Range Based Power Control for Multi-Radio Multi-Channel Wireless Mesh Networks

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

***Index Terms*— Connectivity Transmission Range, Multi-Radio Multi-Channel State Interaction Prediction Algorithm (MMIPA), 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 [3], [4]. Each radio has a single or multiple orthogonal channels. 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 [2]. The IEEE 802.11s [3] working group has been formed to study and recommend for a wireless-based extended service set (ESS) that provides for a wider area communications among distributed clients. This study is expected to contribute towards a self-managing and high capacity wireless mesh networking [2], [3]. That is, the use of multiple radio system in a collaborative manner provides several benefits: the energy management, capacity enhancement, mobility management and channel failure recovery. The last-hop packet scheduling behaviour of the WMN can also be dramatically improved [2].

Multi-radio multi-channel (MRMC) wireless mesh system is, however, a major threat on power conservations. Power constraint problems affect the WMN deployments in rural and remote communities [5]. In such applications, electric power supply outlets are usually not available. Nodes rely on battery power supply for their operations. Due to the nature of topography of most remote communities, mesh networks are expected to deliver packets over long wireless distance ranges. This comes at the expense of additional transmission power consumptions. Nodes transmitting with high power shorten network lifetime and as a result network connectivity fails. Failure in network connectivity degrades the robustness of a self-configuring WMN [2]. Moreover, high power transmissions in a multi-radio system degrade channel reuse in a physical area. Consequently, severe problems of co-channel and adjacent channel interferences may occur [7]. Interference estimations using a conflict graph approach are well known [7]. Conflict graphs exploit protocol interference models [14]. However, finding a global optimal throughput under the protocol interference model is an NP-hard problem [7]. The problem is even complex in a multi-radio system [6]. A key way to manage network interference, energy and connectivity in a dynamic MRMC WMN is to adapt transmission power level based on transmission range [8]. The impact of an individual node's variable-range transmission power control on the physical and network connectivity of a wireless multi-hop networks was studied in [8]. This allows the network to autonomously adapt to nodes entering the network (i.e., introducing short hop ranges) or those exiting the network due to node failures (i.e., energy depletion and or long hop ranges), poor connectivity and so forth.

In this paper, we propose a new connectivity range based power control in a distributed MRMC wireless mesh system. Numerous dynamic power control methods exist for the

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general single radio single channel (SRSC) wireless networks [8]-[12]. Specifically, work in [9] assumes infeasible global knowledge of the wireless multi-hop network. In [10], common transmission ranges among network nodes and queue state-dependent based power control was considered. While in [11], [12] signal to interference plus noise ratios (SINR) at cellular base station receiver were assumed for evaluating the optimal power control level. Instead, we consider backbone wireless mesh network (BWMN) [3] with multiple ranges, multiple radios and multiple channel functionality. The BWMN are Ad Hoc and distributed in nature without common receiving stations [2]. Recently, distributed power control methods have been proposed for the BWMN [13], [14]. In [13] an autonomous interference estimation based distributed dynamic power control was proposed. Network interference influences were estimated and predicted at both sender and receiver nodes so that hidden and exposed terminal node problems could be minimized [7]. Consequently, a judicious power level can be selected such that a desirable network density is achieved. The work in [14] presented the distributed dynamic power control based on the knowledge of the PHY and medium access control (MAC) layers [4]. Local information from neighbouring multiple radio nodes was assumed. The simulation results showed that throughput increases significantly when sufficient MAC information is available to the power control system. However, this paper considers a scalable range based power control for the BWMN.

