Available Bandwidth in Multirate and Multihop Wireless Sensor Networks

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Abstract

In this paper, we derive a theoretical model to calculate the available bandwidth of a path and study its upper and lower bounds with background traffic. We show that the clique constraint widely used to construct upper bounds does not hold any more when links are allowed to use different rates at different time. In our proposed model, traditional clique is coupled with rate vector to more properly characterize the conflicting relationships among links in wireless sensor networks where time-varying link adaption is used. Based on the model, we also investigate the problem of joint optimization of QoS routing and propose several routing metrics. The newly proposed conservative clique constraint performs the best among the studied metrics in estimating available bandwidth of flows with background traffic.

1. Introduction

In recent years, supporting multimedia traffic in wireless sensor networks attracts lots of attention. This is mainly because it could enable many applications, such as wireless streaming at homes, in buildings and on campus via wireless mesh networks, and on-demand video monitoring of wildlife and battlefields via wireless sensor networks. How to fully utilize the multirate capability to support more traffic is an interesting research topic of great importance.

In this paper, we focus on one major QoS metric, i.e., available bandwidth. Before admitting a multimedia flow, it is paramount to know whether a path can provide enough bandwidth for the flow. In the previous work [1], we have developed a theoretical model to calculate path capacity without considering background traffic. However, this problem becomes more difficult when there are some background traffic because the interference between a new flow and existing traffic is hard to estimate and control.

This work was partially supported by the U.S. National Science Foundation under grants CNS-0721744 and CNS-0626881. The work of Fang was also partially supported by the 111 project under grant B08038 with Xidian University, Xi'an, China.

Previous works have focused on estimating nodes' available bandwidth and applying the result to estimating links' and paths' available bandwidth in QoS routing, admission control and flow control ([2]–[8]). A widely used approach is to measure the channel idle time and accordingly calculate a node's available bandwidth. To obtain a path's available bandwidth, interference has to be taken into consideration. Nodes in the same neighborhood or in each other's interference range share the same wireless channel. Total throughput of links interfering with each other along a path cannot exceed the channel bandwidth or the local available bandwidth.

There are also many works using flow contention graph and clique constraints to construct necessary and sufficient conditions or derive lower and upper bounds of paths' throughput to benefit resource allocation, QoS routing, and flow control ([9]–[11]). In these works, a clique is often referred to as a set of links satisfying that every two of them interfere with each other. The clique constraint is simply that the total frequency of links in a clique is not larger than one, where a frequency of a link is defined as the link's throughput divided by the channel bandwidth.

In this paper, we study the path available bandwidth problem with background traffic in multirate and multihop wireless sensor networks ([12]) in a systematic way. We assume that there exists a global optimal link scheduling and calculate the maximum available bandwidth of paths for any given background traffic. For example, a three link topology is shown in the Scenario I of Fig. 1. The problem here is to find the maximum available path bandwidth along a one-hop path over link L_3. Suppose link L_1 and L_2 do not interfere with or hear transmission from each other, but link L_3 interferes with and hear both the transmissions over L_1 and L_2. The background traffic over L_1 and L_2 occupy the same time share λ but their time shares do not overlap with each other. If the contention based IEEE 802.11 MAC protocol ([13]) is used and L_3's demand requires a time share of $1-\lambda$, L_3 can successfully occupy a time share of $1-\lambda$ after some time, and the time shares of L_1 and L_2 will completely overlap with each other. However, using the mechanism of channel idle time to estimate available

1063-6927/09 $25.00 © 2009 IEEE
DOI 10.1109/ICDCS.2009.66

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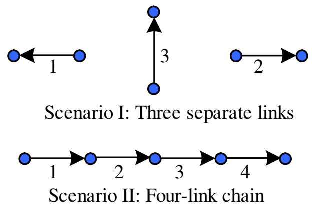

Figure 1. Two simple topologies

bandwidth, the flow over L_3 is only admitted if it occupies a time share not larger than $1-2\lambda$. In this paper, by assuming that a global optimal link scheduling exists, we will correctly calculate the maximum available bandwidth over link L_3.

