On the Formulation and Optimal Solution of the Rate Control Problem in Wireless Mesh Networks

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ABSTRACT

An algorithm is proposed to seek a local optimal solution of the network utility maximization problem in a wireless mesh network, where the architecture being considered is an infrastructure/backbone wireless mesh network. The objective is to achieve proportional fairness amongst the end-to-end flows in wireless mesh networks. In order to establish the communication constraints of the flow rates in the network utility maximization problem, we have presented necessary and sufficient conditions for the achievability of the flow rates. Since wireless mesh networks are generally considered as a type of ad hoc networks, similarly as in wireless multi-hop network, the network utility maximization problem in wireless mesh network is a nonlinear nonconvex programming problem. Besides, the gateway/bridge functionalities in mesh routers enable the integration of wireless mesh networks with various existing wireless networks. Thus, the rate optimization problem in wireless mesh networks is more complex than in wireless multi-hop networks.

Key Words : Wireless Mesh Networks, Rate Control Problems, Algorithms, Optimal Solution, Local Optimum, Global Optimum, End-to-End Session Rates, Convex Optimization, Nonlinear Nonconvex Optimization

I. Introduction

One of the fundamental problems of characterizing the rates in networks is through a network utility maximization problem that is, a problem of maximizing a certain utility function over source rates which satisfy certain constraints such as link-channel constraints, node-radio constraints, interference constraints and capacity constraints. The said problem in wired networks, wired-cum-wireless networks, wireless multi-hop networks and wireless mesh networks has been studied recently [4, 8, 11, 14, 15, and 17]. In our case, the main objective of our paper is to present and solve the network utility maximization problems in wireless mesh networks (WMNs). In addition, we studied the network utility maximization problem in multi-radio multi-channel infrastructure/backbone wireless mesh networks [1]. Our contributions are as follows.

- We have formulated end-to-end session rates that can model the link-channel, node-radio and interference constraints in wireless mesh backbone routers and we have also described that the rate of end-to-end sessions cannot exceed the capacity of links that are traveled in wireless mesh clients.
- We have provided an algorithm for seeking a local optimal solution of the network utility maximization problem in WMNs.
- We have evaluated our algorithm based on simulation examples.

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The rest of this paper is organized as follows. We summarized some of the related works in Section 2. In Section 3, the network and channel models, and some assumptions are provided. The constraints of end-to-end session rates, optimization problem, and the detailed algorithm are described and presented in Section 4. Simulation results are illustrated in Section 5. We present our conclusions and discuss future work in Section 6.

Ⅱ. Related Work

In [8], the problem of network utility maximization in communication networks has been studied by two classes of rate control algorithm, namely primal and dual algorithms. In the assumption that the utility function of sources in a network is increasing and strictly concave, we can say that the network utility maximization problem in [8] is a convex optimization problem. The gradient projection algorithm has been presented to solve the dual of the network utility maximization problem [12]. By replacing the gradient projection algorithm presented in [12] by the Newton algorithm, the network utility maximization problem can be solved by a Newton-like algorithm [3], and this algorithm converges significantly faster than gradient projection algorithm of [12].

Unfortunately, the network utility maximization problems in wired-cum-wireless networks, where CSMA/CA based wireless LANs extend a wired backbone and provide access to mobile users [11, 15] and wireless ad hoc networks [4, 14] are nonconvex optimization problem. In addition, the network utility maximization problems in wired networks are different with wired-cum-wireless networks and wireless networks since each link capacity in wired networks is fixed, in contrast with wired-cum-wireless networks and wireless networks where the link capacity is not fixed [4, 14, 15]. The logarithmic transformation has been used to convert the utility maximization problems into convex optimization problems [4, 11, 14, 15]. In [14, 15], authors have proposed the dual based and penalty based algorithms to solve iteratively the network utility maximization problems. This approach is closely associated to the gradient projection algorithm. The approach in [11] simply solves the network utility maximization problem using the primal-dual interior-point algorithm. In [4] the jointly optimal congestion control and power control algorithm has been proposed to solve the network utility maximization with elastic link capacities in wireless ad hoc networks. In fact, the algorithm in [4] is also connected to the gradient projection algorithm.