In order to make a multi-radio system 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 radios or network interface cards (NICs) [17]. This unification protocol hides the complexity of multiple conventional MAC and physical layers from the upper layers [4]. We refer to this virtual MAC as a power selection multi-radio multi-channel unification protocol (PMMUP). PMMUP enhances functionalities of the original multi-radio unification protocol (MUP) [17]. Such enhancements include: an energy-efficient neighbour discovery, power optimization and the utilization of parallel radios or channels to send data traffic simultaneously. This resolves the need for a single mesh point (MP) node to access mesh client network and route the backbone traffic simultaneously [1]. The routing functionality of the MP node may be of multi-point to multi-point. Like MUP, the PMMUP requires no additional hardware modification. Thus, the PMMUP complexity is comparative to that of the MUP. The PMMUP manages large scale multi-radio systems with a reduced complexity [16]. Moreover, each NIC has independent amount of traffic load at its queue and independent dimension of multiple channel states to estimate. To yield a first convergence rate, each NIC autonomously and locally predicts transmission ranges of multiple channels. Our power optimization algorithm is called a multi-radio multi-channel range interaction state variable prediction algorithm (MMRIPA). The converged transmission range states (i.e., including states from other channels) are exploited for local power optimization.

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

II. 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) [3]. 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., $\|T_A\| \le \|L_A\|$. Each UCG is a subsystem with NIC-pairs as its members. Members of separate UCGs control their transmission powers in parallel [16] through associated PMMUP as the coordinator. PMMUP resolves greedy power control behaviours among individual NICs [12]. Power resources are dynamically adjusted by each NIC pair using intra and inter-subsystem (channel) states.

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 $j \in T_B$ 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 (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].

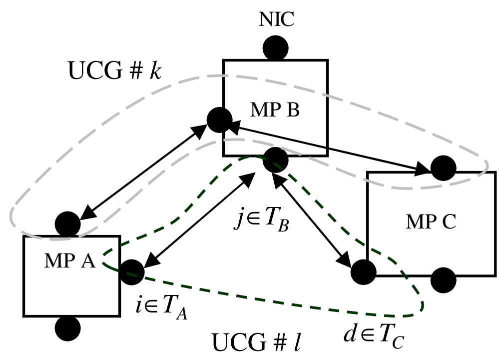

Fig. 1: Multi-Radio Multi-Channel (MRMC) and Multi-hop Wireless Mesh communication system

B. PMMUP Description

The PMMUP: V-MAC architecture is illustrated in Fig. 2. The PMMUP performs neighbour discovery using a fraction of maximum power assigned to NIC, coordinates power selection procedure among multiple NICs and sends data in parallel channels. All these activities need to happen within the same time slot duration. The coordination variables are stored at the neighbour communication power and states (NCPS) table. The NCPS table is shown in Table 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 [4]. PMMUP then initiates communication using an address resolution protocol (ARP) message broadcasted over all the NICs [17]. 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 [17]. Nodes that support PMMUP are classified as PMMUP enabled nodes otherwise qualified as legacy nodes using conventional MACs.

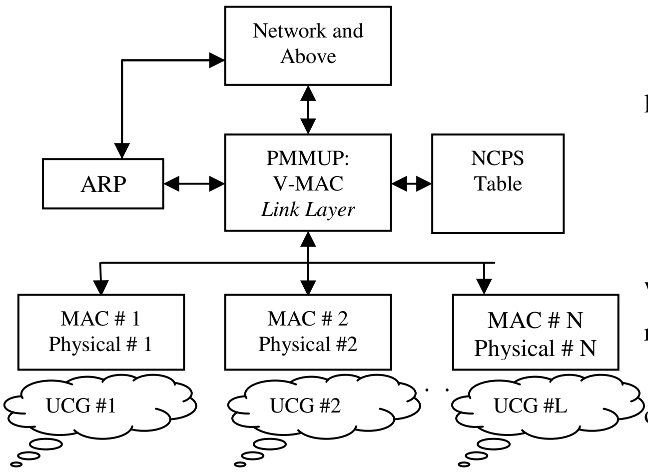

Fig. 2: PMMUP: V-MAC architecture for the WMN

Table 1: 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, Round Trip Time (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 or information.

