMMUP Layer Description

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

Neighbour Discovery: At start-up, NICs of a node are tuned to theoretical orthogonal UCGs [10]. The PMMUP layer then initiates communication using an address resolution protocol (ARP) message broadcasted over all the NICs [8]. Each NIC 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 NIC sends out the ARP responses with the MAC address of the NIC on which it received the ARP requests. Once the originating host receives the ARP responses it proceeds to communicate with the NIC from which it received ARP responses. The PMMUP then classifies neighbours [8]. Nodes that support PMMUP are classified as either PMMUP enabled nodes or as legacy nodes.

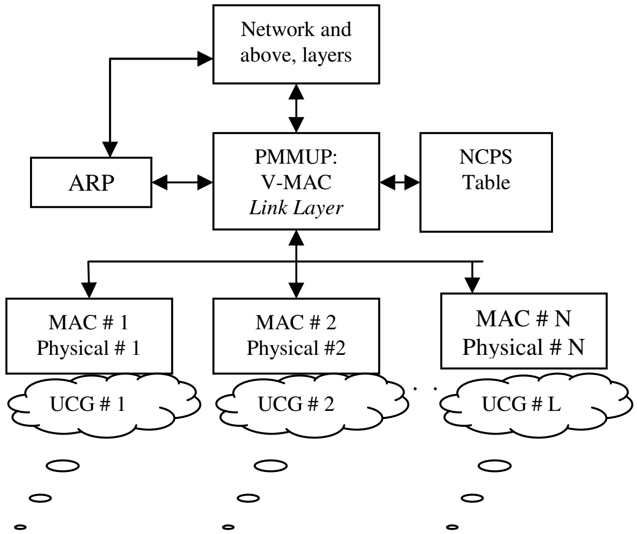

Fig. 2: PMMUP: V-MAC architecture for the WMN

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 common channel multiple 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 to the originating NICs and transmitted through a feedback path 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 an iterative local power optimization algorithm based on the predicted versions of the channel "state information" (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

Other Advantages: The PMMUP layer does not require a global knowledge of the network topology and 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) and therefore cross-layer information interacts with a reduced latency. The NCPS table has not too many information to update. Neighbour discovery occurs once throughout the power optimization interval. This reduces memory and computational complexities.

IV. PROBLEM FORMULATION

The level of transmission power determines the quality of the received signal expressed in terms of signal-to-interference plus noise ratio (SINR) and the range of a transmission [27]. The range of the transmission determines the amount of interference a user creates for other users hence the level of medium access contention. Interference in turn impacts on the link achievable rate [7]. We can then define the decentralized energy-efficient power control strategy for each lth sender-receiver pair (i.e., user) as

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

where $f_l(\mathbf{x}) = f_l(\beta_l(t), I_l(t), \Gamma_l(t), R_l(t))$. $\beta_l(t)$, $I_l(t)$, $\Gamma_l(t)$, $R_l(t)$ as the actual SINR, aggregate co-channel network interference, scheduled transmission rate and the connectivity range between a user and its neighbours during time slot t. Using the Taylor series to obtain first order linear approximations to $f_l(\mathbf{x})$ gives

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

where γ_l^{ss}, I_l^{ss}, Λ_l^{ss} and R_l^{ss} are the steady state values describing the receiver SINR threshold, co-channel interference threshold [12], link capacity and the achievable transmission range of a radio interface, respectively [2].

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. Define the SINR as

$$\beta_l(t+1) = \frac{p_l(t+1)G_{ll}(t+1)}{I_{(i,r),l}(t+1)}. \tag{3}$$

Substitute $p_l(t+1)$ from (1) into (3) to get the predicted SINR:

$\beta_l(t+1) = \left[p_l(t) + f_l(\mathbf{x})\right]H(t)\frac{m(t)}{n(t)}$. We can then derive the SINR deviation as follows:

$$e_\beta(t+1) = \beta_l(t+1) - \beta_l(t)\frac{m(t)}{n(t)} - H(t)\frac{m(t)}{n(t)} f\left(\gamma_l^{ss}, I_l^{ss}, \Lambda_l^{ss}, R_l^{ss}\right),$$

