Localized Cross-Layer Algorithm to Minimize Transmission Delay in Wireless Ad-hoc Networks

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Abstract: Ad-hoc wireless networks are networks formed by a collection of nodes through radio. In wireless networking environment, formidable challenges are presented such as transmission delay. In this paper, an optimal algorithm is presented which addresses the transmission delay in ad-hoc networks. We formulate the rate constraints, scheduling constraints and resource allocation. Since the transmission delay is considered, the resource allocation includes the utility and cost function, together in a maximization problem. The resource allocation is solved using dual decomposition method. This paper presents a detailed description of our approach that shows end to end delay in packet transmission is minimized considerably compared to other routing protocols in ad-hoc networks. Simulation results are included to verify the effectiveness of the proposed approach.

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1. Introduction

Network has a layered structure, thus most network protocols consider this structure and solve the network problems separately and independently at different layers. However, wireless spectrum is rare, interference-limited and limited and it should be to used more efficiently.

The effect of transmission delay in most new algorithms in ad-hoc networks is not considered. The delay time that each node sees to send a packet to other node is related to the length of the link between them and therefore the link cost can express according to the transmission delay and vice versa. The transmission delay in one link impacts on the end-to-end delay over the network.

When there is delay in the network, packet scheduleding will be in trouble. The Delay can also cause or intensify the congestion in the network. Our purpose in this paper is just the time delay associated with the length of link. In fact, the other types of delay, including queuing and buffering delay, are not studied in this paper.

Most routing protocols in ad-hoc networks select the shortest path with minimum number of hop and don’t care about interference, contention and capacity of links. therefore the congestion is occurred at some regions while other regions are not utilized optimally. Therefore, congestion control, routing and scheduling should be jointly designed.

There are many algorithms for congestion control on the basis of utility-based optimization (Kelly et al., 1998), (Low et al., 2003), (Chiang et al., 2005), (Xue et al., 2003), and (Chen et al., 2005). None of these works have considered the transmission delay. However There are some works to handle the queuing delay effect (Nikhil et al., 2003), (Neely et al., 2005), (Xia et al., 2006) and (Shila et al., 2012). Duality theory leads to a vertical decomposition into separate designs of different layers that interact through congestion price. Recent works along this line of “layering as optimization decomposition” includes (Chiang, 2006), (Xiao, 2004), (Chiang et al., 2005), (Chen et al., 2005), (Lee, 2004), (Lin, 2006) In (Chen et al., 2006), a cross-layer joint design for congestion control, routing and scheduling is presented.

In above cross-layer designs, the transmission delay effect has not been considered. The work in (Xia et al., 2006) is based on fuzzy logic to handle the capacity, throughput and delay as a cross-layer scheme. But the authors consider the queuing delay. We present a method to solve this problem by defining a new link cost variable. Indeed we have extended the work in (Shafieirad et al., 2013) to the case that the effect of transmission delay can be considered in congestion control and routing.

In this paper we add the effect of transmission delay on congestion control in ad-hoc networks via a cross-layer design. In this way we extend the work in (Shafieirad et al., 2013) and (Shafieirad, 2007) to handle the transmission delay problem and study its effect simultaneously, in congestion control, routing and scheduling.

We use the distributed method that we presented it in (Shafieirad et al., 2013) where the link cost role added to the basic utility maximization problem. Now, we model the link cost according to the time delay and by this extension, we are able to import the effect of delay in congestion control and solve the maximization problem.

The paper is organized as follows. Section 2 presents the modeling and formulization needed by the proposed algorithm that is presented in section 3. We model the contention between wireless links as a contention flow graph. We use multi-commodity flow variables (Chen, 2006) and (Shafieirad et al., 2013) to formulate rate constraint at the network layer and formulate resource allocation as a maximization problem with those constraints. Also by introducing a new multi-commodity variable for link cost, we consider both utility and delay cost in optimization problem. In section 3, based on modeling described in section 2, we apply duality theory to decompose the system problem vertically into two sub-problem. These two sub-problems interact through congestion prices and delay costs. Based on this decomposition, according to the procedure in (Shafieirad et al., 2013) we obtain a localized algorithm for joint congestion control, transmission delay minimization, routing and scheduling. Some numerical examples to support the efficiency of the proposed algorithm are presented in section 4. Finally, we draw some conclusions.

