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Power-Aware MAC for MultiHop Wireless Networks: A Cross Layer Approach

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***Abstract*— This paper addresses the problem of designing a power-aware Multiple Access Control (MAC) protocol for Multihop Wireless Networks (MHWN). The problem is formulated as a cross layer network utility maximization problem that considers the interaction of transport, MAC and physical layers in the protocol stack. Assuming physical model for successful transmission, a tractable formula for link throughput as a function of link attempt rate and power vectors is derived. Solving the problem, an algorithm for adjusting the session rate and link state i.e. link attempt rate and power, is proposed. At the session source, the algorithm adjusts the rate of the session based on the congestion signals feedback from the links in its path. At the links, the algorithm adjusts link state, based on the link congestion measure and messages received from neighboring links. Simulation results show that for a given link and at equilibrium the link state should be adjusted based on the link location in the network. This result is consistence with previous results that emphasize in MHWN, MAC should be designed by considering both time and space contention between links.**

I. Introduction

Designing an efficient protocol stack to maximize the utilization of network resources and imposing a fairness criterion is a main problem in networking. Traditionally and to be scalable and simple, each layer is designed separately with interfaces to other layers i.e to provide services to upper layer and to get services from lower layer.

Due to the special characteristics of MultiHop Wireless Networks (MHWN), designing each layer in isolation yields to inefficient performance. In other words, efficient use of network resources in MHWN needs coordination between layers and protocol stack should be designed in a cross layer manner [1].

Considering a utility function for each user, a class of cross layer approaches aim to maximize the sum of all users' utility and to satisfy a fairness criterion. A general framework for this approach named as Network Utility Maximization (NUM), was introduced in [2]. The main advantage of this approach is that by proper selection of utility function we can ensure to reach fair as well as optimal solution for resource assignment between competing sessions in the network[3].

The subject of this paper is on designing the MAC for MHWN. Due to the lack of any infrastructure, theses networks use some kind of random access schemes like slotted Aloha to access the channel. The contention between links is controlled at the MAC layer by adjusting the link attempt rate or the contention backoff window. This contention is alike to the one in wired networks e.g. Ethernet, and is called time contention.

Location dependent contention or space contention between links is a main challenge for designing MAC in MHWN. In other words, because of interference in MHWN, the contention level for a link depends on the density of active links around it. This indicates that there should be a coordination between links to adjust their attempt rate. Introducing the concept of contention regions and contention graphs, the problem was considered for designing MAC in [4].

In addition, the performance of the MAC is strongly dependent on the power control scheme at the physical layer [1]. The higher is the transmitter power of a link, the more are the links affected by the interference. Therefore, designing MAC protocol in conjunction with power control can improve the performance of resource utilization. Specifically, by proper control of these parameters we can gain from multipacket reception in MHWN.

Designing MAC layer and power control simultaneously to maximize the network utility is considered in this paper. This is a cross layer problem which includes power control at the physical layer, attempt rate control at the MAC layer and session rate control at the transport layer in the protocol stack. Formulating the problem in the framework of nonlinear optimization, an algorithm for adjusting optimization variables is derived by analysis. At the session source, it regulates the session rate and at the links it adjusts the link state i.e. link attempt rate and power. Session rate and link state are coordinated by congestion signals feedback to sources and messages broadcasted by links.

The problem of simultaneous congestion and power control was introduced in [2] with the JOCP (Jointly Optimal Congestion and Power Control) algorithm. JOCP is based on perfect Code Division Multiple Access (CDMA) and does not consider the MAC layer contentions between links. The problem of jointly congestion and contention control is also discussed in [5], [6], [7]. Our work differs from those since we also consider power variables in our formulation.

The rest of this paper is organized as follow. System model and notation are presented in section II. The problem is formulated in section III. Solution approach and proposed algorithm are discussed in section IV. In section V, link state status at equilibrium is studied. Numerical evaluation of the algorithm and discussion on them are presented in section VI.

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II. System Model and Notation

The MHWN is represented by a directed graph $G = G(N, L)$, where N is the set of nodes and L is the set of logical links. Logical link refers to two nodes that are in the transmission range of each other. The set of sessions are represented by S. Dedicated to each session $s \in S$, there is a utility function $U_s(x_s) : \mathbb{R}^+ \mapsto \mathbb{R}$ which is a function of its end-to-end data rate x_s. It is assumed that the utility function is strictly increasing and strictly concave. The set of links that is used by session s is denoted by $L(s)$. $S(l)$ represents the subset of sessions that are traversing link l.