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

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 predicted aggregate co-channel interference among the neighbouring radio interfaces and derive the associated state deviation as:

$$\begin{aligned} I_l(t+1) &= p_l(t+1)G_{ll}(t+1) + I_{(i,r),l}(t+1) \\ &= \left[p_l(t) + f_l(\mathbf{x})\right]G_{ll}(t)m(t) + I_{(i,r),l}(t)n(t) \end{aligned}$$

$$\begin{aligned} e_I(t+1) = {} & G_{ll}(t)m(t)\alpha_\beta\left(\beta_l(t) - \gamma_l^{ss}\right) + \\ & G_{ll}(t)m(t)\alpha_I\left(I_l(t) - I_l^{ss}\right) + \\ & G_{ll}(t)m(t)\alpha_\Gamma\left(\Gamma_l(t) - \Lambda_l^{ss}\right) + \\ & G_{ll}(t)m(t)\alpha_R\left(R_l(t) - R_l^{ss}\right). \end{aligned} \tag{5}$$

Following a similar procedure the predicted rate and its deviation becomes:

$$\Gamma_l(t+1) = \log p_l(t+1) + \log G_{ll}(t+1) - \log I_{(i,r),l}(t+1)$$

$$e_\Gamma(t+1) = \frac{1}{p_l(t)}\begin{bmatrix} \alpha_\beta\left(\beta_l(t) - \gamma_l^{ss}\right) + \alpha_I\left(I_l(t) - I_l^{ss}\right) + \\ \alpha_\Gamma\left(\Gamma_l(t) - \Lambda_l^{ss}\right) + \alpha_R\left(R_l(t) - R_l^{ss}\right) \end{bmatrix} + \log m(t) - \log n(t). \tag{6}$$

The connectivity range model is described as [24]

$\log R_l(t+1) = \frac{1}{\nu}\log\left(p_l(t) + f_l(\mathbf{x}) - \kappa\right)$, with $\kappa \in \Re \geq 0$ and $2 \leq \nu \leq 6$ is the path loss exponent (PLE) that depends on the physical environmental conditions [23]. The range deviation from steady state becomes,

$$\begin{aligned} e_R(t+1) = {} & \frac{1}{\nu p_l(t)}\alpha_\beta\left(\beta_l(t) - \gamma_l^{ss}\right) + \frac{1}{\nu p_l(t)}\alpha_I\left(I_l(t) - I_l^{ss}\right) + \\ & \frac{1}{\nu p_l(t)}\alpha_\Gamma\left(\Gamma_l(t) - \Lambda_l^{ss}\right) + \frac{1}{\nu p_l(t)}\alpha_R\left(R_l(t) - R_l^{ss}\right). \end{aligned} \tag{7}$$

Let $\mathbf{x}_l \triangleq \left(\beta_l - \gamma_l^{ss} \;\; I_l - I_l^{ss} \;\; \Gamma_l - \Lambda_l^{ss} \;\; R_l - R_l^{ss}\right)^T$ be state measurements of a control system [18]. Combining equations (4), (5), (6) and (7) and introducing an input sequence term, we obtain

$$\mathbf{x}_l(t+1) = \mathbf{A}_l\,\mathbf{x}_l(t) + \mathbf{B}_l\,\mathbf{u}_l(t) + \varepsilon_l(t), \tag{8}$$

where $\mathbf{A}_l$ is a 4 x 4 coefficient matrix given by

$$\mathbf{A}_l = \begin{pmatrix} \frac{m}{n}H\alpha_\beta & \frac{m}{n}H\alpha_I & \frac{m}{n}H\alpha_\Gamma & \frac{m}{n}H\alpha_R \\ mG\alpha_\beta & mG\alpha_I & mG\alpha_\Gamma & mG\alpha_R \\ \frac{\alpha_\beta}{p_l} & \frac{\alpha_I}{p_l} & \frac{\alpha_\Gamma}{p_l} & \frac{\alpha_R}{p_l} \\ \frac{\alpha_\beta}{\nu p_l} & \frac{\alpha_I}{\nu p_l} & \frac{\alpha_\Gamma}{\nu p_l} & \frac{\alpha_R}{\nu p_l} \end{pmatrix}, \text{and}$$