(ii) When the neighbouring NICs receive the "ps-request" message they compute the "state information": connectivity range, queue status, and energy reserves. This information is piggy-backed in the "ps-Ack" message to the originating NICs and sent via feedback path using probing power level.

(iii) Upon receiving the ps-Ack messages, each sending NIC independently computes the connectivity range, queue state, energy reserves and RTT, and copies "state information" to the PMMUP. The PMMUP updates the NCPS table and sends the coordination updates including those from upper layers to lower level NICs for power optimization.

(iv) Each NIC runs local power optimization algorithm based on predicted versions of state information (See Section IV). 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

III. PROBLEM FORMULATION

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

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

where $f_l\left(R_{ij}^{l}\right)$ is a non-linear function of the connectivity range from sender i to receiver j one hop away on UCG l during time slot t. Using Taylor series to obtain a first order linear approximation to $f_l\left(R_{ij}^{l}\right)$ gives

$$f_l\left(R_{ij}^{l}\right) \triangleq f\left(R_l^{ss}\right) + \alpha_R\left(R_{ij}^{l}(t) - R_l^{ss}\right) \; , \qquad (2)$$

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

$$p_{ij}^{l}(t+1) = p_{ij}^{l}(t) + f\left(R_l^{ss}\right) + \alpha_R e_R^{l}(t), \; \forall l \in \{1, \ldots, L\} \, , \quad (3)$$

where $e_R^{l}(t) \triangleq R_{ij}^{l}(t) - R_l^{ss}$, is the connectivity range deviation during time slot t. Let the predicted range for connecting NIC i and NIC j for all neighbouring nodes of the network be derived as:

$$p_{ij}^{l}(t) = c + \left\|NIC_i NIC_j\right\|_2^{\upsilon}, \text{ for any } c \ge 0,$$

$$\left\|NIC_i NIC_j\right\|_2 = \left(p_{ij}^{l}(t) - c\right)^{1/\upsilon}, \quad \text{where } p_{ij}^{l}(t) > 0,$$

$$R_{ij}^{l}(t+1) = \left(p_{ij}^{l}(t+1) - c\right)^{1/\upsilon}, \text{ where } R_{ij}^{l}(t) > 0,$$

$$\log R_{ij}^{l}(t+1) = \frac{1}{\upsilon}\log\left(p_{ij}^{l}(t+1) - c\right). \qquad (4)$$

Here, $\|.\|_2$ is the Euclidean norm and υ is the path loss exponent (PLE) assumed to be $2 \le \upsilon \le 6$, depending on the physical environment conditions [11]. Substitute (3) into (4) to get:

$$\log R_{ij}^{l}(t)=\frac{1}{\upsilon}\log\left(p_{ij}^{l}(t)+f_{l}(x)\right), \quad (5)$$

where $f_l(x)=f_l\left(R_l^{ss}\right)+\alpha_R e_R^l(t)-c$. Let $p_{ij}^l(t)\ge f_l(x)$ and $\log(1+z)\approx z$ when $0\le x<1$. Thus, equation (5) expressed in the predicted version becomes,

$$\log R_{ij}^{l}(t+1)=\frac{1}{\upsilon}\log p_{ij}^{l}+\frac{1}{\upsilon}\log\left(1+\frac{f_{l}(x)}{p_{ij}^{l}(t)}\right),$$

$$=\frac{1}{\upsilon}\log p_{ij}^{l}(t)+\frac{1}{\upsilon}\frac{f_{l}(x)}{p_{ij}^{l}(t)},\quad \forall l\in\{1,...,L\},$$

$$=\frac{1}{\upsilon}\log p_{ij}^{l}(t)+\frac{1}{\upsilon p_{ij}^{l}(t)}f_{l}\left(R_{l}^{ss}\right)+\frac{\alpha_{R}}{\upsilon p_{ij}^{l}(t)}e_{R}^{l}(t)-\frac{c}{\upsilon p_{ij}^{l}(t)}. \quad (6)$$