Dedicated to each link $l \in L$, there is an attempt rate q_l, $0 \le q_l \le 1$, which represents the rate at which the link tries to access the channel, and transmission power p_l, $p_{min} \le p_l \le p_{max}$. $\mathbf{q} = (q_1, q_2, \ldots, q_L)$ and $\mathbf{p} = (p_1, p_2, \ldots, p_L)$ are the vectors of all links attempt rates and powers. The pair (q_l, p_l) is called the state of link l and identify a point in $q-p$ plane i.e. $[0\ 1] \times [p_{min}\ p_{max}]$.

It is assumed that the system is time slotted and uses CDMA at the physical layer. The Signal to Interference plus Noise Ratio (SINR) of link l is denoted by γ_l. If all links transmit in a given slot, γ_l is given by: $\gamma_l = (p_l G_{ll})/(\sum_{k \neq l} p_k G_{lk} + \eta_l)$; where G_{lk} is the path loss from transmitter of logical link k to the receiver of logical link l and η_l is the noise power at the receiver of logical link l. The spreading gain of the CDMA is denoted by SG and is considered in G_{lk} parameters in formulas.

Path losses is computed using the simplified model for path loss as a function of distance, d, which is given by, $G = (\frac{d_0}{d})^\alpha$ for $d > d_0$; where d_0 is a reference distance and α is the path loss exponent [8].

The attainable data rate of link l is denoted by $c_l(\gamma_l)$. In an interference limited wireless network, c_l is given by:

$$c_l(\gamma_l) = \frac{1}{T} \log(1 + K\gamma_l) \tag{1}$$

Where T is the symbol period, assumed to be one unit, and K is a constant depending on the modulation and required bit error rate of the link [8]. It is assumed that the system is in high regime SINR i.e. $K\gamma_l \gg 1$ and $K = 1$.

Due to the interferences, all transmissions are not successful and a fraction of each link capacity can be used effectively. The link throughput is denoted by T_l. We use *Physical Model* [9] to describe when a transmission is successful. In this model, the transmission of link l is successful in a time slot if the received SINR at the receiver is greater than some threshold named β. Therefore, the probability of successful transmission for link l which is denoted by s_l, is given by $s_l = Prob(\gamma_l > \beta)$; i.e. probability that the instantaneous SINR is greater than β.

The average link throughput is computed by the product of attempt rate, the probability of successful transmission and the average attainable data rate of the link i.e. $T_l = q_l s_l \bar{c}_l$.
We also assume that there is one outgoing link for the transmitter of each link and all links carry some flow. In Addition the routing matrix of the network assumed to be fixed and known.

III. Problem Formulation

The objective is to maximize the network utility, subject to the constraints on links throughput. The constraint for each link is that the sum of the rate of all sessions traversing that link should not exceed the link throughput. Therefore, the problem is stated as:

$$\mathbf{P}: \quad \max \quad \sum_{s \in S} U_s(x_s) \tag{2}$$

$$s.t. \quad \sum_{s: s \in S(l)} x_s \le q_l s_l \bar{c}_l \qquad \forall l \in L \tag{3}$$

$$x_{smin} < x_s < x_{smax} \qquad \forall s \in S \tag{4}$$

$$q_{min} \le q_l \le 1 \qquad \forall l \in L \tag{5}$$

$$p_{min} \le p_l \le p_{max} \qquad \forall l \in L \tag{6}$$

Constraints (4-6) indicates the valid range for each variable. The link attempt rate should be greater than a threshold to avoid the session to be timed out at transport layer and obviously should be less than one. The link power also should be greater than some threshold to make detection possible at receiver and less than a threshold because of restrictions at the transmitter electronic.
A general class of concave utility functions and their fairness properties are introduced in as [4]:

$$U_a(x_s) = \begin{cases} \log(x_s) & if\, a = 1 \\ (1-a)^{-1} x^{1-a} & otherwise \end{cases} \tag{7}$$

where x_s is the session rate and a is a parameter used to control the fairness criterion among sessions.