We formulate the path available bandwidth problem using linear programming and propose the concepts of independent sets and cliques to take into consideration of the advantages of link adaptation. An independent set and a clique are not only specified by a set of links but also specified by the link rates. By allowing links to use different rates at different time, the network can obtains higher path available bandwidth compared to cases with any fixed rate assignments. We analyze the upper bounds derived from cliques, which shows that the clique constraint becomes invalid for the feasible link throughput vector, and we accordingly construct a new upper bound.

We also extend the path available bandwidth problem into a joint design of QoS routing and link scheduling to find paths with high available bandwidth.

The rest of this paper is organized as follows. In Section 2, we develop a theoretical model to calculate available path bandwidth. We then study upper bounds and lower bounds derived from cliques and independent sets in Section 3. In Section 4, several routing metrics are proposed. We evaluate the performance of different QoS routing metrics and available bandwidth estimation metrics using the proposed models in Section 5. Finally, Section 6 concludes this paper.

2. Available Bandwidth in Multirate and Multihop Wireless Sensor Networks

2.1. Available Bandwidth Problem

In this section, we assume that traffic load/demand and paths of background traffic are known. Let K denote the number of existing paths, $x_i(1 \leq i \leq K)$ denote the traffic load of the ith path, and $P_i(1 \leq i \leq K)$ denote the ith path. P_i also denotes the set of links on the ith path.

Given a new path P_{K+1}, we want to find out how much more traffic that the network could support over P_{K+1}. Let f_{K+1} denote the throughput over path P_{K+1}. The problem becomes maximizing throughput f_{K+1} over path P_{K+1} while guaranteeing the delivery of throughput $x_i(1 \leq i \leq K)$ over path $P_i(1 \leq i \leq K)$, respectively. Before we study the feasible condition of the $K+1$ flows, we first introduce the multirate capability and study independent sets with multiple discrete rates in the following subsections.

2.2. Multiple Discrete Rates in Wireless Sensor Networks

In multirate wireless sensor networks, each link may have several channel rates to choose for transmission. For example, the IEEE 802.11 protocols supports 2, 5.5, 6, 11, 18, 32, and 54 Mbps. We know that a higher rate travels shorter distance or has smaller transmission range than a lower rate. This phenomenon is captured by the receiver sensitivity, and a higher rate has a higher receiver sensitivity. A successful transmission with certain channel rate requires that the received signal power be larger than the receiver sensitivity of that rate. Let $RX_{se}(k)$ denote the receiver sensitivity of rate r_k.

A successful transmission also requires that the signal to interference plus noise ratio (SINR) be larger than a certain threshold. A higher rate also requires a higher SINR. Let $SINR(k)$ denote the requirement of SINR of rate r_k. Therefore, a successful transmission satisfies two conditions:

$$Pr \geq RX_{se}(k) \text{ and } \frac{Pr}{P_{inf}+P_n} \geq SINR(k), \qquad (1)$$

where Pr is the received power, P_{inf} is the interference power and P_n is the noise power.

2.3. Feasible Link Demands

A link demand vector is denoted as $\overrightarrow{f} = \{f_1, f_2, ..., f_L\}$, where L is the total number of links in the network and f_i is the link demand over link L_i. $\overrightarrow{f}$ is feasible if and only if there exists a link scheduling to deliver throughput f_i over link L_i for all $i(1 \leq i \leq L)$.

A link scheduling S can be described as multiple sets of links and each set is scheduled in one time slot. Each set is referred to as a **concurrent transmission link set** thereafter. Let M be the total number of different sets of links in the link scheduling, $E_i(1 \leq i \leq M)$ be the ith set of links, and $\lambda_i\tau$ be the length of time slot scheduled for links in E_i to transmit, τ is the period that S repeats itself, $\overrightarrow{R_i} = \{r_{i1}, r_{i2}, ..., r_{iL}\}$ is a throughput vector if E_i is scheduled for transmission, r_{ij} is achievable throughput over link L_j if E_i is scheduled for transmission. Apparently, $r_{ij} = 0$ if $L_j \notin E_i$. $\overrightarrow{f}$ is feasible if and only if we can find a link scheduling $S = \{(E_i, \overrightarrow{R_i}, \lambda_i)|_{1 \leq i \leq M}\}$ satisfying

$$\overrightarrow{f} = \sum_{1 \leq i \leq M} \lambda_i \overrightarrow{R_i}, \text{ and } \sum_{1 \leq i \leq M} \lambda_i \leq 1. \qquad (2)$$

