Distributed Rate and Congestion Control for Wireless Mesh Networks

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ABSTRACT

Wireless networks (WNs) are developed and applied widely in a lot of areas. Now, a new generation of wireless networks is coming, and that is Wireless Mesh Network (WMN). At present, there are not so many researches which deal on this area. Most researches are derived from Mobile Ad hoc Networks (MANET) and WNs. In WMNs, there are some applications that require real-time delivery. To guarantee this, rate control and congestion control are needed. This problem leads to optimization issue in transport layer. In this paper, we propose a mathematical model which is applied in rate and congestion control in WNMs. From this model, we optimize rate and congestion control in WMNs by maximizing network utility. The proposed algorithm is implemented in distributed way both in links and sources.

Key Words : Wireless Mesh Networks, Transport Protocol, Rate Control, Congestion Control, Network optimization.

Ⅰ. Introduction

Recently, wireless networks develop very fast. Many devices and applications are widely applied in every area of our life. Some devices, e.g., cell phones, Personal Digital Assistants (PDAs), and sensors, become indispensable utilities which improve one's life standard. Currently, wireless devices and applications are diversified and they can be classified in some groups. Each group forms a type of wireless networks. Some types are Wi-Fi, WiMax networks which are composed by laptops and PDAs, cell networks, sensor networks, and etc. The diversity of wireless networks is good because each wireless network is suitable for some requirements. But this problem leads to a difficulty. For example, people want to use their PDAs or cell phones to control some devices at home. To deal this problem, cell networks and wireless sensor networks should be connected. Unfortunately, cell networks and wireless sensor networks operate in different ways; cell networks use CDMA or GSM technology while sensor networks use Bluetooth or ZigBee technology. Furthermore, it is also difficult to connect two certain networks which are even of the same type. For example, in some countries, there exists CDMA and GSM for mobile network at the same time, some applications are not absolutely connected, e.g, short message service supports 160 characters in GSM but it supports only 80 characters in CDMA. To overcome the above problem, researchers are thinking about solutions which can unify existing and future wireless networks. And Wireless Mesh Network is currently a hot topic which addresses the above problem.

Since WMNs share common features with Ad hoc Network, the transport protocols developed for ad hoc network can be applied to WMNs. But existing protocols have some limitation when applying in WMNs, which include:

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- Some TCP variants do not distinguish losses by congestion and losses by channel. So a sender maybe decrease its data rate in case of losses by channel.
- WMNs are integrated by other networks. No existing protocol is adaptive in all networks.
- Few protocols focus on rate and congestion controls.

In WMNs, there are many applications which require delivery of real-time traffic. To support this kind of traffic, congestion control is needed. So, this paper focuses on rate and congestion control which is an important function of transport layer in WMNs. A mathematical model is proposed for the problem. We use Gradient Projection Method to solve the problem to obtain the optimal data rates which maximize aggregate network utility and do not lead to congestion problem.

The paper is structured as follows. Section 2 presents some relate works about network utility maximization (NUM). We inherit these ideas to modelize our rate and congestion control as NUM issue. Our mathematical model is presented in section 3. Basing on the result from mathematical model, we propose a distributed algorithm to obtain optimal data rate in section 4. Section 5 presents numerical analysis. The results show that our algorithm converges to the optimal solution. Section 6 draws our conclusion and future works

Ⅱ. Related works

In network, rate and congestion control is often modeled as a network utility maximization issue. The basic NUM problem is the following formulation [3], studied since 1960s. TCP variants have recently been reverse-engineered to show that they are implicitly solving this problem, where source rate vector x is the only optimization variables, and routing matrix R and link capacity vector c are both constants:

$$\begin{aligned} & maximize \ \sum_s U_s(x_s) \\ & subject\ to \ \ Rx \leq c \end{aligned} \tag{1}$$

Utility functions U_s are often assumed to be smooth, increasing, concave, and depends on local rate only, although recent investigations have removed some of these assumptions for applications that they are invalid. Utility functions can be picked based on any of the following five grounds: reverse-engineering (a given protocol description implicitly dictates the underlying utility function), user perception behavior models, application traffic elasticity, efficiency of resource allocation, and fairness among competing users.