To complete the formulation of the problem, we should find an achievable bound for the throughput of link l as a function of $\mathbf{p}, \mathbf{q}$.
Let X_k be the random variable that denotes the interference value of link k to link l.

$$X_k = \begin{cases} G_{lk} p_k & with\ probability\ q_k \\ 0 & with\ probability\ 1 - q_k \end{cases} \tag{8}$$

The SINR at the receiver of link l is stochastic and depends on the received interference which is denoted by I_l and is given by:

$$I_l = \sum_{k \neq l} X_k$$

Therefore, the SINR at the receiver of link l is $\gamma_l = \frac{G_{ll} p_l}{I_l}$.

To compute an average for attainable average data rate, $\bar{c}_l$, on each link, we note that $\bar{c} \le \log(\bar{\gamma})$ [8]. Based on Jensen's inequality and the fact that $f(I_l) = 1/I_l$ is convex, we have:

$$\bar{\gamma} = \mathbf{E}\Big[\frac{G_{ll} p_l}{I_l}\Big] \ge \frac{G_{ll} p_l}{\mathbf{E}[I_l]}$$

where $\mathbf{E}$ denotes the mathematical expectation. Therefore, a constraint for the average attainable data rate on each link is given by:

$$\bar{c}_l \le \log_2\Big(\frac{G_{ll} p_l}{\sum_{k \neq l} G_{lk} p_k q_k}\Big) \tag{9}$$

Noting that the success probability, s_l, is related to outage probability, o_l, by $s_l = 1 - o_l$, we first compute o_l since it is more tractable. The outage probability is given by:

$$\begin{aligned} o_l &= Prob(\gamma_l < \beta) = Prob(\frac{G_{ll}p_l}{I_l} < \beta) \qquad (10)\\ &= Prob(I_l \geq \frac{G_{ll}p_l}{\beta}) \leq \frac{\mathbf{E}[I_l]}{G_{ll}p_l/\beta} = \frac{\beta}{G_{ll}p_l}\sum_{k\neq l} G_{lk}p_k q_k \end{aligned}$$

The inequality is based on the Markov inequality for non-negative random variable I_l and $G_{ll}p_l/\beta > 0$. Therefore, a bound for the probability of successful transmission is given by:

$$s_l \geq 1 - \frac{\beta}{G_{ll}p_l}\sum_{k\neq l} G_{lk}p_k q_k \qquad (11)$$

Using (9) and (11), we find a conservative constraint on the achievable throughput for link l given by:

$$T_l \leq q_l(1 - \frac{\beta}{G_{ll}p_l}\sum_{k\neq l} G_{lk}p_k q_k)\bar{c}_l$$

We should mention that it may be possible to find tighter bounds for the average attainable data rate as well as the outage probability to compute the link throughput which itself is an interesting problem. However, our aim in this paper is on the relative assignment of powers and attempt rates to the links, and the derived achievable throughput include all links power and attempt rate. Also, this bound is mathematically tractable as we see in the next section.

IV. Solution Approach

Due to the product terms in (3), problem **P** is not a convex optimization problem. A *max* optimization problem is convex if the objective function is strictly concave and the inequality constraints are convex. The global optimal solution of a convex optimization problem can be achieved using well known convex optimization theory [10]. Fortunately, using *log* transformation, the problem can be turned to a convex optimization problem. By taking logarithm and using transformations $\tilde{x_s} = \log x_s$, $\tilde{p_l} = \log p_l$, $\tilde{q_l} = \log q_l$, (3) turns to a convex constraint given by:

$$\log\Big(\sum_{s:s\in S(l)} e^{\tilde{x_s}}\Big) - \log e^{\tilde{q_l}} - \log s_l - \log \bar{c}_l \leq 0 \qquad (12)$$

It is known that if $g(x)$ is concave and positive, then $\log g(x)$ is concave, and the log of a sum of exponentials of vector **x** is convex [10]. Noting these, we can find that the terms $\log(\sum_{s:s\in S(l)} e^{\tilde{x_s}})$, $-log(s_l)$ and $-\log \bar{c}_l$ are convex. Using this transformation the objective function turns to:

$$\tilde{U}_a(\tilde{x_s}) = \begin{cases} \tilde{x_s} & if\, a = 1 \\ (1-a)^{-1}e^{\tilde{x_s}(1-a)} & otherwise \end{cases} \qquad (13)$$

Which is strictly concave assuming $a > 1$. Therefore, using the *log* transformation and by proper selection of utility function the problem is turned to a convex optimization problem.