$\mathbf{B}_l\mathbf{u}_l(t) = \begin{bmatrix} u_\beta(t) \\ u_I(t) \\ u_\Gamma(t) \\ u_R(t) \end{bmatrix}$ 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 4 x 1 coefficient matrix. The state stochastic shocks term $\varepsilon_l(t)$ is a 4 x 1 random vector with zero mean and covariance matrix

$$\Theta_\varepsilon = \mathrm{E}\varepsilon_l(t)\varepsilon_l^T(t) = diag\left(\sigma_\beta^2, \sigma_I^2, \sigma_\Gamma^2, \sigma_R^2\right). \tag{9}$$

Let us have $l = i$ when the number of channels is the same as the number of radios of a node. The multi-radio interaction state space (MRISS) model representation then becomes [18]

$$\mathbf{x}_i(t+1) = \mathbf{A}_i(t)\mathbf{x}_i(t) + \mathbf{B}_i(t)\mathbf{u}_i(t) + \mathbf{C}_i(t)\mathbf{y}_i(t) + \varepsilon_i(t)$$
$$\mathbf{x}_i(t_0) = \mathbf{x}_{i0},\ \forall i, \tag{10}$$

where $\mathbf{y}_i(t)$, introduced in (10), is a linear combination of states (LCS) from other UCGs available to the ith user (MRMC subsystem). This LCS is defined as

$$\mathbf{y}_i(t) = \sum_{\substack{j=1 \\ j\neq i}}^{N} \mathbf{L}_{ij}(t)\mathbf{x}_j(t) \; + \; \varepsilon_i^y(t), \qquad (11)$$

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 4 x 4 identity coefficient matrix and denotes the coupling weight. 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. This interconnection matrix needs to be evaluated by the PMMUP layer. In what follows, we formulate the control problem for each NIC-pair (user) as the minimization of the following stochastic quadratic cost function subject to the network interaction state equation (10) and coordination states in equation (11):

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

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

Such that

$$\mathbf{x}_i(t+1) = \mathbf{A}_i(t)\mathbf{x}_i(t) + \mathbf{B}_i(t)\mathbf{u}_i(t) + \mathbf{C}_i(t)\mathbf{y}_i(t) + \varepsilon_i^x(t),$$

$$\mathbf{x}_i(t_0) = \mathbf{x}_{i0},\ \forall i$$

$$\mathbf{y}_i(t) = \sum_{\substack{j=1 \\ j\neq i}}^{N} \mathbf{L}_{ij}(t)\mathbf{x}_j(t) \; + \; \varepsilon_i^y(t). \qquad (12)$$

Here, $\mathbf{Q}_i \in \mathbb{R}^{3\times 3} \geq \mathbf{0}$ 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. The joint probability density function (pdf) $\rho_i(\mathbf{x}_i,\mathbf{u}_i)$ denotes the state occupation measure (SOM). The SOM is defined as $\rho_i(\mathbf{x}_i,\mathbf{u}_i) = \Pr(\mathbf{u}_i \mid \mathbf{x}_i)\sum_{\mathbf{u}_i\in\{\mathbf{u}_i\}}\rho_i(\mathbf{x}_i,\mathbf{u}_i)$. 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 (12). 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 (11) and the MRISS constraint (10) respectively, to the cost function. We invoke the dynamic programming value function

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

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

$$\min_{\{\mathbf{u}_t^i\}}\rho\, E\left[V\left(\boldsymbol{\varphi}_{t+1}^T\mathbf{A}_t^i\mathbf{x}_t^i + \boldsymbol{\varphi}_{t+1}^T\mathbf{B}_t^i\mathbf{u}_t^i + \boldsymbol{\varphi}_{t+1}^T\mathbf{C}_t^i\mathbf{y}_t^i + \boldsymbol{\varphi}_{t+1}^T\boldsymbol{\varepsilon}_t^x\right)\right]. \qquad (13)$$