In each concurrent transmission link set E_i, given transmission power at all links in the set, we can calculate the signal to interference plus noise ratio (SINR) $SINR_{ij}$ at each link L_j as follows,

$$SINR_{ij} = \frac{Pr_{jj}}{\sum\limits_{k:L_k \in E_i, k \neq j} Pr_{kj} + P_N}, \quad (3)$$

where Pr_{kj} is the received interference power at link L_j due to the transmission over link L_k, Pr_{jj} is the received signal power of transmission over link L_j, and P_N is the noise power.

Let $\overrightarrow{R_i^*}$ denote the *maximum link rate vector* of E_i, and $\overrightarrow{R_i^*} = \{r_{ij}^*|_{1 \leq j \leq L}\}$, where $r_{ij}^* = 0$ if link $L_j \notin E_i$. r_{ij}^* denotes the *maximum supported link rate* at link L_j in E_i, and it is determined by Pr_{jj} and $SINR_{ij}$ according to Equation (1). Notice that a link L_j in E_i may be able to choose a rate $0 < r_{ij} < r_{ij}^*$. That is to say, there may be many different rate vector $\overrightarrow{R_i}$ for each E_i, which makes the calculation of λ_i in Equation (2) complicated. Fortunately, we can only consider the maximum supported link rate r_{ij}^* for every link L_j in E_i by the following proposition.

Proposition 1: In a concurrent transmission set E_i, any rate vector $\overrightarrow{R_i} = \{r_{ij}|_{1 \leq j \leq L}\}$, and $0 \leq r_{ij} \leq r_{ij}^* (1 \leq j \leq L)$, can be described as a linear combination of rate vectors with the maximum supported rate vectors of several concurrent transmission sets. The proof is omitted here due to the space limit.

Apparently, for any concurrent transmission set, if there are one or more links in the set with the maximum supported rate equal to zero, we can remove these links from the set. Since $SINR$ of other links in the set become larger, these links can support the same link rates as in the original set, and the feasible condition Equation (2) still holds. This is the following proposition.

Proposition 2: In the feasible condition Equation (2), we only need to consider those concurrent transmission sets with a rate vector $\overrightarrow{R_i} = \{r_{ij}(1 \leq j \leq L)\}$ where $r_{ij} > 0$ for any link $L_j \in E_i$.

2.4. Independent Sets in Multirate Networks

An **independent set** E in a multirate network is defined similarly to that in a single-rate network, but needs to be coupled with a rate vector $\overrightarrow{R}$ for links in the set. We call $(E_i, \overrightarrow{R_i})$ is an independent set if each link $L_j \in E_i$ can support rate r_{ij} indicated in $\overrightarrow{R}$ if all links in the set concurrently transmit. Notice that, an independent set may not be an independent set any more if some links in the set transmits with a higher rate than that specified by $\overrightarrow{R}$. A **maximal independent set** is also defined differently from that in a single-rate network. It is an independent set satisfying two additional conditions. First, each link in the independent set chooses the maximum rate it supports when transmitting at the same time with other links in the set. Second, inserting any other link in the set will decrease the link rate of at least one existing link in the set to a smaller value or even zero.

Notice that in multirate networks, where links are allowed to transmit with different rates at different time, a maximum independent set may be a subset of another independent set, however, there are at least one link in the former one with a higher maximum rate than it in the latter one. This is not true for single-rate networks or multirate networks with a fixed rate assignment.

From Proposition 2, only independent sets are necessary to be considered in the feasible condition Equation (2). From Proposition 1, for each independent set, only the maximum supported link rates are necessary to be considered in the feasible condition. Actually, only maximal independent sets with maximum supported rate vectors are necessary to define a feasible condition. This is the Proposition 3.

Proposition 3: Given all maximal independent sets $E_i (1 \leq i \leq \widehat{M})$, where $\widehat{M}$ is the total number of maximal independent sets for all L links, the feasible condition Equation (2) is equivalent to

$$\overrightarrow{f} \leq \sum_{1 \leq i \leq \widehat{M}} \lambda_i \overrightarrow{R_i^*}, \text{ and } \sum_{1 \leq i \leq \widehat{M}} \lambda_i \leq 1. \quad (4)$$

Proof is omitted here due to the space limit.