A. Applying Optimality Conditions

The Lagrangian function for problem **P** is given by:

$$L(\tilde{\mathbf{x}}, \tilde{\mathbf{p}}, \tilde{\mathbf{q}}, \Lambda, \Phi) = \sum_{s\in S}\tilde{U_s}(\tilde{x_s}) - \sum_l \lambda_l \left[log\left(\sum_{s:s\in S(l)} e^{\tilde{x_s}}\right) - \log\left(e^{\tilde{q_l}} s_l \bar{c_l}\right)\right] \quad (14)$$

where $\Lambda = (\lambda_1, \ldots, \lambda_{|L|})$ is used as lagrange multipliers for constraint (3).

Applying Karush-Kuhn-Tucker (KKT) theory [10] to problem and doing some simplification we can find the optimality conditions.

$$\frac{\partial L}{\partial \tilde{x_s}} = 0 \Rightarrow \tilde{U}'_s(\tilde{x_s}) - \sum_{l:l\in L(s)} \lambda_l \frac{x_s}{\sum_{s:s\in S(l)} x_s} = 0 \qquad (15)$$

$$\frac{\partial L}{\partial \tilde{q_l}} = 0 \Rightarrow \frac{\lambda_l}{q_l} - p_l \sum_{k\neq l} G_{kl} m_k = 0 \qquad (16)$$

$$\frac{\partial L}{\partial \tilde{p_l}} = 0 \Rightarrow \frac{\lambda_l(t)}{p_l(t)}\left[\frac{\beta}{\gamma_l - \beta} + \frac{1}{\log(\bar{\gamma_l})}\right] - q_l(t)\sum_{k\neq l} G_{kl} m_k = 0 \qquad (17)$$

where $m_k = \frac{\lambda_k \gamma_k}{G_{kk}p_k}\left[\frac{\beta}{\gamma_k - \beta} + \frac{1}{\log(\bar{\gamma_k})}\right]$.

Also, at equilibrium we have:

$$\begin{cases} if\ \lambda_l > 0 \ \Rightarrow \sum_{s:s\in S(l)} x_s = q_l s_l \bar{c}_l \\ if \sum_{s:s\in S(l)} x_s < q_l s_l \bar{c}_l \Rightarrow \lambda_l = 0 \end{cases} \qquad (18)$$

Therefore, based on gradient projection method and to reach optimal point solution, optimization variables should be updated as follow:

$$x_s(t+1) = \left[x_s(t) + \gamma\left(x_s^{1-a} - \sum_{l:l\in L(s)} \lambda_l \frac{x_s}{\sum_{s:s\in S(l)} x_s}\right)\right]_{x_{smin}}^{x_{smax}} \qquad (19)$$

$$q_l(t+1) = \left[q_l(t) + \xi\left(\frac{\lambda_l(t)}{q_l(t)} - p_l \sum_{k\neq l} G_{kl} m_k\right)\right]_{q_{min}}^{1} \qquad (20)$$

$$p_l(t+1) = \left[p_l(t) + \kappa\Big(\frac{\lambda_l(t)}{p_l(t)}\left[\frac{\beta}{\gamma_l - \beta} + \frac{1}{\log(\bar{\gamma_l})}\right] - q_l(t)\sum_{k\neq l} G_{kl} m_k\Big)\right]_{p_{min}}^{p_{max}} \qquad (21)$$

where $0 < \gamma, \xi, \kappa < 1$ are constants that should be selected small enough to ensure the convergence of the algorithm [10]. λ_l act as the congestion measure at link l and used to regulate the optimization variables. To find the required formula to update the congestion measures, one solution is through solving the dual problem of **P**. The dual function is:

$$\begin{aligned} D(\Lambda) = \quad & max \quad {}_{\tilde{\mathbf{x}},\tilde{\mathbf{p}},\tilde{\mathbf{q}}} L(\tilde{\mathbf{x}}, \tilde{\mathbf{p}}, \tilde{\mathbf{q}}, \Lambda) \\ & s.t. \quad Constraints(3-6) \end{aligned} \tag{22}$$

To solve the dual problem we should solve:

$$\begin{aligned} \mathbf{D}: \quad & min \quad D(\Lambda) \\ & s.t. \quad \Lambda > 0 \end{aligned} \tag{23}$$