2. Model Description

In this section, at first we present a model for network and then a model for cost associated with transmission delay. Finally, we formulate the optimization problem.

Consider an ad hoc wireless network with a set N of nodes and a set L of links. The network is directed and symmetric, i.e., link $(j,i) \in L$ if and only if $(i,j) \in L$. Also the nodes are not mobile. Each link $l \in L$ has a fixed capacity c_l, i.e., we assume that the wireless channel is fixed.

2.1. Transmission Delay Model

In order to illustrate the benefits of considering transmission delay effect, an example is shown in Figure 1. Node A is source and node B is destination. It is obvious that if the transmission delay is controllable, it may be more efficient to transmit packets from A to B using shortest route ADB, because the routes ACB, AECB and AEDB are longer than route ADB.

the link cost as delay cost:

$$cost(n_i,n_j) = \alpha d^{\beta}(n_i,n_j) \qquad (1)$$

where n_i and n_j are the nodes i, j , d is the length of link between i, j , and α is the weight coefficient and β is a real parameter for modeling polynomial delay

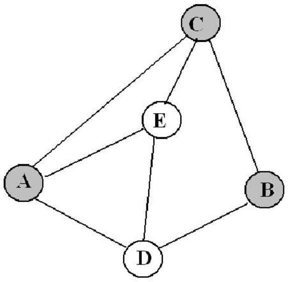

Figure 1. A network with 5 nodes
(According to our explanations we can define).

It should be noted that if we consider only the transmission delay, it may occurs congestion in node D, for example. Therefore in our new algorithm we have considered the price of congestion and delay, simultaneously. Indeed, after executing our new algorithm, it may that the route AEDB be the best route in some episode of transmission scenario.

2.2. Flow Rate Constraints

In this paper, like the work in (Shafieirad et al., 2013) we consider the primary interference model and use conflict graph (Jain et al., 2003) and (Hajek, 1988) that shows the contention relations among the links. In the conflict graph, each vertex represents a link, and an edge between two vertices denotes the contention between the two corresponding links that cannot transmit at the same time. Figure 2 shows an example of a wireless ad-hoc network and its conflict graph with primary interference model.

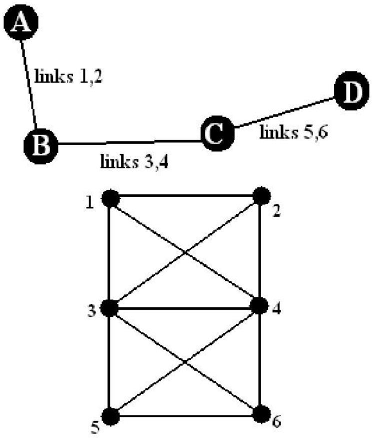

Figure 2. An ad hoc wireless network with 4 nodes and 3 bidirectional links and its conflict graph

The independent set e is a set that all links in it can transmit simultaneously. For instance, in Figure 2, {1, 6}, {1,5}, {2,5} … are some independent sets. We introduce the rate vector r^e, where the l th entry is:

$$r_l^e := \begin{cases} c_l & if\ \ l \in e \\ 0 & otherwise \end{cases} \qquad (2)$$

The feasible rate region Π at the link layer as a convex hull of these rate vectors is as following:

$$\Pi := \{r : r = \sum_e a_e r^e, a_e \geq 0, \sum_e a_e = 1\} \qquad (3)$$

Thus, for a link flow vector such z, the schedulability constraint says that $z \in \Pi$.