2.5. Linear Programming Formulation of the Available Path Bandwidth Problem

Now we are ready to solve the available path bandwidth problem by constructing the feasible condition using maximum independent sets, which always use the maximum supported rate vectors.

Following the notation we used in Section 2.1, we define $P = \bigcup\limits_i P_i$. In P, we first find all maximum independent sets E_α $(1 \leq \alpha \leq \widehat{M})$ and the corresponding maximum supported rate vectors $\overrightarrow{R_\alpha^*}$ for each E_α of P. Let $I(P_k)$ be a row indicator vector in $R^{|P|}$, and

$$I_e(P_k) = \begin{cases} 1, & e \in P_k \\ 0, & e \notin P_k, e \in P. \end{cases} \quad (5)$$

Then the problem to find the maximum throughput over path P_{K+1} can be formulated as

$$\begin{aligned} & \text{Maximize } f_{K+1} \\ & \text{Subject to:} \\ & \quad \sum_{\alpha=1}^{\widehat{M}} \lambda_\alpha \leq 1, \\ & \quad \sum_{\alpha=1}^{\widehat{M}} \lambda_\alpha R_\alpha - \sum_{k=1}^{K} x_k I(P_k) - f_{K+1} I(P_{K+1}) \geq 0, \\ & \quad \lambda_\alpha \geq 0 \ (1 \leq \alpha \leq \widehat{M}), \ f_{K+1} \geq 0, \end{aligned} \quad (6)$$

which can be solved by some standard linear programming approach. If the solution of this optimization problem f_{K+1}

is larger than or equal to the flow's demand x_{K+1}, the new flow's demand can be supported over the path P_{K+1} without affecting the bandwidth requirements of background traffic.

The above formulation can also be easily extended into the cases where there are more than one flow with corresponding demands joining the network simultaneously.

3. Upper and Lower Bounds

Link conflict graphs and cliques have been widely used to derive upper and lower bounds of throughput in wireless sensor networks. However, we will show that the clique constraint is not valid any more for the maximum supportable throughput in multirate networks where links are allowed to use different transmission rates at different time. To demonstrate this observation and derive a new upper bound, we first extend the concepts of cliques and maximum cliques into the ones in multirate networks. At the end of this section, we also discuss lower bounds derived from independent sets.

3.1. Cliques in Multirate Networks

Traditionally, a clique is a set of links among which any two cannot transmit successfully at the same time. In multirate networks where links are allowed to transmit with different rates at different times, a clique needs to be coupled with a rate vector, which is similar to the concept of independent sets discussed in the previous section.

In this paper, a **clique** C is defined as a set of multiple couples of a link and its transmission rate (L_i, r_i), and $C = \{(L_i, r_i)\}\forall i$. For any two links L_i and $L_j (i \neq j)$ in a clique C, not both transmissions will be successful if L_i transmits data with a rate r_i and L_j transmits data with a rate r_j at the same time. This phenomenon is also referred as that L_i with rate r_i **interferes** with L_j with rate r_j.

A **maximal clique** C is defined as a clique which satisfies that $C \cup \{(L_i, r_i)\}$ is not a clique for any couple (L_i, r_i), where $L_i \notin C$ and r_i is a positive rate if L_i transmits alone. A **maximal clique with maximum rates** is defined as a maximal clique C which satisfies that C will not be a maximal clique by replacing (L_i, r_i) with (L_i, r'_i) for any $L_i \in C$ and $r'_i > r_i$, where r'_i is an achievable rate over L_i if L_i transmits alone.

For example in a four-link chain topology as shown in Fig. 1, we assume that all links can only support 36 and 54Mbps if each of them transmits alone. We also assume that any two of links 1, 2, and 3 interfere with each other whichever rates they use for transmission, and the same for links 2, 3, and 4. Links 1 and 4 interfere with each other if link 1 transmits with 54Mbps, but they do not interfere with each other if link 1 transmits with 36Mbps. Therefore, $\{(L_1, 54), (L_2, 54), (L_3, 54)\}$ is a clique but not a maximal clique; $\{(L_1, 36), (L_2, 36), (L_3, 36)\}$ is a maximal clique but not a maximal clique with maximum rates; both $\{(L_1, 54), (L_2, 54), (L_3, 54), (L_4, 54)\}$ and $\{(L_1, 36), (L_2, 54), (L_3, 54)\}$ are maximal cliques with maximum rates.