Since the dual problem is also convex, we can use gradient projection again to find the required update equation for link congestion measure.

$$\lambda_l(t+1) = \left[\lambda_l(t) + \gamma \left(\frac{\sum\limits_{s:s\in S(l)} x_s(t) - q_l(t) s_l \bar{c}_l}{q_l(t) s_l \bar{c}_l} \right) \right]^+ \tag{24}$$

B. Interpretation of Update Equations

To simplify the interpretation of update equations, assume that in each time slot each link like k broadcast m_k as its congestion status by a message. According to (19-21) and (24), there are two terms affecting the equilibrium value of each variable. The first is the excitatory term appeared with positive sign and the second is an inhibitory term appeared with negative sign. We present an interpretation for these terms in (19-21) and (24).

According to (19), the excitatory term tends to increase the session rate which depends on the utility function. The inhibitory term is the weighted sum of all congestion measures on the session path. The weight for each link is the session rate to the total rate of the link. Therefore, the congestion measures and weights should be feedback from the links on the session path to the session source.

Each link should regulate its attempt rate based on (20). The excitatory term is the current congestion measure of the link moderated by dividing to the current attempt rate. The inhibitory term is computed using other links messages. The content of receiving messages broadcasted by other links like k multiplied by G_{kl}, feedback the share of link l on the congestion status of link k. The sum of these terms are then multiplied by the link power and yields the inhibitory term. The larger is the transmission power of a link, the more is the effect of other links messages. This imposes links with higher power to use a lower attempt rate.

Each link regulates its transmission power based on (21). The excitatory factor is based on current congestion level divided by the current power and current average capacity. The inhibitory term is computed similar to the one described for attempt rate computations unless that multiplied by link attempt rate q_l. The larger is the attempt rate the more is the effect of the received messages to decrease the transmission power of the link.

These descriptions indicated that different link states are possible depending on the link location in the network i.e. a higher attempt rate or a higher transmission power.

The interpretation of the link congestion measure i.e. λ_l in (24) is based on the rule of supply and demand. If the demand by source nodes on a link is higher than the link throughput, the link congestion measure λ_l is increased indicating sessions which use this link, reduce their rate. $\lambda_l(t)$ can also be interpreted as the backlog of link l at time t.

C. Proposed Algorithm

Based on the analysis in section IV.A the following algorithm should be run in links and sources until the convergence.

Algorithm

In each time slot $t = 1, 2, \ldots$

1- Computations at links

The transmitter of each link:

(1-a) Estimates the average link congestion measure from (24).

(1-b) Broadcasts its message

(1-c) Updates link state from (20-21)

2- Computations at sources

Each session:

(2-a) Computes its congestion on all links in its path

(2-b) Updates its rate from (19)

This algorithm can be implemented in distributed fashion by message passing in the network. Distributed implementation requires that $G_{lj}\,\forall l, j$ parameters can be estimated at the transmitter of link l through the training sequences. According to (27-28), for a given transmitter node, the farther is the distance from a neighboring link k i.e lower G_{lk}, the less is the effect of its message. Therefore, To reduce the overhead of message passing, it is possible to do tradeoff between the overhead of message passing and the optimality of the result as it is explained in [2].

V. Link State at Equilibrium

While there are infinite possible link states for a link in the $q-p$ plane, they can be grouped in three main categories depending on whether each variable reaches to its bound or not. We name these three categories by A, B and C. We also note that at equilibrium $p_l(t+1) = p_l(t)$, $q_l(t+1) = q_l(t)$.

A. Category A

For a link in this category, none of variables p_l, q_l reaches their bound i.e. $q_{min} < q_l < q_{max}, p_{min} < p_l < p_{max}$. Therefore, substituting (21) in (20), at equilibrium we have:

$$\frac{\beta}{\gamma_l - \beta} + \frac{1}{\log \gamma_l} = 1 \tag{25}$$

$$p_l q_l = \frac{\lambda_l}{\sum\limits_{k\neq l} G_{kl} m_k} \tag{26}$$

Equation (25) indicates that the SINR of a link in this category converges to a target given by this equation. The target SINR depends only on the SINR threshold β. Adjusting the power, the link adjust its attempt rate to satisfy (26). See Fig. 1. We also note that the message of such a link is reduced