The result of Kelly[3] has widely accepted and used in wired network. But the assumption that link capacity vector is constant is not true in wireless network. Different from wired networks, there are interferences between links in wireless networks. Therefore, when a link is used to transfer data, some others, which are in its reference region, should not be used. Furthermore, link capacity depends on many factors like coding/decoding technical, scheduling, and power. Therefore, the original model is extended by many researchers to adapt in wireless networks. The hottest trend to solve this problem is to cooperate between layers in networks to achieve global optimal network utility. Network protocols may instead be holistically analyzed and systematically designed as distributed solutions to some global optimization problems in the form of generalized Network Utility Maximization (NUM) [4-9]. Some co-operation schemes are presented, e.g., physical layer and MAC layer[5,8], MAC layer and transport layer[5,9], physical layer and transport layer[6], network layer and transport layer[7].

In most cases, authors use iterative methods to solve optimization problems[4-13]. To use these methods, the problem should be convex. Unfortunately, this assumption is not always true. Some authors are thinking solutions for non-convex problem[8, 10, 11, 12].

By inheriting the mathematic model and optimization method in those related works, we propose a new mathematical model which solves rate and congestion control problem in WMNs.

Ⅲ. Mathematical Model

Consider a wireless mesh network which is composed of link set *L*. Each link $l \in L$ has capacity of c_l. Denote *S* source set. Each source $s \in S$ is characterized by a utility function $U_s(x_s)$ which is strictly concave, increasing, differentiable in its transmission rate x_s. Denote $L(s) \subset L$ set of links which are used by source *s* to send data. Data from source *s* is encoded into packets where we need to add more control information. Assume that the ratio of useful information size before encoder and packet size after encoder is t_s. In WMNs, there are many kind of sources, therefore, this ratio are much different. Denote r_s data rate after encoder, we have:

$$t_s = \frac{x_s}{r_s} \tag{2}$$

From (2), if we want to send useful information with data rate x_s, we need to transfer data over links with data rate:

$$r_s = \frac{x_s}{t_s} \tag{3}$$

Real-time applications require that data rate is greater or equal to a threshold:

$$x_s \geq x_{s\min} \tag{4}$$

The threshold depends on the particular application.

Assume that $l \in L$ is an arbitrary link. Denote $S(l) \subset S$ set of sources which send data through the link *l*. The aggregate data which passes link *l* is $\sum_{S(l)} \frac{x_s}{t_s}$. This aggregate data cannot exceed link capacity, therefore, we obtain:

Fig. 1. Encode and decode

$$\sum_{S(l)} \frac{x_s}{t_s} \leq c_l \tag{5}$$

Our objective is to choose data rate x_s that maximizes aggregate network utility function. Hence, the rate and congestion control becomes the following problem:

$$\begin{aligned} &maximize && \sum_s U_s(x_s) && \\ &subject\ to && x_s \geq x_{s\min} && \forall s \in S \\ & && \sum_{s \in S(l)} \frac{x_s}{t_s} \leq c_l && \forall l \in L \end{aligned} \tag{A}$$

We can see that the constraint of the problem is linear; therefore, feasible solution region is convex. Furthermore, the objective function $\sum_s U_s(x_s)$ is strictly concave. Hence, the problem (A) is convex problem and there exists unique vector x^* that solves the problem. Our objective is to find a distributed algorithm to obtain x^*.

We can see that the source rates *x* are coupled in the constraint while they are separable in the objective function. Therefore, we use Lagrangian relaxation to separate data rates and obtain x^* in a distributed way.

The Lagrangian is

$$\begin{aligned} L(x,p) &= \sum_s U_s(x_s) - \sum_l p_l \left(\sum_{s \in S(l)} \frac{x_s}{t_s} - c_l \right) \\ &= \sum_s \left(U_s(x_s) - \left(\sum_{l \in S(l)} p_l \right) \frac{x_s}{t_s} \right) + \sum_l p_l c_l \end{aligned} \tag{6}$$

Where vector *p* is Lagrangian multiplier and plays link price role.