Apparently, if only links are considered, a maximal clique could be a subset of another maximal clique. This cannot happen in single-rate networks or in multirate networks where each link always uses a fixed rate.

3.2. Upper Bounds Derived from Cliques

In this subsection, we discuss how to obtain an upper bound of a feasible link demand vector $\overrightarrow{Y} = \{y_1, y_2, ..., y_L\}$ and the upper bound of available bandwidth f_{K+1} of a new path P_{K+1}, where $y_i (1 \leq i \leq L)$ is the throughput over link L_i.

In a single rate wireless network, several work ([10], [11]) have shown that the total time share for successful transmissions over all links in a clique can not exceed one or the maximum available time share. Thus,

$$\sum_{L_i \in C} \frac{y_i}{r} = \frac{\sum\limits_{L_i \in C} y_i}{r} \leq 1.$$

Given the requirement that all links deliver the same throughput, each link's throughput is upper bounded by $s \leq \frac{r}{N}$, where r is the link rate and N is the size of the clique.

In [1], we showed a similar result for multirate wireless network where each link selects a fixed rate from multiple choices and used the clique transmission time to derive an upper bound of throughput. Let $r_i (1 \leq i \leq N)$ denote the link rate over link L_i in a clique with N links. We can have:

$$\sum_{L_i \in C} \frac{y_i}{r_i} =\leq 1.$$

Given the requirement that all links deliver the same throughput, each link's throughput is upper bounded by

$$s \leq \frac{1}{\sum\limits_{i=1}^{N} \frac{1}{r_i}} = \frac{1}{\hat{T}}, \tag{7}$$

where $\hat{T}$ is defined as the clique transmission time for one unit of traffic in [1].

However, an upper bound derived from a given rate vector is not necessarily an upper bound for a network where each link may choose a different transmission rate at different time, which is a typical case with some appropriate link adaptation scheme.

Now let us analyze the upper bound of throughput in a wireless network where each link is allowed to use different rates at different time. Let $\overrightarrow{Y} = \{y_1, y_2, ..., y_L\}$ be the demand vector of links $L_i (1 \leq i \leq L)$. $C_{ij} (1 \leq j \leq M_i)$ is the jth clique given a rate vector $\overrightarrow{R_i} = \{r_{i1}, r_{i2}, ..., r_{iL}\}$, and M_i is the total number of different cliques for $\overrightarrow{R_i}$. Let $\overrightarrow{I}_{C_{ij}}$ be an indicator vector for clique C_{ij}, and

$$\overrightarrow{I}_{C_{ij}}(k) = \begin{cases} 1, L_k \in C_{ij} \\ 0, L_k \notin C_{ij}, L_k \in P. \end{cases}$$

Let T_{ij} be the clique time share of C_{ij} given $\overrightarrow{R}_i$ and $\hat{T}_i$ be the maximum value of T_{ij} for all cliques $C_{ij}(1 \leq j \leq M_i)$ given $\overrightarrow{R}_i$:

$$T_{ij} = \sum_{k=1}^{L} \frac{y_k}{r_{ik}} \overrightarrow{I}_{C_{ij}}(k), \text{ and } \hat{T}_i = \max_{1 \leq j \leq M_i} T_{ij}.$$

Let $\overrightarrow{g_i} = \{g_{i1}, g_{i2}, ..., g_{iL}\}$ be a feasible throughput vector for all links given a rate vector $\overrightarrow{R}_i$. For any feasible $\overrightarrow{Y}$, we can find a set of γ_i and feasible $\overrightarrow{g_i}$ to satisfy

$$y_j = \sum_{i=1}^{\Omega} \gamma_i g_{ij} (1 \leq j \leq L), \text{ and } \sum_{i=1}^{\Omega} \gamma_i \leq 1$$

where γ_i is the time share when $\overrightarrow{R}_i$ is used, and Ω is the total number of possible values of $\overrightarrow{R}_i$. We know that if $\overrightarrow{g_i}$ is feasible,

$$T_{ij_g} = \sum_{k=1}^{L} \frac{g_{ik}}{r_{ik}} \overrightarrow{I}_{C_{ij}}(k) \leq 1, \text{ for all } i, j.$$