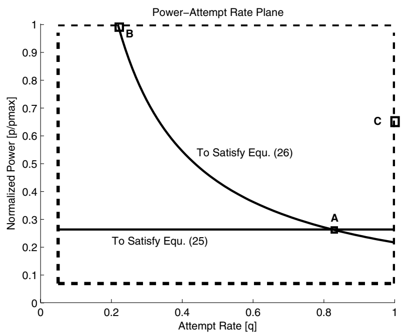

Fig. 1. Link state in q-p Plane. Admissible range is depicted by a dashed square in the state plate

TABLE I

PARAMETER VALUES IN SIMULATIONS

Parameter	Value
α,path loss exponent	2
p_0, initial links power	4.0 [mW]
p_{max}, maximum allowed power	8.0 [mW]
p_{min}, minimum allowed power	0.5 [mW]
q_0, initial links attempt rate	0.5
q_{min}, minimum allowed attempt rate	0.05
β, SINR Threshold	10

to a simple form: $m_l = \frac{\lambda_l \gamma_l}{G_{ll} p_l}$. A special case is where all links are in this category and hence all links converge to the same SINR at equilibrium. Due to the same SINR, the success probability of all links would also be the same.

B. Category B

In this category, the link power reaches to one of its bound i.e. $p_l = p^*$, where $p^* \in \{p_{max}, p_{min}\}$. Therefore, the link attempt rate is given by: $q_l = \frac{\lambda_l}{p^* \sum\limits_{k \neq l} G_{kl} m_k}$. This case is depicted by point B on Fig. 1.

C. Category C

In this category, the attempt rate of the link reaches to one of its bound i.e. $q_l = q^*$, where $q^* \in \{q_{max}, q_{min}\}$. Therefore, the link power converges to the solution of equation: $\frac{\lambda_l(t)}{p_l(t)} \left[\frac{\beta}{\gamma_l - \beta} + \frac{1}{\log(\bar{\gamma}_l)} \right] - q^* \sum\limits_{k \neq l} G_{kl} m_k = 0$. This case is also depicted on Fig. 1. The link SINR at equilibrium in categories B and C depends on the link state and β.

VI. NUMERICAL EVALUATION

The simulation results for algorithm evaluation are done at the link level. The network topology is a simple network topology that contains all aspects of the algorithm and is shown in Fig. 2. In this figure, the distance between adjacent nodes are the same and equal $d = 2d_0$; where d_0 is the reference distance in path loss model. There are four end-to-end sessions denoted by $S_1 \ldots S_4$ on the figure. The utility function of all sessions and their weights are alike in the objective function. Other simulation parameters are summarized in Table I.

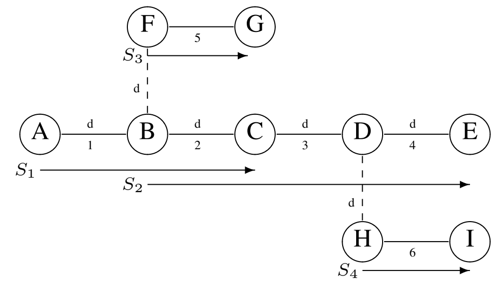

Fig. 2. Network topology and end to end sessions

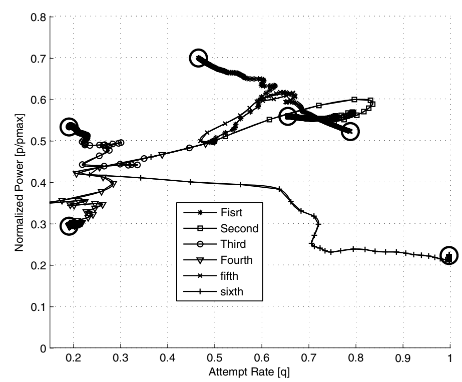

Fig. 4. Variation of links state in $q - p$ plane. Final states are depicted by circles

Depending on the value of spreading gain, links converge to different state categories. In the first experiment we set $SG = 20$. Fig. 3-a, 3-b, 3-c, 3-d show the variations of links power, sessions rate, links attempt rate and links success probability respectively until the convergence of the algorithm. In this experiment links $1-5$ are in category A and have same success probability i.e. .59 and SINR i.e. 24.5 at equilibrium. The target SINR is consistant with (25). Link 6 is in category C. Fig. 4 shows the variation of links state in $q-p$ plane until convergence. The value of link parameters at equilibrium are summarized in Table II.

