Scalable Power Selection Method for Wireless Mesh Networks

T. O. Olwal, B. J. van Wyk, *Member, IEEE,* Y. Hamam, *Senior Member, IEEE* and N. Ntlatlapa

Abstract— **This paper addresses the problem of a scalable dynamic power control (SDPC) for Wireless Mesh Networks (WMNs) based on IEEE 802.11 standards. An SDPC model that accounts for architectural complexities witnessed in multiple radios and hops communication system is designed. The key contribution is that we have first developed a general multiple transmission activity (MTA) model for each radio link. We then present a power selection policy that depends on average cross-layer network fluctuations as opposed to instantaneous fluctuations. Through simulations, we have observed that the SDPC modelled at the link layer, with the knowledge of imperfect and often delayed information, can significantly yield much power savings.**

Index Terms— **Wireless Mesh Networks, Dynamic power control, PHY-layer, MAC-layer, Physical model, Protocol interference model.**

I. INTRODUCTION

Wireless mesh networks (WMNs) are composed of wireless mesh routers (WMRs) and mesh clients (WMCs). While WMRs have minimal mobility and form the backbone of WMNs, the WMCs can either be stationery or mobile and form client mesh network among themselves and with mesh routers [1]. Through multiple hop communications, each mesh node can forward packets on behalf of other nodes that may not be within direct wireless transmission ranges (WTR) of their destinations. WMRs thus, can achieve same coverage with much lower transmission power than conventional wireless routers. WMNs are also capable of dynamically self-organizing and self-configuring, with the nodes in the network autonomously establishing and maintaining mesh connectivity among themselves. This feature gives WMNs many advantages such as low up-front cost, easy network maintenance, and reliability service coverage. The flexibility of mesh routers has been shown to improve further via the installation of multiple wireless interfaces (multiple radios) built on either the same or different wireless access technologies [2]. Multiple radios are capable of performing routing and configuration between mesh routers and at the same time accessing end users to the network, thus improving capacity [1]. These attractive structural and functional features have fuelled the importance of WMNs for rural community owned broadband applications [8]. Motivated by such rural applications, limited supply of energy and complex dynamic properties, it is imperative to design a distributed dynamic power selection (control) policy (DDPSP) for mesh nodes. Furthermore, power control techniques in wireless networks minimize aggregate multiple access interference (MAI) so that a network can have: optimal network connectivity attributes, a high network throughput, a guaranteed multiple hop communications, increased network lifetime and a high network capacity.

The power control problem in wireless networks has been widely studied in the context of Cellular, Ad Hoc and Sensor networks [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21]. However, little research attention has been driven towards power control problem in WMNs. This is because, recent studies have assumed that WMRs have limited mobility and are energy unconstrained and that power control problem affects only WMCs such as Ad Hoc and Sensor nodes   [8], [1]. In view of characteristic differences in different networks, power control design approaches in Cellular, Ad Hoc and Sensor networks can not be applied directly to the WMNs. For instance, each WMR node may have multiple and independent radio devices (RD) each with its own medium access control (MAC) and physical (PHY) layers. Moreover, distributive properties of WMRs and WMCs make them naturally flexible and robust to network faults and link failures compared to the centralised Cellular networks. Furthermore, designing a radio link based power adjustment method for multiple radio link WMNs can significantly reduce the effects of dead zones witnessed in traditional IEEE 802.11 wireless local area networks (WLANs) [7].

In studies related to our approach, MAC-based on directional antenna [3] and MAC with power control [4] have been recently proposed to reduce power consumptions [5], [6]. Such schemes can reduce exposed node problems, especially in a dense network. The works in [22], [23], [24], [25] present power control methods used within the carrier sense multiple access with collision-avoidance (CSMA/CA) MAC scheme to improve spatial spectrum-reuse. For instance, the work in [22] presents a power control MAC protocol that allows nodes to vary transmission power level on a per-packet basis. Results in [22] show that schemes in [26], [27] can degrade network throughput and result in a higher energy consumption than in the case of no power

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control. Schemes applying specifically to CSMA/CA-based systems do not guarantee that the allocated transmission power levels are minimal [17]. This is because *clear channel assessment* (CCA) signalling messages are performed at full transmission power. Full transmission power degrades mesh scalability performance when applied to multiple hop communications [1], [8].