That is to say if $\overrightarrow{R}_i$ is fixed and $\overrightarrow{Y}$ is achievable over $\overrightarrow{R}_i$, $T_{ij} \leq 1 (1 \leq j \leq M_i)$ and $\hat{T}_i \leq 1$. However, if $\overrightarrow{R}_i$ has multiple choices, $T_{ij} \leq 1 (1 \leq j \leq M_i)$ is not always true any more and even the following hypothesis is wrong.

$$\textbf{Hypothesis}: \min_i \hat{T}_i \leq 1 \tag{8}$$

A counterexample is the four-link chain topology in Fig. 1 and is analyzed in Section 5.

Therefore, it is not easy to derive an upper bound for the feasible throughput vector $\overrightarrow{Y}$ by directly applying $\overrightarrow{Y}$ over cliques. Here we use upper bounds for achievable link throughput vectors over individual $\overrightarrow{R}_i$ to construct an upper bound of $\overrightarrow{Y}$. Then an upper bound is given by the following optimization problem.

$$\begin{array}{l} \text{Maximize } f_{K+1} \\ \text{Subject to:} \\ \quad \sum_{k=1}^{L} \frac{g_{ik}}{r_{ik}} \overrightarrow{I}_{C_{ij}}(k) \leq 1 (1 \leq j \leq M_i, 1 \leq i \leq \Omega), \\ \quad \sum_{i=1}^{K} x_i \overrightarrow{I}(P_i) + f_{K+1} \overrightarrow{I}(P_{K+1}) \leq \overrightarrow{Y} = \sum_{i=1}^{\Omega} \gamma_i \overrightarrow{g_i}, \\ \quad \sum_{i=1}^{\Omega} \gamma_i \leq 1, \\ \quad 0 \leq \gamma_i \leq 1, 0 \leq g_{ik} \leq r_{ik}, f_{K+1} \geq 0. \end{array} \tag{9}$$

The first constraint considers all clique constrains for all $\overrightarrow{R}_i$. The second constraint satisfies the link demands required by the end-to-end throughput $x_i (1 \leq i \leq K)$ and f_{K+1}.

If the total number of different rates is Z, Ω can be as large as $Z^L - 1$, i.e., $\Omega \leq Z^L - 1$. For each i, the total number of different cliques M_i also increases quickly with L. Though only maximal cliques are necessary to solve the problem, finding all maximal cliques for each i is still a computationally difficult problem.

To reduce the computation complexity of the above problem, we can use a small number of cliques for each i to derive a loose upper bound of $\overrightarrow{g_i}$, and develop some algorithms to remove some unnecessary rate vectors $\overrightarrow{R}_i$. These are left for future studies.

3.3. Lower Bounds Derived from Independent Sets

Although the clique constraint becomes invalid, we can still use a part of all (maximum) independent sets to construct lower bounds of available path bandwidth. This is because, by using a part of independent sets, the new solution space is a subset of the original solution space.

4. Joint Design of QoS Routing and Link Scheduling, and Distributed QoS Rotuing

In previous section, we study how to determine available bandwidth or the maximum end-to-end throughput of paths given the demands of background traffic and their paths. In this section, we focus on how to find available bandwidth from a source to its destination without known paths between them but with known background traffic. This is a joint design problem of QoS routing and link scheduling. The optimization problem is NP-hard and requires to consider all possible links in the network. In this section, we focus on distributed algorithms.

In distributed wireless networks, it is often not feasible to timely obtain the global link scheduling information and accordingly calculate accurate available bandwidth of a new path. Therefore, it is important to develop a distributed algorithm to find a path and estimate the available bandwidth of that path with background traffic in mind.