Denote the set of destination nodes of network layer flows by D.

Let $f_{i,j}^k \geq 0$ denote the amount of capacity of link (i,j) allocated to the flow to destination k. Then $f_{i,j} = \sum_{k \in D} f_{i,j}^k$ is the aggregate capacity on link (i,j). From the schedulability constraint, $f =: \{f_{i,j}\}$ should satisfy the condition:

$$y \in \Pi \qquad (4)$$

Let $\mathrm{x}_\mathrm{i}^\mathrm{k} \geq 0$ denote the flow generated at node i to destination k. Then the aggregate capacity for its incoming flows and generated flow to the destination k should not exceed the sum of the capacities for its outgoing flows to k:

$$x_i^k \leq \sum_{j:(i,j) \in I} f_{i,j}^k - \sum_{j:(i,j) \in I} f_{j,i}^k \qquad (5)$$

where $i \in N, k \in D, i \neq k$.

Equation (5) is the rate constraint for resource allocation.

2.3. Problem Formulation

We denote a link by node pair $(\mathrm{i},\mathrm{j}) \in \mathrm{N} \times \mathrm{N}$, a source node by s and a destination node by k. Assume each source s achieves to utility $\mathrm{U_s}(\mathrm{x_s})$ when it can transmit with rate $\mathrm{x_s}$ packets per second.

We introduced multi-commodity cost variables in (Shafieirad et al., 2013), which correspond to the link cost and now we use it to describe the effect of transmission delay. Also the multi-commodity flow variable $\mathrm{f}_{\mathrm{i,j}}^\mathrm{k}$ is used to describe the capacity allocated to the flow towards destination k.

For cost function, we introduce the multi-commodity link cost variable for each link. According to the transmission delay in subsection 2.1 we model the delay cost with link cost. For each link we set a cost. This cost is a function of link length. For example, if the length of a link decreases, consequently its cost decreases. Thus, we use $\lambda_{\mathrm{i,j}}^\mathrm{k}$ for link cost. It is means that the link (i,j) to transmit data $\mathrm{f}_{\mathrm{i,j}}^\mathrm{k}$ to destination k, incurs the cost $\lambda_{\mathrm{i,j}}^\mathrm{k}$. A good description for $\lambda_{\mathrm{i,j}}^\mathrm{k}$ according to (1) is:

$$\lambda_{i,j}^k = cost(n_i, n_j) = \alpha d^\beta(n_i, n_j) \qquad (6)$$

Each node via GPS can be aware of its distances with other nodes. Also a more convenient way to find the distance between nodes can be through the radio via radio sensors.

The resource allocation is formulated as a utility minus cost maximization problem with rate constraints. Our goal is to find source rates x_s and allocated capacities $f_{i,j}^k$ so as to solve the following optimization problem:

$$max_{X_s \geq 0, f_{i,j}^k \geq 0}\left(\sum_s U_s(x_s) - \sum_{(i,j),k} \lambda_{i,j}^k f_{i,j}^k\right) \qquad (7)$$

$$x_i^k \leq \sum_{j:(i,j) \in L} f_{i,j}^k - \sum_{j:(i,j) \in L} f_{j,i}^k \qquad (8)$$

$$f \in \Pi \qquad (9)$$

where $i \in N, k \in D, i \neq k$, and $x_i^k = 0$ if $[i,k] \notin S \times D$.

3. Localized Cross-Layer Algorithm

Solving the system problem (7-9) directly requires coordination among all sources and links, thus is impractical in real network. However, localized algorithms can be derived by formulating and solving Lagrange dual problem of (7). In this section, we solve the dual problem and interpret the resulting algorithm as a localized algorithm.