We dropped subscripts and superscripts in (13) for notational convenience. In all cases, variables are t-time slot-dated and ith user dynamics. Differentiating (13) w. r. t. $\mathbf{u}$ and solving in terms of $\mathbf{u}$ implies

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

$$\mathbf{u}^* = -\mathbf{F}\mathbf{x}, \qquad (14)$$

with
$$\mathbf{F} = \left(\mathbf{R}+\rho\mathbf{B}^T\boldsymbol{\varphi}\mathbf{P}\boldsymbol{\varphi}^T\mathbf{B}\right)^{-1}\rho\mathbf{B}^T\boldsymbol{\varphi}\mathbf{P}\boldsymbol{\varphi}^T\mathbf{A},$$

$$\mathbf{F} = \left(\mathbf{R}+\rho\mathbf{B}^T\mathbf{P}_{\boldsymbol{\varphi}}\mathbf{B}\right)^{-1}\rho\mathbf{B}^T\mathbf{P}_{\boldsymbol{\varphi}}\mathbf{A}. \qquad (15)$$

Let $\mathbf{P}_{\boldsymbol{\varphi}} \triangleq \mathbf{P}$ be a Riccati matrix [18] 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

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

Hitherto, $\mathbf{y}$ signifies states from other UCGs (coordination vector), $\boldsymbol{\varphi}$ and $\boldsymbol{\pi}$ signify *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. Coordination variables (CV), $\mathbf{y}$ and $\boldsymbol{\pi}$ are updated by the PMMUP. While each NIC solves the local optimization problem given by the value function keeping the CV fixed. Thus, MRSIPA algorithm constitutes steps (iii) and (iv) of the PMMUP protocol discussed in Section IIIB.

V. MRSIPA ALGORITHM

Algorithm 1: MRSIPA: Predicts MRMC Interaction Variables Asynchronously and Optimize Transmission Power

Input: $\boldsymbol{\pi}$, $\mathbf{y}$; */*PMMUP Coordination Variables (CV)*/*

$\mathbf{x}_i$; */*ith subsystem/user Interaction Variable (IV)*/*

Output: $\mathbf{u}_i^*$ */*ith subsystem/user optimal power signal*/*

At each time step k user i performs the following operations.

1: **while** $(k \geq 1)$ **do**
2: **Predict:** $\mathbf{x}_i(k) \leftarrow \mathbf{x}_i(k+1)$; */*min of (13) w. r. t. $\boldsymbol{\varphi}_{t+1}$*/*
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** converged IV states to PMMUP layer;
5: **go to** Step 11;
6: **else /****IV 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;
10: **end if**
11: **if** *(*$e(k+1) \leq \varepsilon_{rr}$*, a small positive value)* **then do**
12: **Compute:** $\mathbf{u}_i^* = -\mathbf{F}\mathbf{x}_i^*$; */* Local Optimization from (14)*/*
13: **Add** $\mathbf{u}_i^*$ **to** Equation (1);
14: **else do go to** Step 1;
15: **end if**
16: **end while**

Here,

$$e(k+1) = \left\| \mathbf{g}(k+1) - \mathbf{g}(k) \right\|, \mathbf{g}(t) = \left[\mathbf{y}_i^T(k) \ \boldsymbol{\pi}_i^T(k) \right]^T$$

$$\text{and} \quad \mathbf{g}(k+1) = \left[\mathbf{y}_i^T(k+1) \ \boldsymbol{\pi}_i^T(k+1) \right]^T.$$

VI. Simulation Tests And Results

In our simulations, we used MATLAB™ version 7.1*[21]. 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 II. The model matrices discussed in Sections IV and V were computed from one hop node interaction with its neighbours using specified parameters from Table II and channel environment settings in [23].