We then formulate connectivity range transition equation as

$$e_{R}^{l}(t+1)=\log R_{ij}^{l}(t+1)-\frac{1}{\upsilon p_{ij}^{l}(t)}f_{l}\left(R_{l}^{ss}\right)-\log R_{ij}^{l}(t), \quad (7)$$

where $\log R_{ij}^{l}(t)=\frac{1}{\upsilon}\log p_{ij}^{l}(t)-\frac{c}{\upsilon p_{ij}^{l}(t)}$. Thus, (7) is re-written as, $e_R^l(t+1)=\frac{1}{\upsilon p_{ij}^l(t)}\alpha_R e_R^l(t)$. Or, more succinctly,

$$e_R(t+1)=A_R(t)\,e_R(t), \quad (8)$$

Introducing an input power control sequence and noise terms to (8) and assuming a time-invariant system we have

$$e_R(t+1)=A_R\,e_R(t)+B_R\,u_R(t)+\varepsilon_R(t), \quad (9)$$

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

Let $i=l$ so that the multi-radio multi-channel range state interaction (MRSI) model representation becomes [15]

$$e_i(t+1)=A_i\,e_i(t)+B_i\,u_i(t)+C_i\,y_i(t)+\varepsilon_i(t),$$
$$e_i(t_0)=e_{i0},\ \forall i, \quad (10)$$

where $y_i(t)$, introduced in (10), is a linear combination of states (LCS) from other UCGs available to the ith NIC/user. This LCS is defined as

$$y_i(t)=\sum_{\substack{k=1\\k\neq i}}^{N}L_{ik}\,e_k(t)+\varepsilon_i^y(t), \quad (11)$$

where $\varepsilon_i^y(t)$ denotes the coordination process shocks with zero mean and covariance σ_ε^y. C_i is a unity coefficient matrix and L_{ik} is the inter-channels state coupling matrix available between ith NIC-pair and kth NIC-pair. 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 cross-channels interaction range state equation (10) and coordination states in equation (11):

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

Subject to equations (10) and (11). (12)

Here, $Q_i\in\mathbb{R}\ge\mathbf{0}$ is assumed symmetric, positive semi-definite matrix and $R_i\in\mathbb{R}>\mathbf{0}$ is assumed symmetric, positive definite matrix. For brevity, we choose Q_i to be an identity matrix and R_i to be a matrix of unity entries. The joint probability density function (pdf) $\rho_i(e_i,u_i)$ denotes the state occupation measure (SOM). The SOM is defined as $\rho_i(e_i,u_i)=\Pr(u_i\mid e_i)\sum_{u_i\in\{u_i\}}\rho_i(e_i,u_i)$. It gives the steady state probability that the control system is in state $e_i\in\{e\}$ and the driving control parameter $u_i\in\{u_i\}$ is chosen. Thus, we seek an optimal $u_i\in\{u_i\}$ that solves the problem in (12). First, we introduce a Lagrange multiplier π_t^i and a state unification (SU) weight φ_{t+1}^i to augment the LCS equality in (11) and the MRSI constraint (10) respectively, to the cost function. We invoke the dynamic programming value function for (12) as

$$V\left(e_t^i\right)=\min_{\{u_t^i\}}\left\{e_t^{iT}Q_t^i\,e_t^i+u_t^{iT}R_t^i\,u_t^i\right\}+$$
$$\min_{\{u_t^i\}}\rho E\left[V\left(-\pi_t^T y_t^i+\pi_t^T\sum_{\substack{j=1\\j\neq i}}L_t^{ij}e_t^j+\pi_t^T\varepsilon_t^y\right)\right]+$$
$$\min_{\{u_t^i\}}\rho\,E\left[V\left(\varphi_{t+1}^T A_t^i e_t^i+\varphi_{t+1}^T B_t^i u_t^i+\varphi_{t+1}^T C_t^i y_t^i+\varphi_{t+1}^T\varepsilon_t^x\right)\right]. \quad (13)$$