In (6), the data rates *x* are separate. The objective function of the dual problem thus

$$\begin{aligned} D(p) &= \sup_{x \geq x_{\min}} L(x,p) \\ &= \sum_s \sup_{x_s \geq x_{s\min}} \left(U_s(x_s) - \left(\sum_{l \in L(s)} p_l \right) \frac{x_s}{t_s} \right) + \sum_l p_l c_l \end{aligned} \tag{7}$$

The expression $U_s(x_s)-\left(\sum_{l\in L(s)} p_l\right)\frac{x_s}{t_s}$ is maximized at x^*. Using Karush-Kuhn-Tucker condition, x^* is expressed as:

$$x_s^* = max\left\{x_{s\min}, U_s'^{-1}\left(\frac{\sum_{l\in S(l)} p_l}{t_s}\right)\right\} \quad (8)$$

The dual problem is:

$$\min_{p\ \geq\ 0} D(p) \quad (9)$$

The primal objective function is strictly concave, therefore, by Lagrangian theorem; the dual objective function is strictly convex. Hence, we can use gradient projection method where the link price is updated as following iterative:

$$p_l(t+1) = max\left\{0, p_l(t) - \gamma\frac{\partial D}{\partial p_l}(p(t))\right\}. \quad (10)$$

γ is a stepsize.

Since $U_s(x_s)$ is strictly concave, therefore, $D(p)$ is continuously differentiable and its derivative is given by

$$\frac{\partial D}{\partial p_l} = c_l - \sum_{s\in S(l)}\frac{x_s}{t_s} \quad (11)$$

Substituting (11) into (10), we obtain:

$$p_l(t+1) = max\left\{0, p_l(t) - \gamma\left(c_l - \sum_{s\in S(l)}\frac{x_s}{t_s}\right)\right\} \quad (12)$$

When $U_s(x_s)$ is strictly concave and the stepsize γ is small enough, the iterative generated by (8) and (12) converges to the optimal solution.

Basing on the above iterative, we propose a distributed algorithm in the next section.

Ⅳ.Distributed Rate and Congestion Control Algorithm

In the previous section, we present the mathematical basis to solve the NUM problem. To apply in network engineering, the algorithm should be implemented in a distributed way. This section describes the implementation of above solution. The algorithm is implemented in two parts, one is in links and the other is in sources.

4.1 Link *l*'s algorithm

At times *t*=1, 2,..., link *l*:

- Receives rates $x_s(t)$ from all sources $s \in S(l)$ that use link *l* to send data.
- Updates its new price using (12).
- Communicates its new price to all sources $s \in S(l)$ that use link *l*.

4.2 Source *s*'s algorithm

At times *t*=1, 2,..., source *s*:

- Receives prices $p_l(t)$ from all links $l \in L(s)$ that are used by source *s* to send data.
- Updates its new price using (8).
- Communicates its new rate to all links $l \in L(s)$ that are used by source *s* to send data.

The key idea of the algorithm is that each source and link collect network condition and adapt its operation to new condition. For example, if there exists congestion in a link *l*, this link will notify to all sources $s \in S(l)$ with very expensive price $p_l(t)$. Therefore, all sources $s \in S(l)$ should decrease its data rate. Similarly, if link *l* do not use its full capacity, it will decrease its price, and all sources $s \in S(l)$ can increase their data rate.

Ⅴ. Numerical Analysis

Let's consider rate and congestion problem in the following scenario (Fig 2).

In this scenario, assume that two flows x_1 and

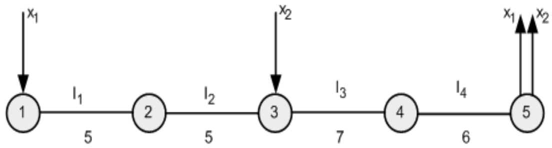

Fig. 2. Network topology

x_2 share network links. This maybe leads to congestion problem in links, especially in links l_3 and l_4. Our objective is to control flow rates x_1 and x_2 so that the aggregate network utility is maximized and at the same time congestions in links are avoided.

Ratios of useful information size before encoder and packet size after encoder at flows 1 and 2 are 0.9 and 0.95 respect. Link capacities are 5Mbps, 5Mbps, 7Mbps, and 6Mbps as shown in Fig. 2. Assume that application requires that data rate should be greater or equal to 1Mbps. Furthermore, network utility function is a logarithm function of data rate. Clearly, logarithm function is differentiable, strictly concave, and increasing, that means it satisfies all requirement of network utility function.