Recent results in [2, 9, 10, and 17] have provided characterizing rates in multi-radio multi-channel in wireless mesh networks. The joint channel assignment and routing problem in multi-radio in WMNs has been studied in [2]. Efficient channel assignment and routing are essential for rate optimization in WMNs. In [9, 10], the problem of achieving a given rate vector for multi-radio multi-channel wireless networks has been studied, which is characterized by the use of multiple orthogonal channels and nodes with the ability to simultaneously communicate with many neighbors using multiple radios (interfaces) over orthogonal channels. Next, a general framework has been presented to model and solve the problem of optimizing multicast throughput in a multi-hop WMN [17]. However, the results in [2, 9, 10] have only been considered in mesh backbone routers. Particularly, the network model in which all wireless link capacities depend on their transmission power has been considered in [17]. It differs from the WMN model [1], in which wireless mesh routers have no constraints on power consumptions and mobility which is closely related to the approach in [4].

Our paper considers a WMN consisting of mesh backbone routers for multiple orthogonal channels and nodes with multiple radios interfaces and mesh clients which are only Wi-Fi networks based on the CSMA/CA protocol, adopted by IEEE 802.11 standards. We first established necessary conditions for the achievability of rate vector in both mesh routers and mesh clients. The key studies that are related to the network model proposed in this paper are found in [2], [10] and [13]. In [13], the approximation of the wireless link capacity with local topology information has been presented. Therefore, we apply this result as constraints for the wireless link in mesh clients. A similar problem is also considered in [15] as constraints of the wireless link in wired-cum-wireless network models.

Ⅲ. System Model and Assumptions

We start with the underlying network model, and explain basic definitions and concepts used with the rest of the paper.

Our work pertains to multi-hop WMNs [1], for ease of exposition we assume that the mesh clients contain Wi-Fi networks only, an example of which is shown in Fig. 1. These networks consist of static wireless mesh routers and end mobile clients. Some of the static wireless routers are equipped with gateway/ridge functionality that enables the integration of WMNs with various Wi-Fi networks. Some of the other routers are also equipped with gateway functionality to enable connectivity to the wired Internet through wired links. Each mesh router is usually equipped with multiple wireless interfaces. In contrast, mesh clients usually have only one wireless interface. For the network model in this paper, we assume that we use the protocol model of interference, which is based on the CSMA/CA protocol, adopted by IEEE 802.11 standards.

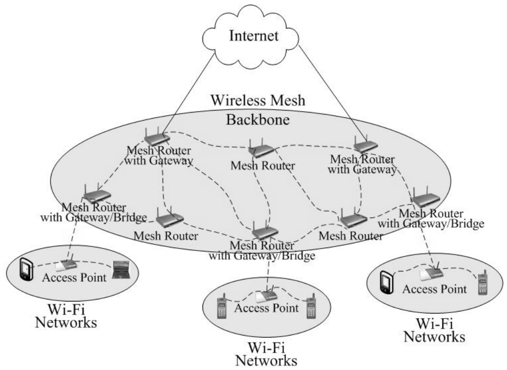

Fig. 1. An infrastructure/backbone wireless mesh network

The main characteristics of mesh router of the WMN considered in this paper are summarized as follows.

- There are multiple wireless channels of operation and these channels are orthogonal to each other.
- Routers are not mobile and have multiple radio transceivers, which allow them to communicate, interference-free, simultaneously with more than one neighbor at the same time using different channels.
- Full duplex operation is possible at each router.
- Among routers in mesh router, some of routers have gateway functionality and provide connectivity to the wired Internet through wired links which have an unlimited capacity. While some of other routers have gateway/bridge functionality and provide connectivity to access points of Wi-Fi networks, using high capacity bidirectional wireless links.

We consider a WMN modeled as a directed graph $G=(V,E)$, where V represents the set of nodes, and E denotes the set of directed links in the network. The set of nodes and links are denoted as

$$V=\{t\}\cup V^G\cup V^R\cup V^C\cup V^A\cup V^H$$

and

$$E=E^G\cup E^R\cup E^C\cup E^H.$$

Here, t represents the wired Internet; V^G denotes the set of nodes which have gateway functionality; V^C is the set of nodes that have gateway/bridge functionality; V^A denotes the set of access points in mesh client that have Ethernet connections to mesh router; V^H is the set of mobile hosts in mesh client; V^R denotes the set of routers which are neither with gateway functionality nor routers with gateway/bridge functionality; E^G denotes the set of wired links that connect to the wired Internet and have unlimited capacity; E^C represents the set of high capacity bidirectional wireless links between access points and routers with gateway/bridge functionality; E^H denotes the set of directed wireless links in mesh client; and E^R is the set of directed wireless links in mesh router. We denote by V^F the set of nodes in mesh router, that is, $V^F=V^G\cup V^R\cup V^C$.