Similar to the work (Shafieirad et al., 2013), the Lagrangian problem with respect to rate constraints is as following:

$$L(p,x,f) = \sum_s U_s(x_s) - \sum_{(i,j),k} \lambda_{i,j}^k f_{i,j}^k - \sum_{i \neq k} p_i^k \left(x_i^k - \sum_{j:(i,j) \in L} f_{i,j}^k - \sum_{j:(i,j) \in L} f_{j,i}^k\right) \qquad (10)$$

The dual problem to the problem (7-9) is:

$$min_{p \geq 0} D(p) \qquad (11)$$

with partial dual function:

$$D(p) = max(L(p,x,f)) \quad and \quad f \in \Pi \qquad (12)$$

where we relax the constraint (8) by using Lagrange multiplier p_i^k for node i and destination k. The maximization problem in (12) can be decomposed into the following two sub problems:

$$D_1(p) = max_{x_s \geq 0} \sum_s U_s(x_s) - \sum_s x_s p_s \qquad (13)$$

$$D_2(p) = \underset{f_{i,j}^k \geq 0}{max} \sum_{i \in N, k \in D, i \neq k} p_i^k \left(\sum_{j:(i,j) \in L} f_{i,j}^k - \sum_{j:(i,j) \in L} f_{j,i}^k\right) - \sum_{(i,j),k} \lambda_{i,j}^k f_{i,j}^k \qquad (14)$$

If we interpret p_i^k as the congestion price, the first sub problem is congestion control (Low & Lapsley, 1999) and (Low, 2003), and the second one is the joint routing and scheduling since to solve it we need to determine the amount of capacity $f_{i,j}^k$ that link (i,j) is allocated to transmit the data flow towards destination k. Thus, by dual decomposition, the flow optimization problem decomposes into separate "local" optimization problems of transport, network and link layers, respectively, and they interact through congestion prices.

If we suppose that $\mathrm{U_s}(.)$ is continuously differentiable, increasing and strictly concave. The congestion control problem (13) yields to:

$$x_s(p) = U_s^{'-1}(p_s) \qquad (15)$$

It means that the source node adjusts its rate according to the congestion price of itself. In contrast to traditional TCP congestion control where the source adjusts its rate according to the aggregate price along its path, in our algorithm the congestion price is generated locally at the source node. Because of this we have named our new algorithm as *localized* algorithm.

In (Shafieirad et al., 2013), we presented a localized algorithm for congestion control and routing with consideration the mobility effect of nodes. Now we propose a localized algorithm similar to the algorithm presented in (Shafieirad et al., 2013) for minimiztion the transmission delay.

We emphasize that in this paper, we present model the delay as cost function and other computations and sub-algorithms such scheduling and convergence analysis are similar to the work (Shafieirad et al., 2013). We will not mention the details and readers are reffred to (Shafieirad et al., 2013).

4. Numerical Examples

In this section, some numerical examples are provided to show the performance of the proposed localized algorithm. Consider the network in Figure 3.

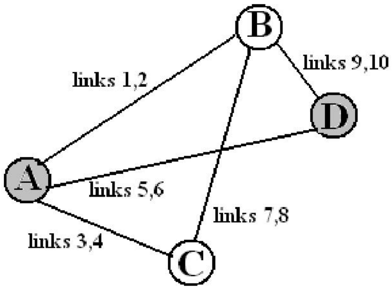

Figure 3. An ad-hoc wireless network with 4 nodes and 5 bidirectional links

We assume that node A is the source and node D is destination. the utility of node A is $U_A(x_A) = log x_A$. All links in network have 2 unit of capacity. Also the length of links AB, AC, AD, DB and CB are 4, 3, 5, 2 and 4, respectively.

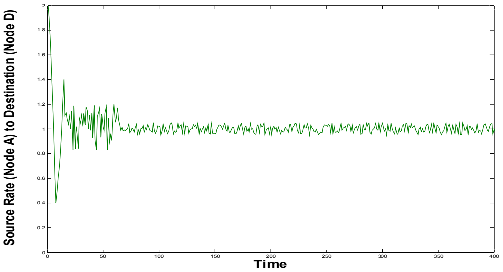

Figure 4. Source rate for node A
(There is not delay)

We first simulate the localized cross-layer algorithm without any cost, i.e. $\lambda_{ij}^k = 0$. In fact we have supposed that there is no transmission delay in network. Figure 4 shows the source rate for node A. We see that after 50 miliseconds, it converge to an average value about 1.