TABLE II
SIMULATION SPECIFICATION

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 transmission power efficiency versus one hop ranges among neighbouring nodes. The probability of selecting transmission power that is greater than the probing power level increases with the connectivity range at different path loss exponents (PLE). When the PLE is high it implies a bad wireless channel environment, hence high transmission power. Specially, at range = 220m, the system consumes 5%, 5.8%, 15%, 25% and 42% of energy with PLE = 2, 3, 4, 5 and 6, respectively.

Fig. 4 shows the simulation results 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 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 a high data volume implies high transmission energy consumption [23]. At 20 packets per slot, MRSIPA requires 28.57% more power than dynamic channel assignment with power control (DCA-PC) [10], 22.22%, 88.89%, and 66.67% less power than load-based concurrent access protocol (LCAP) with directional antennas [16], Load Sensitive (LS) Striping [11] and MUP without power control [8], respectively. This is because the PMMUP enabled MRSIPA is based on awareness of the battery power supply and queue load. MRSIPA predicts cross-channel states asynchronously. Asynchronous prediction boosts the convergence rate resulting in a low computational and transmits power. MRSIPA recorded more power consumption than DCA-PC because MRSIPA assumes static channel assignments with all NICs during a time slot. However, channels are switched after the elapse of one time slot. The DCA-PC allows for the channels switching with only a few NICs being active leading to a reduction in transmission power [10].

Fig. 5 illustrates throughput performance with 95% confidence intervals when offered loads were varied. MRSIPA recorded the most superior throughput performance at various loads compared to the related methods. Specifically, at 90 packets/s of load: MRSIPA yielded 72.73% more throughput performance measured in terms of packets per time slot duration than MUP algorithm. This is because MRSIPA 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 per node. MRSIPA provided 66.67%, 48.15% and 22.22% more throughput than LS-striping [11], LCAP with directional antennas [16] and the DCA-PC [10] methods, respectively. MRSIPA is asynchronous while LS-striping [11] is synchronous. MRSIPA exploits all channels simultaneously while DCA-PC [10] utilizes assigned channels for transmission. MRSIPA method selects transmission power based on the knowledge of the neighbourhood conditions while LCAP is based on only the traffic load [16]. 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 [12].

* Matlab is a registered trademark of The MathWorks, Inc.