We assume that there are K orthogonal channels numbered from 1 to K in our network model, denoted by the set OC= $\{1,\dots,K\}$. Each node $u\in V^F$ has $\kappa(u)$ radios and each data link $e\in E^R$ uses no more than a certain number of channels $\zeta(e)$. Given a link $e\in E^R$, we use $t(e)$ to represent the transmission end of the link e and $r(e)$ to be the receiving end of the link

e. Each link $e \in E^R$ has capacity $c_i(e)$ on channel $i \in$ OC and assumes that for a given topology, the capacity is fixed for any given channel across a link. We also assume that the system operates in a synchronous time-slotted mode. In the computation of the schedule for nodes, we assume that the schedule is periodic and has T time slots in each period.

In this paper, we consider a WMN, modeled as a graph $G=(V,E)$, with link capacities $c_i(e)$ associated with data link $e \in E^R$ and channel $i \in$ OC. We have a total of M source destination mobile host pairs, denoted by $(s(k),d(k))$ for $k=\overline{1,M}$. Let $S^C(k)$, $D^C(k) \in V^C$ be the routers with gateway/bridge functionality such that the $s(k)$'s access point denoted by $S^A(k) \in V^A$ and $d(k)$'s access point denoted by $D^A(k) \in V^A$ communicate with them respectively. We assume that mobile hosts $s(k)$ and $d(k)$ do not connect to the same access point in the network, i.e., $S^A(k) \neq D^A(k)$. Let r_k represent the total rate that has to be routed from source mobile host $s(k)$ to destination mobile host $d(k)$.

Ⅳ. Problem Formulation and Algorithm

In the previous section, we have described our WMN system model. Now, we present a mathematical constraint model for end-to-end session rates r_k ($k=\overline{1,M}$). Let $y_i^t(e)$, $e \in E^R$ $i=\overline{1,K}$, $t \geq 1$ be the indicator variable, namely

$$y_i^t(e) = \begin{cases} 1 & \text{if link } e \text{ is active on channel } i \text{ in time slot } t, \\ 0 & \text{Otherwise.} \end{cases}$$

Link-Channel constraint: From the maximum number of channels that can be active on link e at any time slot t is $\zeta(e)$, we have

$$\sum_{i=1}^{K} y_i^t(e) \leq \zeta(e), \quad \forall e \in E^R, \forall t. \tag{1}$$

Node-Radio constraint: We assumed that each node $u \in V^F$ can use at most $\kappa(u)$ radios in a given time slot for transmission or reception or both. This leads to the following constraint

$$\sum_{e \in E(u)} \sum_{i=1}^{K} y_i^t(e) \leq \kappa(u), \quad \forall u \in V^F, \forall t, \tag{2}$$

where $E(u)$ is the set of data links to and from u.

Interference constraint: It is well known that interference will occur only among users sharing the same channel. Let one of the links e in $E(u)$ be active on channel i and let v be the other endpoint of the link e. For link e to be active on channel i, all other links incident on node e, $E(u)\backslash\{e\}$, have to be idle and, in addition, each neighbor of u must remain idle on channel i. We obtain the interference constraints in terms of links $e \in E^R$ as follows

$$\sum_{e' \in E(t(e)) \cup E(r(e))} y_i^t(e') \leq 1, \quad \forall e \in E^R, \forall i=\overline{1,K}, \forall t. \tag{3}$$