In this paper multiple radio interfaces operating in multi-channel MAC protocols are considered [23], [1]. A general DDPSP in response to average cross-layer feedback information is designed. Each active device in a given time slot averages interference measurements from neighbours over possible occurrences of the network activity. Network activities are random processes occurring in each time slot. Time slot durations are too large compared to the network interference measurement time. A key feature of our model is that we evaluate average values of aggregate MAI over all possible network multiple transmission activity (MTA). Recent works have considered instantaneous MAI values [15], [17], [36]. Instantaneous MAI responses yield unreliable power updates and QoS estimations due to network uncertainties. Unlike our previous work [36] where power selection was performed in a CSMA/CA system, this paper proposes a power selection problem at the link layer in order to reduce cross-layer delay limitations. Furthermore, our formulation presents average convex cost function and additional bi-directional constraints. Finally, to improve network scalability and capacity, we consider time-slotted CDMA MAC systems [30], [35]. The advantages of such MAC schemes can be exploited in designing distributed MAC protocols for WMNs [28]

The paper is organised as follows: Section 2 presents the system model and assumptions, while Section 3 discusses the problem formulation. In Section 4, an adaptive transmission power control algorithm is developed. Section 5 presents and analyses the simulation results. Section 6 concludes the paper.

II. SYSTEM MODEL

Consider a wireless mesh network composed of stationary nodes equipped with multiple radios for network access and for relaying packet at the mesh network backbone. We assume that mesh nodes with packets waiting in the queue are assigned fixed time slot durations. Each time slot accounts for power control adjustment mini-slot time, packet transmission mini-slot time and a guard time interval. In the system, we assume also that actively transmitting wireless radio links are faced with co-channel interference at their intended receivers and interference from other channels (adjacent channel interferences) are insignificant. Classification proposed in [29] presents two possible interference models for multiple hop wireless networks, namely the protocol interference model (PIM) and the physical model (PM). The PIM describes interference constraints according to a conflict graph but does not take into account the cumulative effect of MAI, while the PM directly considers the signal to MAI plus noise ratio (SINR) constraints at the receivers. We present a mathematical formulation in section 3, in which each link employs the PM in the objective function subject to a set of the PIM constraints.

In this paper, we describe links in the *active* set as those links having their radio transmission power switched on with packets in queues waiting to be transmitted. While *inactive* set of links do not have packets in their queue and have their radio transmission power switched off. Links that can simultaneously transmit their packets according to a joint MAI and TSP based power *control* (selection) policy are said to belong to the *feasible* set, otherwise infeasible set. Mathematically, the network model can be described with a directed graph $G(V,E)$, where vertices V, represent wireless mesh devices (MDs) and edges E, represent physical links. The SINR at receiver device r when a signal is transmitted by sender device i in time instant k is given by

$$\beta_{ir}(k) = \frac{S_i\, p_{ir}(k)G_{ir}(k)x_{ir}(k)}{\sum_{(l,m)\neq(i,r)} p_{lm}(k)G_{lr}(k)x_{lm}(k) + \eta_r(k)}, \qquad (1)$$

where S_i is the spreading gain (or the bandwidth expansion factor) of the spread-spectrum system, $p_{ir}(k)$ is the transmission power emitted by i on link (i,r), $G_{ir}(k)$ is the gain of the radio channel between i and r, η_r is the thermal noise at receiver r, and $x_{ir}(k)$ is an on/off random variable indicator, i.e.,

$$x_{ir}(k) = \begin{cases} 1 \text{ if device } i \text{ transmits to device } r \text{ in timeslot } k \\ 0 \text{ otherwise} \end{cases}$$

$$(2)$$

We assume that devices use long, orthogonal pseudo-random sequences [30] and also that each time device i transmits to device r, the (instantaneous) MAI level at device r depends on devices in $V_r \subset V$ (or links in $E_r \subset E$) that are transmitting concurrently with device i. Instantaneous MAI from eq (1) can be defined as

$$q_{-ir}(k,\mathbf{p}_{-ir}) = \sum_{(l,m)\neq(i,r)} p_{lm}(k)G_{lr}(k)x_{lm}(k) + \eta_r. \qquad (3)$$