It can be inferred from Table II, that links which are less exposed to other links interference e.g. link 6, converge to lower power and higher attempt rate compared to link that are more exposed to interference e.g. link $1, 5$.

The second experiment is done with $SG = 50$. The Final

TABLE II

LINK VARIABLES AT EQUILIBRIUM FOR $SG = 20$

Link Number	p_l/p_{max}	q_l	s_l	λ_l	γ_l
1	0.70	0.47	0.59	0.45	24.5
2	0.56	0.66	0.59	0.77	24.5
3	0.53	0.19	0.59	0.46	24.5
4	0.29	0.19	0.59	0.32	24.5
5	0.52	0.79	0.59	0.99	24.5
6	0.22	1.00	0.69	0.99	32.8

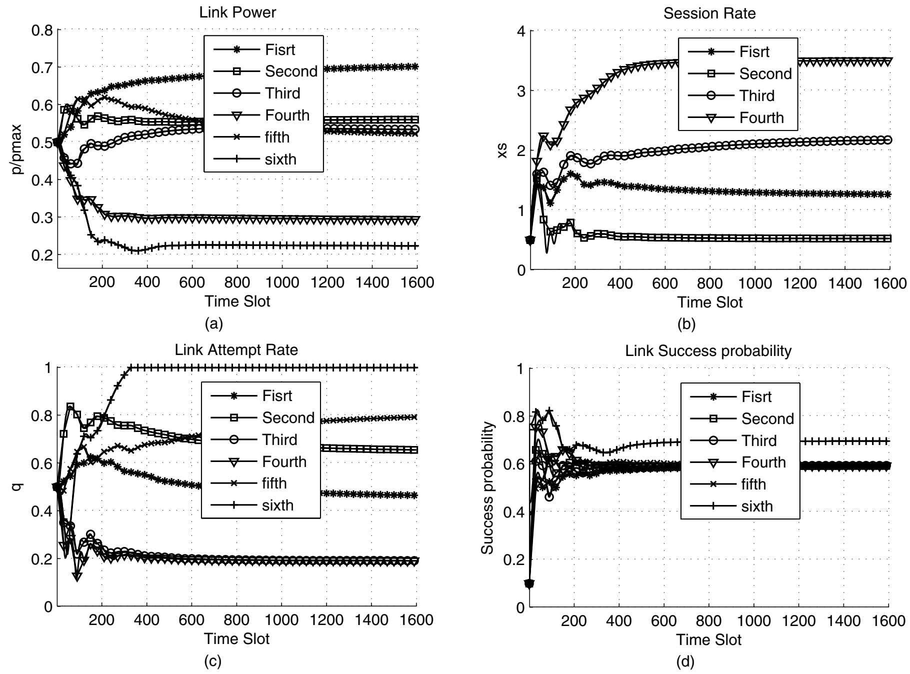

Fig. 3. Variation of problem variables until convergence. (a)Link power, (b)Session rate, (c)Link attempt rate, (d)Link success probability

TABLE III

LINK VARIABLES AT EQUILIBRIUM FOR $SG = 50$

Link Number	p_l/p_{max}	q_l	s_l	λ_l	γ_l
1	0.50	1.00	0.62	0.28	26.0
2	0.76	1.00	0.81	1.13	52.6
3	0.34	0.63	0.59	0.32	24.5
4	0.19	0.63	0.59	0.25	24.5
5	0.64	1.00	0.74	0.98	39.3
6	0.32	1.00	0.84	0.98	61.1

value of link parameters at equilibrium are summarized in Table III. In this experiment, links $3, 4$ converge to state category A and links $1, 2, 5, 6$ to state category C at equilibrium. It can be inferred from Table III that increasing the spreading gain which ends to reduction in effective interference for all links, causes to increase the attempt rate for all links. The result that is reasonable and is predicted.

VII. CONCLUSION

In this paper a power aware MAC protocol for MHWN is designed. The problem is formulated as a network utility maximization problem. The aim is to find the session rate and link state i.e. the link attempt rate and power as optimization variables. Assuming a physical model for successful transmission a conservative tractable formula for link throughput as a function of power and attempt rate vectors is computed. Solving the optimization problem, an algorithm for updating session rate and link state is proposed and is evaluate by simulation. Results of simulation show that coordination between links is required to adjust links state and the link state is dependent on the link location in the network.

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