Similar to [2] and [10], we need to seek a relaxation of the integral constraints to continuous variables in terms of end-to-end session rates. Now, for any link $e \in E^R$, we denote $x_i(e)$ as the total rate at which data is transferred across the link e on channel i. It implies that the total rate on channel i over the link e that is given by the following formula

$$x_i(e) = \frac{c_i(e) \sum_{t \leq T} y_i^t(e)}{T}. \tag{4}$$

Now, using Eq. (4) we restate constraints (1)-(3) in terms of the total rates:

$$\sum_{i=1}^{K} \frac{x_i(e)}{c_i(e)} \leq \zeta(e), \quad \forall e \in E^R, \tag{5}$$

$$\sum_{e \in E(u)} \sum_{i=1}^{K} \frac{x_i(e)}{c_i(e)} \leq \kappa(u), \quad \forall u \in V^F, \tag{6}$$

$$\sum_{e' \in E(t(e)) \cup E(r(e))} \frac{x_i(e')}{c_i(e')} \leq 1, \quad \forall e \in E^R, \forall i=\overline{1,K}. \tag{7}$$

Recall that our primal goal in this section is to find the constrained conditions for end-to-end session rates. Our network model has M source destination mobile host pairs $(s(k),d(k))$ for $k=\overline{1,M}$. Notice that multiple paths can exist between the source mobile host $s(k)$ and the destination mobile host $d(k)$ for each commodity k. We denote P_k as the set of (link, channel) paths between source router $S^C(k)$ and destination router $D^C(k)$ of commodity k ($k=\overline{1,M}$). For any $p\in P_k$, let $r(p)$ denote the data rate associated with the path p. By definition, the total rate r_k of commodities k ($k=\overline{1,M}$) have to satisfy the following equalities

$$r_k=\sum_{p\in P_k} r(p),\quad \forall k=\overline{1,M}. \tag{8}$$

Observe that the total rate of flows on channel $i\in$ OC over link $e\in E^R$, denoted by $x_i(e)$ is given by

$$x_i(e)=\sum_{k=1}^{M}\sum_{p\in P_k:(e,i)\in p} r(p),\quad \forall e\in E^R,\forall i=\overline{1,K}. \tag{9}$$

By substituting (9) into (5), (6) and (7) respectively, we have obtained

$$\sum_{i=1}^{K}\frac{\sum_{k=1}^{M}\sum_{p\in P_k:(e,i)\in p} r(p)}{c_i(e)}\le\zeta(e),\quad \forall e\in E^R, \tag{10}$$

$$\sum_{e\in E(u)}\sum_{i=1}^{K}\frac{\sum_{k=1}^{M}\sum_{p\in P_k:(e,i)\in p} r(p)}{c_i(e)}\le\kappa(u),\quad \forall u\in V^F, \tag{11}$$

$$\sum_{e'\in E(t(e))\cup E(r(e))}\frac{\sum_{k=1}^{M}\sum_{p\in P_k:(e',i)\in p} r(p)}{c_i(e')}\le 1,\quad \forall e\in E^R,\forall i=\overline{1,K}. \tag{12}$$

Now, we consider constrained conditions for the total rate r_k of commodities k ($k=\overline{1,M}$) in mesh client. For any access points $u\in V^A$, the set of u's out-neighbors, $D_u=\{t:(u,t)\in E^H\}$, and the set in-neighbors of u, $J_u=\{t:(t,u)\in E^H\}$. Let $\rho_{t,r}$ be the transmission rate for wireless link $(t,r)\in E^H$ in mesh client, and put $\rho=\left(\rho_{t,r}:(t,r)\in E^H\right)$. According to Wang and Kar [13] the attainable throughput on wireless links $\left(s(k),S^A(k)\right)$ and $\left(D^A(k),d(k)\right)$ are given by

$$c_{s(k),S^A(k)}(\rho)=\frac{\rho_{s(k),S^A(k)}}{1+\sum_{j\in D_{S^A(k)}}\rho_{S^A(k),j}+\sum_{j\in J_{S^A(k)}}\rho_{j,S^A(k)}}, \tag{13}$$

$$c_{D^A(k),d(k)}(\rho)=\frac{\rho_{D^A(k),d(k)}}{1+\sum_{j\in D_{D^A(k)}}\rho_{D^A(k),j}+\sum_{j\in J_{D^A(k)}}\rho_{j,D^A(k)}}. \tag{14}$$