In reality, channel gains, received power, MAI and SINR are random processes fluctuating in time. Power selection should not respond to instantaneous fluctuations of the SINR in time but the average trends reflecting true QoS changes. That is, if the number of multiple transmission activity at the device r is $|V_r| = N_r$, then there are exactly 2^{N_r-1} possible combinations of MAI in the set V_r excluding the transmitting node itself during time slot k. The average MAI is then dependent on the probability that a time-variant random variable $C_{ir}(k)$ has a realization c_{ir} in each combination. Therefore, we model the average MAI over all possible combinations as

$$\langle q_{-ir}(k,\mathbf{p}_{-ir})\rangle = \sum_{m=0}^{2^{N_r-1}-1}\Pr\{C_{ir}(k)=c_{irm}\}q_{-ir,m}(k,\mathbf{p}_{-ir}),$$

$$= \sum_m \prod_{a\in c_{irm}}^{Active\,Set}\tau_a \prod_{d\in \bar{c}_{irm}}^{Inactive\,Set}(1-\tau_d)q_{-ir,m}(k,\mathbf{p}_{-ir}),$$

$$(4)$$

where τ_{ir} denotes a general MAC-dependent transmission scheduling probability (TSP) for any actively transmitting link. Intuitively, TSP in eq (4) is analogous to probability density function of network inference measurements taken by each link. The TSP is a function of the transmission power that must be determined for successful transmission. In what follows, we describe the successful transmission rate in terms of the transmission power and the possible MAI combination of occurrences as [31],

$$
\begin{aligned}
\upsilon_{ir}(k, p_{ir}) &= \Pr\{transmission\ succcess\}, \\
&= \sum_{m=0}^{2^{N_r-1}-1} \Pr\{transmission\ success \mid p_{ir}, C_{ir}(k) = c_{irm}\}, \\
&= \sum_{m} \{1 - P_b[\beta_{irm}(k, p_{ir})]\}^{\ell} \Pr\{C_{ir}(k) = c_{irm}\}, \quad (5)
\end{aligned}
$$

where $P_b[.]$ denotes the bit error rate (BER) and ℓ is the length of the PHY-layer convergence protocol data unit (PPDU). The general model provided in equations (4) and (5) applies to any MAC protocols and upper-layers. The problem of power control with the knowledge of cross-layer information involves maximizing network throughput. Thus, assessing eq (1) and deducing from eq (4), the average SINR deteriorates when the first product term is maximal, i.e., all interfering links are transmitting concurrently. On the other hand the level of SINR increases when the second product term is maximal, i.e., none of interference links are transmitting concurrently. However, such performance improvement is achieved at the cost of a degraded network capacity. Thus, the consideration of a time-slotted CDMA MAC protocol would naturally improve network capacity performance. Furthermore such protocols have been shown to significantly improve network scalability [28], [30]. In such systems each active device/link has fixed time slot duration to transmit its pending packets at a controlled transmission power so as to allow the admission of other network users into the network.

So far, we have assumed that power selection policy is affected by the average network activity at the receiver end. In practice, the wireless links are asymmetrical i.e., $G_{ir} \neq G_{ri}$ and thus power attenuation is also asymmetrical. This implies that the optimality of transmission power should take into account network conditions in both the transmitter and the receiver set. Moreover, before actual DATA packet transmission with optimal power, bi-directional *clear channel assessment* (CCA) also known as channel probing must occur. Power selection algorithm is performed during this period in order to guarantee packet transmission QoS. To allow for reliable QoS estimation the power selection *update timescale* (time between consecutive power updates) should be significantly larger than the *transmission timescale* (time to transmit a bit/message/packet) Therefore, the expression in eq (5) under asymmetrical wireless channels would be given as follows:

$$
\begin{aligned}
\upsilon_e(k, p_e) &= \sum_{m}\sum_{n} \{1 - P_b[p_{irm}]\}^{\ell} \Pr(C_{ir} = c_{irm})\{1 - P_b[p_{rin}]\}^{\ell} \\
&\quad \times \Pr(C_{ri}(k) = c_{rin}) \ \forall\ e \in E.
\end{aligned}
$$
$$(6)$$