For notations convenience we drop superscript i and subscripts t from (13). Differentiating w.r.t. u and solving in terms of u implies,

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

Or, more succinctly

$$u^*=-Fe, \quad (14)$$

with

$$F=\left(R+\rho B^T\varphi P\varphi^T B\right)^{-1}\rho B^T\varphi P\varphi^T A,$$
$$F=\left(R+\rho B^T P_\varphi B\right)^{-1}\rho B^T P_\varphi A. \quad (15)$$

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

$$P_{k+1}=Q+\rho A^T P_k\,A-\rho^2 A^T P_k\,B\left(R+\rho B^T P_k\,B\right)^{-1}B^T P_k\,A. \quad (16)$$

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

IV. MMRIPA ALGORITHM

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

Input: π_i , y_i ; */*Coordination Variables*/*

e_i ; */*ith System Interaction Variable*/*

*A, B, C,Q and R; /*Control System Matrices*/*

Output: u_i^* */*ith NIC system optimal power control signal*/*

1: **while** $(k \geq 1)$ **do**

2: **for each** *(NIC-pair* $i \in [1, N]$ *)*

3: Predict: $e_i(k) \leftarrow e_i(k+1)$; */*from min of function (13)*/*

4: **end for each**

5: **if** *(* $\Delta(k+1) \leq \varepsilon_{rr}$ *, a small positive value)* **then**

6: Compute: $u_i^* = -Fe_i^*$ *;/* Local Optimization from (14)*/*

7: **Add** u_i^* **to** Equation (1) ;

8: **else do go** to Step 1;

9: **endif**

10: **end while**

Here,

$\Delta(k+1) = \left\| e_i(k+1) - e_i(k) \right\|$.

V. SIMULATION TESTS AND RESULTS

In our simulations, we used MATLAB™ version 7.1[18]. We assumed 50 stationary wireless nodes randomly located in a 1200m x 1200m 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 2.

Table 2: 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	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 simulation results for the transmit power consumption of a multi-radio multi-channel (MRMC) wireless network. The results reveal that when the connectivity range among neighbouring NICs was 200m and rate was 6Mbps then a high adjacent channel power leakage factor, delta = 1 results in more power consumptions. More power leakage factor implies more coupling interferences hence excess power losses. At any UCG, there are 283.33% more power saving with delta = 0 than with delta = 1.0.

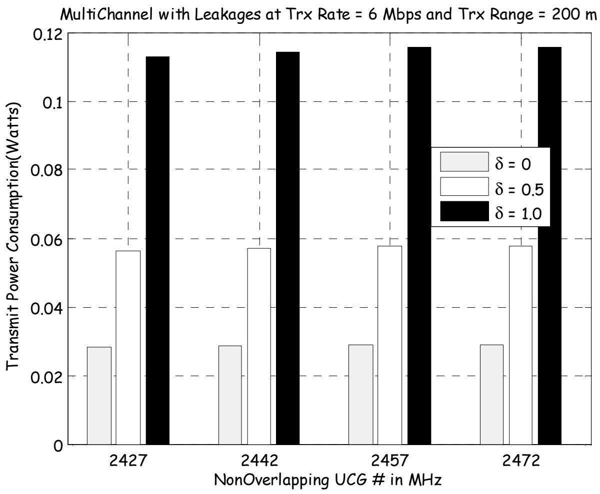

Fig. 3: Multi-channel power consumption

Fig. 4 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 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. In Fig. 5, throughput versus hop by hop range performance is depicted. Throughput is defined as the link rate multiplied by the packet successful rate (PSR) [14].

$$\mathrm{T}_i(t) = \frac{L}{M} \Gamma_i(t) f\left(SINR_i(R_i)\right), \qquad (17)$$

where L is the source packet size, M is the source packet plus the forward error correction (FEC) packet size, $\Gamma_i(t)$ is the data rate on link i during time slot t and $f\left(SINR_i(R_i)\right)$ defines the PSR given as an implicit function of the connectivity range among neighbouring NIC-pairs denoted by R_i.