Basing above assumption, we can obtain rate and congestion control as following problem:

$$\begin{aligned} &maximize && (\log x_1 + log x_2) \\ &subject\ to && x_1 \geq 1 \\ &&& x_2 \geq 1 \\ &&& \frac{x_1}{0.9} \leq 5 \\ &&& \frac{x_1}{0.9} + \frac{x_2}{0.95} \leq 6 \end{aligned} \tag{B}$$

Because $U_1(x_1) = log x_1$, therefore, $U_1'(x_1) = \frac{1}{x_1}$. Thus, the invert function of $U_1'(x_1)$ is $U_1'^{-1}(p) = \frac{1}{p}$. Substituting this expression into (8), we have $x_1^* = max\left\{1, \frac{t_1}{p_1+p_2+p_3+p_4}\right\}$. Similarly, we obtain the optimal rate for flow 2 by the following equation $x_2^* = max\left\{1, \frac{t_2}{p_3+p_4}\right\}$

And each link updates its price by (12).

We implement the distributed rate and congestion control algorithm in MatLab. In this program, we evaluate the convergence of algorithm to optimal solution. Table 1 shows initial price, data rate, and γ.

Fig. 3 shows the convergence of data rates to the optimal solution while Fig. 4 shows the one of prices. The horizontal axis shows iteration which represents cycle. The vertical axis shows flow rates in Fig. 3 and link prices in Fig. 4. According to these figures, with an arbitrary

Table. 1. Initial parameters

Parameters	Initial values
x_1	1
x_2	1
p_1	0
p_2	0
p_3	0
p_4	0
γ	0.05

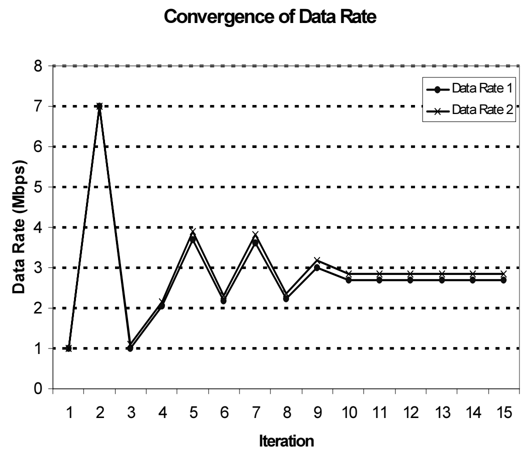

Fig. 3. Convergence of Data Rate

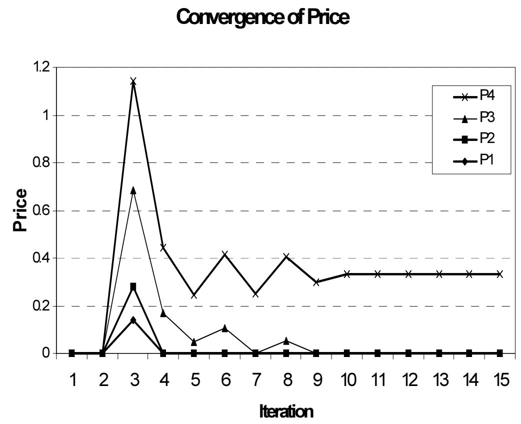

Fig. 4. Convergence of Price

initial condition, within 10 steps, flow rates and link prices converges to the stable state which maximizes the aggregate network utility and prevents links from congestion.

These above results prove that our algorithm converges fast to optimal solution. And this algorithm can be implemented in distributed way.

Ⅵ. Conclusion and Future Works

Rate and congestion control is a very important mechanism in WMNs, especially in real-time service and applications. It guarantees reliability, congestion control, and real-time delivery. Currently, few studies focus on this area. We propose an optimization model for rate and congestion control in WMNs. An algorithm to get optimal solution is proposed. In the future, the result should be extended as follows:

- Add more constraints for WMNs (interference, considering multi-channel, multi-hop,...).
- Convergence condition, convergence speed.

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