The scheduling and power control system dynamically adjusts its power scheduling disciplines for the MTA of the network in response to input feedback depicted by expression (6). In general $\tau_e(k)$ is a non-linear dynamic function of $\upsilon_e(k-1)$. This relationship takes the form

$$
\tau_{e \in E}(k) = f_{e \in E}(\upsilon_{e \in E}(k-1)). \quad (7)
$$

If $\tau_e(k)$ has a continuous *n*th derivative throughout the interval [0, 1] then, Taylor series expansion is given by

$$
\begin{aligned}
\tau_e(k) &= f_e(0) + \upsilon_e(k-1)f_e'(0) + \ldots + \upsilon_e^n(k-1)f_e^{(n)}(0)/n!, \\
&\cong f_e(0) + \upsilon_e(k-1)f_e'(0) \approx f_e'(0)\upsilon_e(k-1), \\
&= \phi\upsilon_e(k-1) \ \forall\ e \in E, \quad (8)
\end{aligned}
$$

where ϕ is a design constant that may be considered much less than unity as the network scales large. In what follows, we present a power selection policy in response to the average MAI using eq (4) for link $e \in E$ as:

$$
\begin{aligned}
p_{e \in E}(k+1) &= p_{e \in E}(k) + \alpha_{e \in E}(k)\langle q_{-e \in E}(k, \mathbf{p}_{-e \in E})\rangle, \\
&\quad \forall\ k \in \{1, 2, \ldots, K\}. \quad (9)
\end{aligned}
$$

Here, eq (9) depicts an adaptive transmission power execution per link at the *k*th iteration time under uncertainties of interferences and the per-link TSP dynamics. The notation $\alpha_{e \in E}(k)$ represents the distributed power controller gain. In order to improve the convergence time of the dynamical execution of power level, the average MAI and the TSP need to be estimated by a robust control filter described in [32] at the same rate with power iteration procedure. In this paper we assume that power iteration procedure converges exponentially fast so that power *update timescale* does not introduce excessive network delays. This assumption is reasonable since in WMNs transmission rates are expected to be high [28], [29]. Furthermore, wireless channel links between devices with limited mobility can be assumed to follow slow shadowing and fading processes [19]. This implies that channel may hold their state constant within the period of power convergence. Using the proposed slot-by-slot power control policy in eq (9), each link drives the average SINR to desired value and at the same time maintains the network average interference as low as possible. Such design problems are formulated in Section III.

III. PROBLEM FORMULATION

In the context of per-link and network centric objective function proposed in [10], [15], each node in the network, minimises its cost function independently. This can significantly improve network scalability properties for single hop communications. However, instantaneous fluctuations of SINR and MAI in time, and lack of bi-directional network information can yield unreliable QoS estimations. This implies that such models would yield a degraded capacity performance in multi-hop communication systems. In this paper, we present a similar cost function

with minor modifications, namely at each node at least two radio devices may be equipped. Each radio device has independent PHY and MAC layer functionalities [1], [2]. Therefore, in such cases, a power selection formulation must take into account network condition averages and additional cross-layer constraints. In particular, we consider that each mesh radio link autonomously adjusts its MAC-dependent power levels so that its average SINR is at least the SINR threshold and the aggregate MAI level in the network is minimal. The objective function minimising the average SINR deviation and aggregate MAI under the physical model (PM) during each time slot is

$$\min J_{e \in E}(k) \qquad \forall k \in \{1, 2, \ldots, K\} \ , \qquad (10)$$

where $\quad J_{e \in E}(k) = \omega_{e1}\, \varepsilon_{e \in E}^2(k+1) + \omega_{e2}\, \left\langle q_{e \in E}(k+1) \right\rangle^2$ [15].

The objective function in eq (10) depends on time period since each device can change its power management goals during each time slot. For instance when channel conditions are favourable for successful transmissions and more power supply is available at the node, a device may choose to adapt its power greedily during that time period. On the other hand when channel conditions are worse and the available energy is low the devices choose to be energy-efficient and go on power save mode. From eq (10) the average SINR deviation for asymmetrical link $e \in E$ is given by

$$\varepsilon_{e \in E}(k+1) = \gamma_{e \in E} - \left\langle \beta_{e \in E}(k+1) \right\rangle, \qquad (11)$$

and the average aggregate MAI is given by

$$\left\langle q_{e \in E}(k+1) \right\rangle = \left\langle q_{-e \in E}(k+1) \right\rangle + \left\langle p_{e \in E}(k+1) G_{e \in E}(k+1) \right\rangle. \qquad (12)$$