High range implies high transmission power hence high interference caused to the network resulting in throughput drops. The result reveals that at 180m MMRIPA yields 51.61% and 70.97% more throughput than Variable-Range Transmission Power Control (VRTPC [8]) and Autonomous Interference based Dynamic Power Control (AIDPC [12]), respectively. This is because MMRIPA exploits multiple interfaces to transmit data on non-overlapping channels and also predicts ranges that impact on medium access by multiple users [17]. The VRTPC determines the number of other nodes contending for the medium of the same channel. This results in network interference dynamics [7]. The AIDPC presents the poorest throughput with connectivity range because nodes are assumed to have invariable connectivity ranges [12].

Fig. 6 illustrates throughput performance when offered loads were varied. MMRIPA recorded the most superior throughput performance at various loads compared to the related methods. Specifically, at 90 packets/s of load, MMRIPA yielded 54.84% and 80.65% more throughput than VRTPC [8] and AIDPC [12], respectively. This is because MMRIPA stripes packets using all the Interfaces and at a judicious power level. This phenomenon decongests the queues, improving throughput.

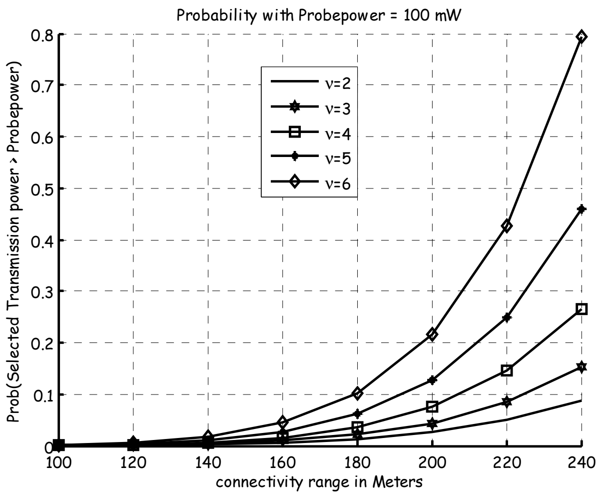

Fig. 4: Transmission Power Probability function versus Range

VI. CONCLUSION

This paper has demonstrated effectively the benefits of a connectivity range based transmission power control for an MRMC WMN. Simulation results showed that using autonomous range estimations, power control yields significant power conservations and throughput improvement for a multi-radio system. Transmission range implies good connectivity hence proper topology control [2].

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] H.-J. Ju and Rubin, "Efficient Backbone Synthesis Algorithm for Multi-Radio Wireless Mesh Networks" Proc. *IEEE Wireless Communication and Network Conference,* (WCNC) 2006.

[3] IEEE 802.11s Standard Working Group, Draft amendment available at https://mentor.ieee.org/802.11/public/04/11-04-0662-16-0001-usage-models-tgs.doc.

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

[5] J. Ishmael, S. Bury, D. Pezaros and N. Race, "Deploying Rural Community Wireless Mesh Networks," *IEEE Internet Computing,* pp. 22-29, 2008.

[6] S. Merlin, N. Vaidya and M. Zorzi, "Resource allocation in multi-radio multi-channel multi-hop wireless networks," in Proc. *INFOCOM*, pp. 610-618, 2008.

[7] N. Ramachandran, E. M. Belding, K. C. Almeroth, M. M. Buddhikot, "Interference-Aware Channel Assignment in Multi-Radio Wireless Mesh Networks," in *Proc. Infocom'* 2006.

[8] J. Gomez and A. T. Campbell, "A Case for Variable-Range Transmission Power Control in Wireless Multi-hop Networks," in Proc. *IEEE INFOCOM* 2004.