Since the commodity k traveled across both wireless link $\left(s(k),S^A(k)\right)$ and wireless link $\left(D^A(k),d(k)\right)$, it implies that the total rate r_k of the commodity k cannot exceed the capacity of the two wireless links $\left(s(k),S^A(k)\right)$ and $\left(D^A(k),d(k)\right)$. Hence, we have

$$r_k\le c_{s(k),S^A(k)}(\rho),\quad \forall k=\overline{1,M}, \tag{15}$$

$$r_k\le c_{D^A(k),d(k)}(\rho),\quad \forall k=\overline{1,M}. \tag{16}$$

From (8), (10)-(12) and (15)-(16), we have obtained a rate control problem, which provides proportional fairness between end-to-end sessions in the WMN, formulated as follows

$$\begin{aligned}
&\text{maximize}\ \sum_{k=1}^{M}\log(r_k)\\
&\text{subject to}\ r_k=\sum_{p\in P_k} r(p),\quad \forall k=\overline{1,M},\\
&\quad\sum_{i=1}^{K}\frac{\sum_{k=1}^{M}\sum_{p\in P_k:(e,i)\in p} r(p)}{c_i(e)}\le\zeta(e),\ \forall e\in E^R,\\
&\quad\sum_{e\in E(u)}\sum_{i=1}^{K}\frac{\sum_{k=1}^{M}\sum_{p\in P_k:(e,i)\in p} r(p)}{c_i(e)}\le\kappa(u),\forall u\in V^F,\\
&\quad\sum_{e'\in E(t(e))\cup E(r(e))}\frac{\sum_{k=1}^{M}\sum_{p\in P_k:(e',i)\in p} r(p)}{c_i(e')}\le 1,\\
&\qquad\qquad\forall e\in E^R,\ \forall i=\overline{1,K},\\
&\quad r_k\le c_{s(k),S^A(k)}(\rho),\quad \forall k=\overline{1,M},\\
&\quad r_k\le c_{D^A(k),d(k)}(\rho),\quad \forall k=\overline{1,M},\\
&\quad r(p)\ge 0,\forall p\in P_k\ (k=\overline{1,M}),\ \rho_{t,r}\ge 0,\forall(t,r)\in E^H.
\end{aligned} \tag{17}$$

We can eliminate the equality constraints of the optimization problem (17) by substituting these constraints into the objective function and in the fifth and sixth set of constraints of the problem (17). It leads to the equivalent problem as follows.

$$\begin{aligned}
&\text{maximize} \sum_{k=1}^{M} \log\left(\sum_{p\in P_k} r(p)\right) \\
&\text{subject to} \sum_{i=1}^{K} \frac{\sum_{k=1}^{M}\sum_{p\in P_k:(e,i)\in p} r(p)}{c_i(e)} \le \zeta(e),\ \forall e\in E^R, \\
&\sum_{e\in E(u)}\sum_{i=1}^{K} \frac{\sum_{k=1}^{M}\sum_{p\in P_k:(e,i)\in p} r(p)}{c_i(e)} \le \kappa(u), \forall u\in V^F, \\
&\sum_{e'\in E(t(e))\cup E(r(e))} \frac{\sum_{k=1}^{M}\sum_{p\in P_k:(e',i)\in p} r(p)}{c_i(e')} \le 1, \\
&\qquad \forall e\in E^R,\ \forall i=\overline{1,K}, \\
&\sum_{p\in P_k} r(p) \le c_{s(k),S^A(k)}(\rho), \quad \forall k=\overline{1,M}, \\
&\sum_{p\in P_k} r(p) \le c_{D^A(k),d(k)}(\rho), \quad \forall k=\overline{1,M}, \qquad (18) \\
&r(p)\ge 0, \forall p\in P_k\ (k=\overline{1,M}),\ \rho_{t,r}\ge 0, \forall (t,r)\in E^H.
\end{aligned}$$

where $c_{s(k),S^A(k)}(\rho)$ and $c_{D^A(k),d(k)}(\rho)$ are given by formulae (13) and (14).

Observe that (18) is a nonlinear nonconvex optimization problem. The key difference from the rate control problems in wired-cum-wireless network [11,15], wireless multi-hop network [4,14] and wireless mesh network [17] is that we can not convert the problem (18) into a convex optimization problem after the logarithmic transformation. This makes the optimization problem (18) more difficult to solve. In this paper, we have solved the nonlinear nonconvex optimization problem (18) by centralized computation using the primal-dual interior-point (PDIP) method for nonlinear nonconvex programming [5, 6]. In fact, we only find a local optimal solution to problem (18) by using the PDIP algorithm. To the best of our knowledge, there is no algorithm yet, which could solve a global optimal solution of a general nonlinear nonconvex optimization problem. However, we now believe that the problem (18) has a unique local optimal solution, this problem will be shown in our future work that means we obtain the global optimal solution of the problem (18) by using the PDIP method.