The cost function in eq (10) must be minimised subject to the MAC protocol and transmission power constraints:

$$x_{e \in E}(k) \in \{0,1\} \ \ \forall e \in E, \ k = 1, \ldots, K \ , \qquad (13)$$

$$\sum_{(i,r) \in E} x_{ir}(k) + \sum_{(r,i) \in E} x_{ri}(k) \leq 1 \ \ \forall i \in V, \ k = 1, \ldots, K, \qquad (14)$$

$$0 \leq \tau_{e \in E}(k) \leq 1 \ \ \forall e \in E, \ k = 1, \ldots, K, \qquad (15)$$

$$\left\{ \frac{d_{e \in E}}{R_T^{Max}} \right\}^{\rho} P_{e \in E}^{Max} \cdot x_e(k+1) \leq p_{e \in E}(k+1) \leq P_{e \in E}^{Max} x_e(k+1), \qquad (16)$$

Here, Constraint (13) is a binary constraint that indicates concurrent transmission of link $e \in E$ with other links in the network. Equation (14) implies that each device is active in at most one link in each iteration slot. Constraints (13) and (14) depict that packets are in the queue and the device is in a nonzero power state. While constraint (15) characterizes the transmission activity state (occupation measure), that is when TSP is zero then it implies an unfavourable network condition for transmission so the device is in power save mode. When TSP is unity then an ideal network condition may be assumed. The device can transmit with maximum power in order to attain the desired QoS. Equation (16) is the necessary condition for a successful transmission under the protocol interference model (PIM). Parameters ρ, d_e,

and R_T^{Max} are the path-loss exponent, transmission distance, the maximum transmission range, respectively for link $e \in E$. Proof for equation (16) can easily be shown by extending analytical results in [29]. Equation (16) offers a practical minimum power level that can be chosen for channel probing scheme [14].

Proposition 1: *For a link executing the power iteration in eq (9), the optimum controller gain $\alpha_{e \in E}^*(k)$ in the kth iteration can be as shown:*

$$\alpha_e^*(k) = \frac{A_k - \omega_e \left\langle q_{-e \in E}(k+1) \right\rangle^2 \left\{ \left\langle q_{-e \in E}(k+1) \right\rangle + \left\langle p_{e \in E} G_e(k) \right\rangle \right\}}{B_k \left\{ 1 + \omega_e \left\langle q_{-e \in E}(k+1) \right\rangle^2 \right\}}$$

$$\qquad (17)$$

where

$$A_k = \left\langle q_{-e \in E}(k+1) \right\rangle^2 \gamma_{e \in E} - \left\langle p_{e \in E} G_{e \in E}(k) \right\rangle, \qquad (18)$$

$$B_k = \left\langle G_{e \in E}\, q_{-e \in E}(k) \right\rangle, \qquad (19)$$

$$\omega_{e \in E} = \omega_{e2} / \omega_{e1} \ . \qquad (20)$$

From equations (11), (18) and (20) the notations $\gamma_{e \in E}$ and $\omega_{e \in E}$ are respectively, the target QoS threshold and the network priority based non-negative weighting factor for the minimization of the objective function in eq (10).

Proof: The outline of the proof is as follows: If we substitute the value of $p_e(k+1)$ in eq (11) and eq (12) with the expression in eq (9) and evaluate the first partial derivative of eq (10) with respect to $\alpha_{e \in E}(k)$, and set the result to zero, we get the result in eq (17).

As shown through simulations in section 5, the optimal controller gain $\alpha_{e \in E}^*(k)$, tracks channel uncertainties exponentially fast, leading to a rapid power selection convergence. Proof for update convergence for eq (9) can be found in [36].

IV. ADAPTIVE POWER CONTROL ALGORITHM

This study assumes a distributed time-slotted system that controls multiple channel contentions and enhances multiple hop communications [28], [35]. We also consider orthogonal code sequence system because of its anti-jamming capabilities, robustness to multipath effects, lower power spectrum density, and potential for multi-user access through CDMA techniques. Thus, the proposed algorithm assumes that the power selection update *timescale* consists of a few mini-time slots for channel probing and power selection signalling time. The outline of the algorithm during each time slot is given as:

1) Initially all radio devices are assumed active, i.e., there are packets in each queue waiting to be transmitted.

2) Initially the feasible set is empty, i.e., no radio link has optimal power level that satisfies the objective function in eq (10).

3) Each active radio link, say link l_{ir}^a, measures its thermal receiver noise, i.e., η_r.

4) Each active radio link, say link l_{ir}^a, measures its direct channel gain, i.e., $G_{ir}(k)$.