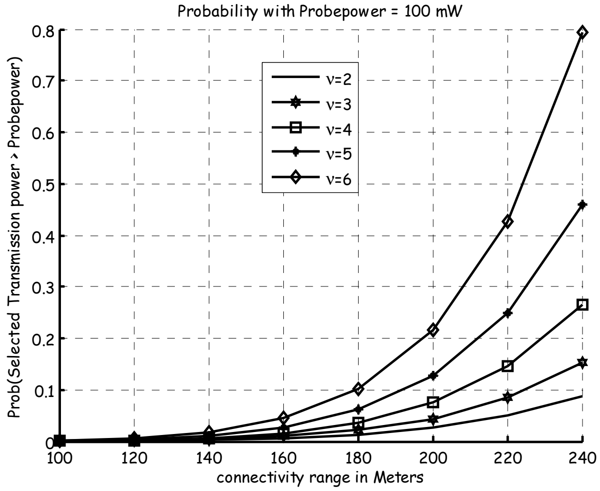

Fig. 3: Transmission Power Probability function versus Range

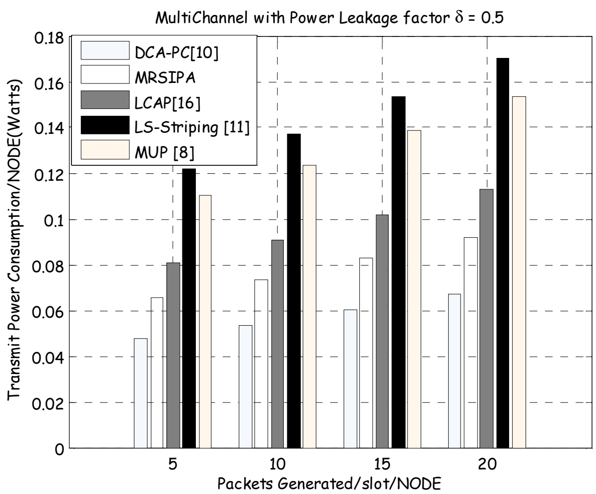

Fig. 4: Transmission Power needed per NODE

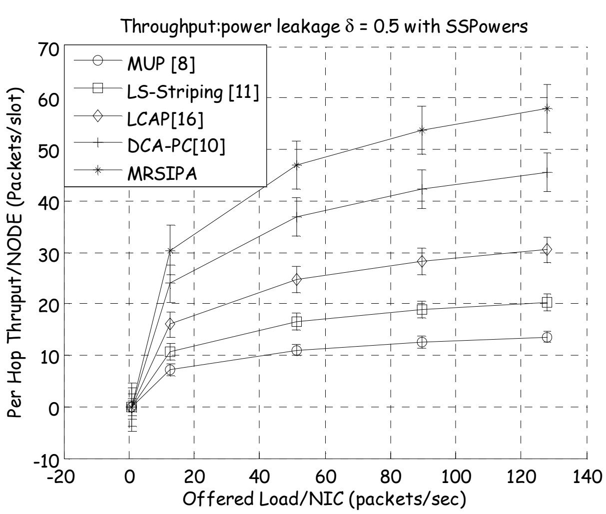

Fig. 5: Average Throughput per NODE Vs Offered Load with 95% Confidence Interval Level

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 with knowledge of multiple channel states yields significant power conservations and throughput improvement for a multi-radio system.

ACKNOWLEDGEMENT

This work was supported in part by CSIR.

References

[1] I. F. Akyilidiz, 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; 1^{st} Ed (December 1999), 188 pages.

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

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

[5] 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.

[6] 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.

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

[8] 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.

[9] 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.

[10] 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.

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

[12] 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.

[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] 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.

[15] 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.

[16] 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.

[17] J. H. Winters, C. C. Martin and N. R. Sollenberger, "Forward Link smart antennas and power control for IS-136,"in Proc. *IEEE 48^{th} Vehicle Tech. Conf. 1998*, vol. 1, pp. 601-605.

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

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

[20] 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.
[21] MathWorks Inc., http://www.mathworks.com
[22] H. Zhu, K. Lu and M. Li, “Distributed Topology Control in Multi-Channel Multi-Radio Mesh Networks,” In *Proc. ICC 2008*, pp. 2958-2962.
[23] T. Shu, M. Krunz and S. Vrudhula, “Joint Optimization of Transmit Power-Time and Bit Energy Efficiency in CDMA wireless sensor networks,” *Technical Report*, TR-UA-ECE-2005-3, April 14, 2005.
[24] T. O. Olwal, B. J. van Wyk, K. Djouani, Y. Hamam, P. Siarry and N. Ntlatlapa, “Range Based Power Control for Multi-radio Multi-channel Wireless Mesh Networks,” In *Proc. SATNAC 2009*, Aug. 30-Sept. 2, 2009
[25] T. O. 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 *Proc. Ad Hoc Now 2009*, Sept. 22-25, 2009
[26] S. Merlin, N. Vaidya, M. Zorzi, “Resource allocation in multi-channel multi-radio multihop wireless networks,” *Technical Report*, Padova University, Italy, 2007.
[27] V. Kawaidia and P. R. Kumar, “Principles and Protocols for Power Control in Wireless Ad Hoc Networks,” *IEEE Jnl. Selected Areas in Commun.: SI Wireless Ad Hoc Networks*, vol. 23, no. 5, pp. 78-88, Jan. 2005.

Thomas O. Olwal (M’09), obtained BSc. (1st *Class Hons.*) in Electrical & Electronic Engineering from the University of Nairobi, Kenya 2003, an MTech (*cum laude*) in Telecommunication from the Tshwane University of Technology (TUT) 2006, South Africa, MSc. Electronic Engineering from ESIEE-Paris 2007 and currently working on a PhD thesis with TUT and Paris-Est University, France.

He works for Council for Scientific and Industrial Research (CSIR) as a researcher. His research interests are in Energy-Efficient operations for Backhaul Wireless Mesh Networks in Energy-constrained applications.