It is well known that in the PDIP algorithm we are to solve linear systems to obtain primal-dual search directions. Moreover, under certain assumptions, these linear systems always have a unique solution [5]. It is shown [6] that the matrices of these linear systems become increasingly ill-conditioned in a highly structured way as the iteration converges. Although this ill-conditioning is usually harmless [16], we still obtain warning of ill-conditioning from Matlab when the computations of our simulation results are carried out as given in Section 5. In order to overcome this drawback, we solve iteratively these linear systems using a stabilized conjugate-gradient (SCG) method [7]. The SCG algorithm is an efficient algorithm for ill-conditioned linear system from the PDIP method.

V. Simulation Result

In this section, we illustrate the results of Section 4 through a discussion of an example. Consider a WMN that has 12 routers denoted as $R_1,\ldots,R_{12}$ where routers R_3 and R_9 have gateway functionality which connected to the Internet through wired links, labeled i_1 and i_2, respectively. Moreover, routers R_1, R_6 and R_{12} have gateway/bridge functionality. The network has 3 access points as AP_1, AP_2 and AP_3, and 5 mobile hosts as A, B, C, D and E. The configuration of the WMN is shown in Fig. 2.

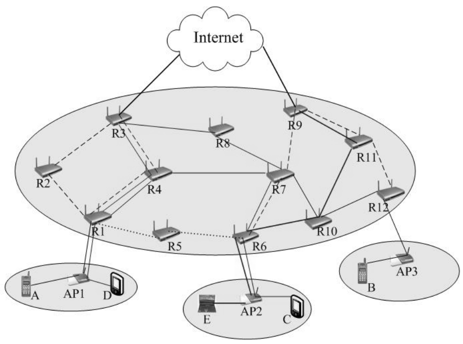

Fig. 2. The configuration of infrastructure/backbone wireless mesh network

The number of radios of the routers R_1, R_2, R_3, R_4, R_5, R_6, R_7, R_8, R_9, R_{10}, R_{11} and R_{12} are 3, 3, 4, 5, 4, 5, 5, 2, 3, 4, 3 and 2 respectively. There are 6 orthogonal channels in mesh router of the network, denoted as 1, 2, 3, 4, 5 and 6. Table 1 shows information about the links in the network. The source node and sink node of links, channels that are active on the links, and the maximum number of channels that are active on the links, i.e., $\zeta(e_i)$ ($i=1,\ldots,19$), are shown. The capacities of the links for each channel are shown in Table 2. There are 3 end-to-end sessions in this network, labeled as 1, 2 and 3, and they are set up as shown in Table 3.

Table 1. The information of links in the network

Link	Source node	Sink node	Channel	$\zeta(e_i)$
e_1	R_1	R_2	1	1
e_2	R_1	R_4	6	3
e_3	R_2	R_3	4	2
e_4	R_4	R_7	2	1
e_5	R_7	R_{10}	5	2
e_6	R_9	R_{11}	1	1
e_7	R_{11}	R_{12}	4	2
e_8	R_{10}	R_{12}	2	2
e_9	R_6	R_7	2, 3	1
e_{10}	R_7	R_8	6	1
e_{11}	R_8	R_3	3	2
e_{12}	R_3	R_4	1, 5	2
e_{13}	R_4	R_1	2, 3	3
e_{14}	R_6	R_5	1	2
e_{15}	R_5	R_1	4	1
e_{16}	R_7	R_9	1	2
e_{17}	R_6	R_{10}	4	1
e_{18}	R_{10}	R_{11}	3	2
e_{19}	R_{11}	R_9	2	1
a_0	A	AP_1	-	-
a_1	AP_1	R_1	-	-
b_0	AP_3	B	-	-
b_1	R_{12}	AP_3	-	-
c_0	C	AP_2	-	-
c_1	AP_2	R_6	-	-
d_0	AP_1	D	-	-
d_1	R_1	AP_1	-	-
e_0	E	AP_2	-	-

In this example, we have denoted $r_{1,1}$ and $r_{1,2}$ as the total rate of the first and second paths of the first session respectively; $r_{2,1}$, $r_{2,2}$ and $r_{2,3}$ the total rate of the first, second and third paths of the second session respectively; and $r_{3,1}$ the total rate of the third session. The computations of the PDIP algorithm were done using Matlab 7.0, on a machine with 3.00Ghz Pentium processor, and 1.00GB of RAM.