5) Each active radio link, say link l_{ir}^a, draws an independent uniform random variable to select an initial (probing) power level. If an integer parameter Q represents the total number of power levels to which a transmitter can be adjusted then,

$$\vec{P}_{uniform}(0) = \left\{ \frac{1}{Q} p_{ir}^{Max}, \frac{2}{Q} p_{ir}^{Max}, \ldots, p_{ir}^{Max} \right\}. \qquad (21)$$

Such random choice helps in resolving starvation conflicts [19]. In a special case link l_{ir}^a computes the lower bound in the constraint (16) as its probing power. The probing power helps a link to exchange cross-layers' signalling information with its neighbours. Such information helps a link to decide on its attempt to transmit its packet with successful probability.

6) Each radio link, say link l_{ir}^a, measures, estimates and predicts through a robust filter [32] an average MAI using the model in eq (4). It should be noted that predicted values of MAIs are used to evaluate optimal control gain sequences in eq (17). Instantaneous MAI measurements yield unreliable power control signals.

7) Each radio link, say link l_{ir}^a, computes its TSP using eq (8) for optimal power selection. At this stage if a link's TSP is zero then that link goes on power-save mode, i.e., transmit power is set to zero, otherwise that link executes power iteration.

8) Each radio link, say link l_{ir}^a, computes the average received SINR.

9) Each radio link, say link l_{ir}^a, executes optimal power iteration in K iterations' time. If power iteration converges then DATA packets are transmitted using the updated power level. Otherwise, that link defers its transmission for a predefined finite/back-off time. This back-off time depends on the channel state and the traffic application priority [15]. When the actual mean SINR reaches steady state the algorithm converges [36].

10) If packets arrive in the queue in the next time slot, the algorithm repeats steps (4) through (10).

V. PERFORMANCE TESTS AND EVALUATION

For performance test, we used MATLAB^{TM} version 7.1 [33], partly because of its accuracy in handling matrices of power values at the lower network layers and partly because we considered a small optimization network density problem. We placed collections of 2 to 50 mesh devices randomly within a 1000 x 1000 m^2 area, i.e., a size big enough to deploy a multi-hop network. We assumed that each device with transmission range of 250 m and the maximum interference range of 500 m. Performance metrics were evaluated by Monte Carlo simulations for 60 independent runs for each random network configuration (instance). For all network configurations, we assumed that all devices have at least one neighbour, and that there were considerable channel contention and hidden terminal

problems. However, such problems could be resolved by the distributed time-slotted signalling and the knowledge of the bi-directional signalling (or the TSP) information. We further considered packet arrival at the radio link queues according to independent Poisson processes. Packet sizes of 1000 bytes, data rate of 2 Mbps, code spectrum gain of 128 and channel bandwidth of 10 MHz, were also assumed. We assumed typical carrier frequency of 2.4 GHz in order to calculate the signal wavelength for channel gain, while modulation and coding techniques as in [34]. It was further assumed that every mesh device has a maximum transmission power (Pmax) of 1000 mW and a minimum transmission power of 0 mW. For the implementation in this paper, we used initial (probing) power of eq (21) in all simulation runs. The propagation path loss model exponent and a white Gaussian noise (AWGN) were also assumed to be 4 and 0.001mW respectively.

In Fig.1, performance tests of the optimally designed per link power control gain as a function of estimated channel information show that when priority based weighting factor is zero and the channel condition is poor for transmission then the gain is a large positive value that decreases exponentially when the channel condition improves. This can be explained as follows: in a bad channel condition and with a zero weighting factor, a mesh radio link (MRL) increases the transmission power greedily in order to achieve a user-centric target QoS. However, this increase is performed at the expense of high energy depletion and without regard to the interference caused to other network users. On the other hand, the MRL stabilises the dynamic power selection (DPS) system when the channel condition becomes favourable for successful transmission (ST). Under favourable ST-conditions, the optimal controller gain (OCG) ensures that the transmission power remains stable after steady state. Also evident from Fig. 1, is that the OCG approaches a zero from negative when the weighting factor is a positive large value. This implies that each link, in a bad channel becomes energy-efficient and the transmission power is decreased towards a low value. An energy-efficient link may eventually switch off its transmission power and opt-out of transmissions. As the channel condition becomes more favourable, an energy-efficient link will increase its transmission power by setting the parametric OCG to a near zero or a stable value.
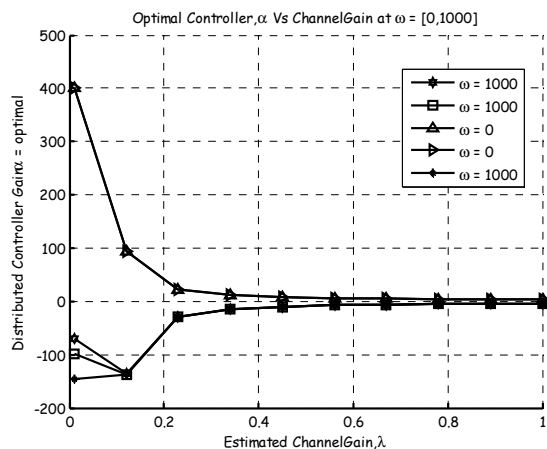