Now if we suppose that there is transmission delay and apply the localized algorithm without consideration delay, certanily the average source rate would be much lower than 1. Also the ocsilation about average is more than last case. See figure 5.

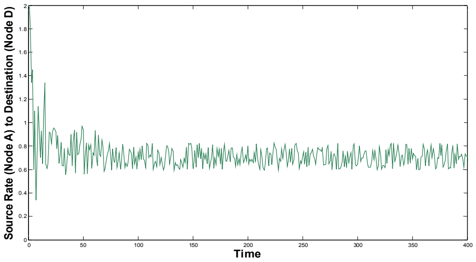

Figure 5. Source rate for node A
(There's delay but its effect isn't considered)

Table 1 shows the average link rate allocated to flow $A \rightarrow D$ when there is delay but we have not conidered it in our algorithm. In this table, the first column is the sending nodes and the first row is the receiving nodes of each directed link. Its obvious that the total rate of source A is about 0.733.

Table 1. Average rates of different links
(Localized Algorithm without delay effect)

Rates	A	B	C	D
A	-	0.215	0.189	0.329
B	0	-	0	0.404
C	0	0.189	-	-
D	0	0	-	-

Now, based on presented model in subsection 2.1 for transmission delay, we simulate the localized cross-layer algorithm.

Figure 6 shows the source rate of node A when we apply the localized algorithm with consideration the effect of transmission delay.

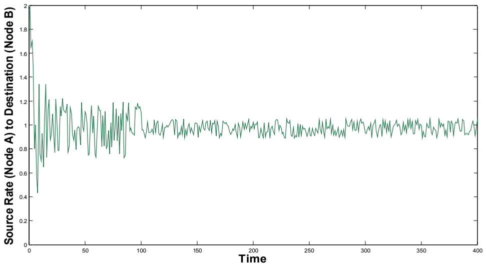

Figure 6. Source rate node A
(Delay effect is considered)

It is obvious that the source rate is convereged to an average value about 1, after 90 miliseconds. It should be noted however the convergence time is a little more than the convergence time in figure 4, but it does not mean that the localized algorithm act ineffectively, in the presence of delay. Actually, our algorithm have the ability of handling the transmission delay and the result must be compared with figure 5.

In table 2 we have summarized the average link rate when we have considered the effect of delay. If we compare table 2 with table 1, we conclude that the link rates have changed. From this table, we can tell which paths the flow has used. We see that the average flow of longest route, i.e. ACBD is about 0.012, i.e. the links in this route is not used as link AD which its average flow is 0.694. the highest average flow is for link AD because its the shortest path from source to destination. From table 1 we see that the total average flow of source A is 0.954 which in figure 4 its obvious that the average cnverged rate of A is about this value. Note that any flow is transmitted from D to other nodes because it is the destination.

Table 2. Average rates of different links (Localized Algorithm with delay effect)

Rates	A	B	C	D
A	-	0.248	0.012	0.694
B	0	-	0	0.260
C	0	0.012	-	-
D	0	0	-	-

5. Discussions

We have presented a model for transmission delay minimization in ad-hoc wireless networks by extending the utility-cost maximization problem and distributed algorithm presented in paper (Shafieirad et al., 2013). We added the effect of transmission delay to utility problem by introducing link cost as a multi-commodity variable. By dual decomposition, we derive a sub gradient algorithm that is not only distributed spatially, but more interestingly, decomposes the system problem vertically into three protocol layers where delay minimization, congestion control, routing and scheduling jointly solve the network utility maximization problem. The effectiveness of the proposed algorithm was demonstrated by some numerical examples.

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