[9] M. Neely, E. Modiano and C. E. Rohrs, "Dynamic Power Allocation and Routing for Time-Varying Wireless Networks," *IEEE Journal on Selected Areas in Commun.*, vol. 23(1), pp. 89-103, 2005.

[10] B. Ata, "Dynamic Power Control in a Wireless Static Channel Subject to a Quality of Service Constraint," *Journal of Operation Research,* vol. 53 (2), pp. 842-841, 2005.

[11] A. Subramanian and A. H. Sayed, "Joint Rate and Power Control Algorithms for Wireless Networks," *IEEE Trans. On Signal Processing,* vol. 53 (11), pp. 4204-4214, 2005.

[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] T. O. Olwal, F. O. Aron, B. J. van Wyk, Y. Hamam, N. Ntsibane and M. Odhiambo, "Improved Distributed Dynamic Power Control for Wireless Mesh Networks," In *Proc. 7th International Conference, ADHOC-NOW 2008,* LNCS 5198, France, Sept. 10-12, 2008.

[14] T. O. Olwal, F. Aron, B. J. van Wyk, Y. Hamam, N. Ntlatlapa and D. Johnson, "Transmission Probability-based Dynamic Power Control for Multi-Radio Mesh Networks," in *SATNAC 2008*, Wild Coast Sun, Sept. 7-10.

[15] V. Dragan and T. Morozan, "The linear Quadratic Optimization Problem for a class of Discrete-Time Stochastic Linear Systems. *International Journal of Innovative Computing, Information and Control,* vol. 4(9), pp. 2127-2137, Sept. 2008, ISSN 1349-4198.

[16] Z. Gajic and X. Shen, *Parallel Algorithms for Optimal Control of Large Scale Linear Systems,* Springer-Verlag, 1993.

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

[18] Math Works Inc., http://www.mathworks.com

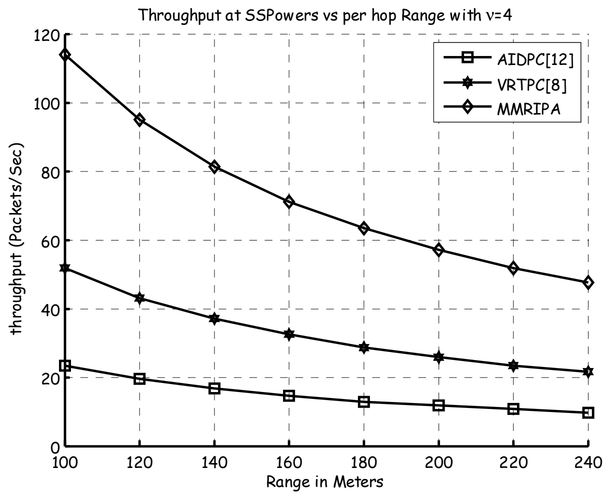

Fig. 5: Throughput per UCG versus one hop Range

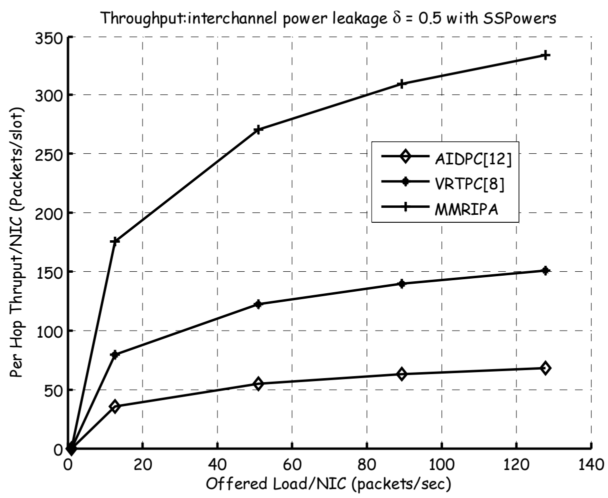

Fig. 6: Throughput per NIC versus the Offered Load

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