Fig. 1. The per link optimal control gain as a function of estimated channel conditions.

In Fig. 2, the parametric OCG graph smoothly tends to a zero value from a large negative with increase in MAI levels when the link is energy efficient. This implies that, irrespective of the choice of the initial transmission power in each radio link, an energy-efficient radio link attempts to reduce its transmission power as others introduce excessive interferences in the network. This powering down is done at the expense of a degraded QoS requirements. At 20 *m*W of MAI powers, the parametric OCG is noted to be -15 when the initial probing power is 60 *m*W and it is -65 when the initial probing power is 100 *m*W. This implies that initial choice of transmission powers have significant effects on the value of parametric OCGs. For a given interference level, the higher the initial power the larger the magnitude of response of the control system to stability region. High transmission powers overcome MAI effects at receiver, yielding reliable receiver decoding estimates. Negative signs of the OCG indicate that an energy-efficient link stabilises only when its transmission power converges from a positive to zero value.
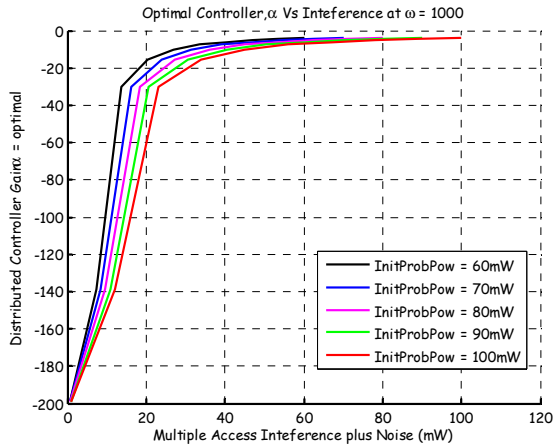

Fig. 2. The per link optimal controller gain as a function of MAI for an energy efficient radio link

However, in Fig. 3, the greedy algorithm depicted by a zero value of the weighting factor, implies that each radio link increases its power to attain the QoS target even when other transmissions are causing excessive MAI to the network. At 10 *m*W of the MAI powers, the parametric OCG was noted to be about 100 when the initial transmission power was 60 *m*W and it was about 200 when the initial transmission power was 100 *m*W. This implies that for a given MAI level and high initial powers, a greedy radio link increases its power selection rapidly in order to attain the desired system stability.

For different SINR thresholds, five senders' transmission power iteration and the corresponding received SINR responses are shown in Fig. 4. Figure 4 depicts that for a random choice of the weighting factor of the designed cost function, i.e., between zero and any positive large value, the transmission power iterations converge fast to a nearly fixed point. Furthermore, all radio links can be noted to have met their target QoS, i.e., each link has its received SINR as being above SINR threshold. This implies that in this simulation run, the channel condition was favourable for the successful transmission.
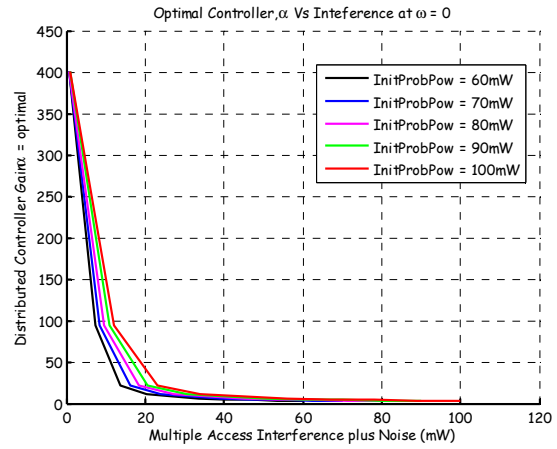