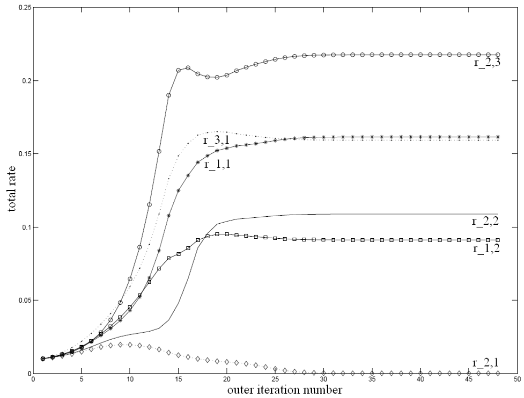

Fig. 3. The total rates for the paths of the end-to-end sessions

Fig. 3 shows how the total rates converge using the PDIP method. After 48 outer iterations and a CPU-time of 1.094 seconds, the PDIP algorithm gives the total rate of paths of the end-to-end sessions as $r_{1,1}$=0.161538, $r_{1,2}$=0.091166, $r_{2,1}$=0.000000, $r_{2,2}$

Table 2. The capacities of the links for each channel in the network

Channel	Link																		
	e_1	e_2	e_3	e_4	e_5	e_6	e_7	e_8	e_9	e_{10}	e_{11}	e_{12}	e_{13}	e_{14}	e_{15}	e_{16}	e_{17}	e_{18}	e_{19}
1	.2	-	-	-	-	.5	-	-	-	-	-	.2	-	.4	-	.5	-	-	-
2	-	-	-	.3	-	-	-	.35	.2	-	-	-	.1	-	-	-	-	-	.4
3	-	-	-	-	-	-	-	-	.3	-	.45	-	.2	-	-	-	-	.3	-
4	-	-	.4	-	-	-	.45	-	-	-	-	-	-	-	.6	-	.25	-	-
5	-	-	-	-	.6	-	-	-	-	-	-	.15	-	-	-	-	-	-	-
6	-	.25	-	-	-	-	-	-	-	.4	-	-	-	-	-	-	-	-	-

Table 3. The paths between source node and sink node of the flows in the network

Session	Source node	Sink node	Link and channel on path
1	A	B	1st path: a_0, a_1, e_2, e_4, e_5, e_8, b_1, b_0 2nd path: a_0, a_1, e_1, e_3, i_1, i_2, e_6, e_7, b_1, b_0
2	C	D	1st path: c_0, c_1, (e_9, 2), e_{10}, e_{11}, (e_{12}, 5), (e_{13}, 2), d_1, d_0 2nd path: c_0, c_1, (e_9, 3), e_{16}, i_2, i_1, (e_{12}, 1), (e_{13}, 3), d_1, d_0 3rd path: c_0, c_1, e_{14}, e_{15}, d_1, d_0
3	E	Internet	e_0, c_1, e_{17}, e_{18}, e_{19}, i_2

=0.108834, $r_{2,3}$=0.217669 and $r_{3,1}$=0.159305 and the objective function is -4.331789. Notice that we do not care about the behavior of the transmission rates at the wireless links of the mesh client. We only present results of the optimal end-to-end session rates.

Ⅵ. Conclusion

We have studied the algorithm for the rate control problem in multi-radio multi-channel WMN. We have considered WMN using only one type of wireless network as a mesh client. We have presented a network utility maximization problem using nonlinear nonconvex programming and proposed a centralized computation to solve this problem by the PDIP algorithm.

For future work, we would like to prove that the rate control problem in WMN has a unique local optimal solution. The rate control problem in WMN can be solved using the PDIP algorithm because the PDIP method only seeks local optimal solution of the optimization problem when the nonlinear problem is not convex. We would like also to propose an efficient distributed algorithm that can solve the rate control problem in WMN. Finally, our approach can be extended for other architectures of WMN utilizing various existing wireless networks such as cellular, wireless sensor, worldwide inter-operability for microwave access (WiMAX) in mesh client or hybrid wireless mesh networks.

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