Fig. 3. The per link optimal controller gain as a function of the MAI for a greedy radio link.
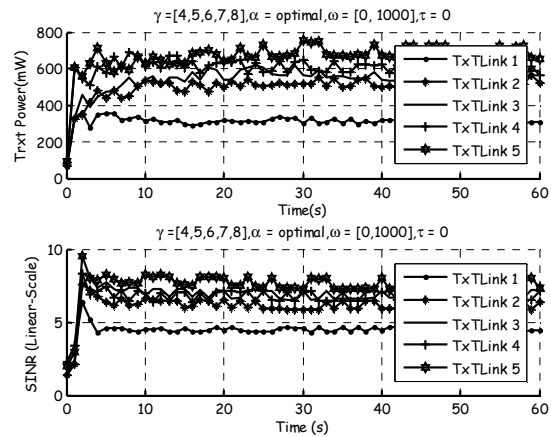

Fig. 4. Autonomous adaptive power iteration

Figure 5 presents autonomous dynamic power selection policy whereby a scalable scheduling discipline (SSD) is incorporated. It was noted that links 2, 4 and 8 demonstrate transmit power savings aperiodically between time 17-24 seconds and time 40-60 seconds. That is, if such links can compute their scheduling rates independently, they can determine whether or not to transmit with optimal power. Link 6 performs independent CCA and finds favourable network conditions. Link 6 then joins the network at these periods. In this manner network capacity can significantly improve via admission of other network users. The rest of the links execute iterative power selection throughout the steady state time. In the network perspective, autonomous sleep, wake-ups and power selection procedures improve capacity and power savings.
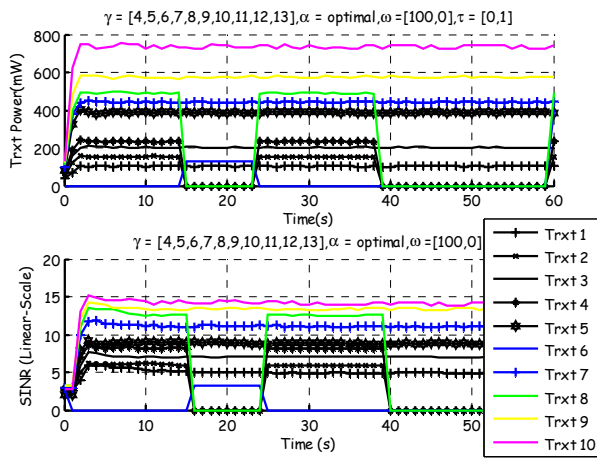
Fig. 5. Autonomous dynamic power allocation for power savings

In Fig. 6, a comparative performance analysis of average transmission powers after convergence is shown. In general, the average transmission power drops exponentially as the number of sender links/users increases. However, the proposed cross-layer based dynamic power control indicates more power savings than the recently proposed iterative methods [15][17]. In Fig. 4, there is 50% more power saving at 15 users compared to the common base station based method. This implies that the proposed method allows for network density scalability with insignificant performance degradations. Thus, the scalable dynamic power control method provides a natural alternative solution for multiple hop communications in WMNs.
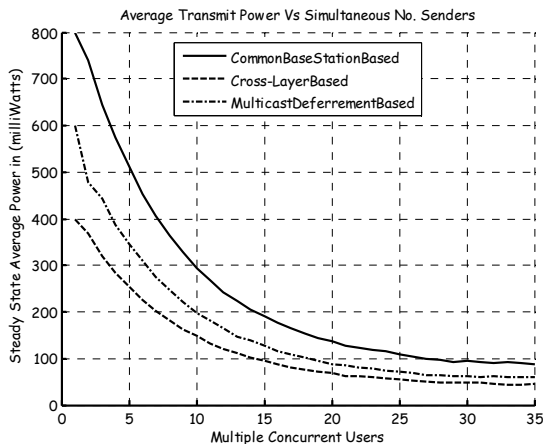

Fig. 6. Power consumptions for Multi-hop enhancement

VI. CONCLUSION

In this paper we have addressed the problem of a scalable dynamic power selection suitable for WMNs. Through joint autonomous average interferences and scheduling rates evaluation, a distributed power selection model was designed. The distributed method can reduce the system complexities significantly. The simulation results show that it is possible to have each mesh device self-adjusting its own transmission power in response to the channel and cross-layer protocol dynamics. The results also reveal that the average transmission power is low as the network scales large compared to the conventional methods.

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