To obtain information of background traffic, each node is required to observe the channel utilization. This can be done by carrier sensing. A node assumes that it can transmit during channel idle periods, and not otherwise. It calculates a channel idleness ratio $\lambda_{idle} \leq 1$, i.e., the ratio of the length of time it senses an idle channel to the total sensing time. A link L_i assumes that it can transmit new traffic for a time share λ_i indicated by the smaller value λ_{idle} of its two end nodes, and

$$\lambda_i \leq \min\{\lambda_{idle,n_{it}}, \text{ and } \lambda_{idle,n_{ir}}\}, f \leq \lambda_i \times r_i, \tag{10}$$

where n_{it} and n_{ir} are the transmitter and the receiver of link L_i, respectively, r_i is the effective data rate of link L_i and f is the available bandwidth of link L_i.

To estimate available bandwidth of a path, we still need to consider the interference among links of that path. We here define a local interference clique for a path. A **local interference clique** is a clique and all links in the clique are in a sequence on the path. We follow the approach in paper [1] to find the local interference cliques. For a clique $C = \{L_1, L_2, ..., L_{|C|}\}$, and the corresponding idle time ratio for these links, $\overrightarrow{\lambda} = \{\lambda_1, \lambda_2, ..., \lambda_{|C|}\}$, we have

$$\sum_{i=1}^{|C|} \frac{f}{r_i} \leq 1. \tag{11}$$

We can further have

$$f \leq \min\{\frac{1}{\sum_{i=1}^{|C|} \frac{1}{r_i}}, \lambda_i \times r_i (1 \leq i \leq |C|)\}. \tag{12}$$

This actually provides an upper bound of the available end-to-end bandwidth of a path P given the rate vector $\overrightarrow{R} = \{r_1, r_2, .., r_{|P|}\}$ and the link idleness vector $\overrightarrow{\lambda}$.

The above estimation assumes that any two links' idle time are not overlapped. It may give a loose upper bound. A conservative estimation is to add another constraint by assuming that the time share λ_i of link L_i is shared by all links in a clique with their individual time share less than λ_i, which bounds the throughput for any k links in C by:

$$\sum_{i=1}^{k} \frac{f}{r_i} \leq \max_{1 \leq i \leq k} \lambda_i.$$

If λ_i is ordered in increasing order as $\{\lambda_1 \leq \lambda_2 \leq ... \leq \lambda_{|C|}\}$, then it is equivalent to

$$\sum_{j=1}^{i} \frac{f}{r_j} \leq \lambda_i (1 \leq i \leq |C|),\ f \leq \min_{i:1 \leq i \leq |C|} \frac{\lambda_i}{\sum_{j=1}^{i} \frac{1}{r_j}} \tag{13}$$

We propose to use the minimum value of estimated available bandwidth calculated by Equation (11), (12) or (13) for all (local) maximal cliques as routing metrics and as well as metrics to estimate the path available bandwidth. Each intermediate node on a path estimates the available bandwidth from the source to itself on that path, and uses it in distributed routing algorithms as any other routing metrics such as hop count.

In traditional routing algorithms without considering background traffic, several works such as [1] have shown that both end-to-end transmission delay (E2ETD) and local clique transmission time (LCTT) are good routing metrics to find a path with a high end-to-end path capacity. Here, we design two routing metrics based on E2ETD and LCTT to consider the background traffic. We know that link L_i's available throughput f_i is less than or equal to $\lambda_i \times r_i$, and hence the average delay for one unit of traffic is larger than or equal to $\frac{1}{\lambda_i \times r_i}$. The average end-to-end delay T_{e2e} of path P and the maximum average clique transmission delay T_C^* satisfy

$$T_{e2e} \leq T_{e2e}^* = \sum_{L_i \in P} \frac{1}{\lambda_i r_i},\ T_C^* = \max_{C:clique} \sum_{L_i \in C} \frac{1}{\lambda_i r_i}. \tag{14}$$

Similar to Equation (7) which uses clique transmission time to construct an upper bound, here we propose a new estimate of available bandwidth by considering both clique constraint and background traffic for given $\overrightarrow{R}$ and $\overrightarrow{\lambda}$, i.e.,

$$f \leq \frac{1}{T_C^*} = \frac{1}{\max_{C:clique} \sum_{L_i \in C} \frac{1}{\lambda_i r_i}}. \tag{15}$$

5. Performance Evaluation

In this section, we use the developed theoretic model to study path available bandwidth in simple scenarios as well as random topologies.

5.1. Simple Scenarios II where Clique Constraints Become Invalid, and Link Adaptation Can Improve Throughput

In this subsection, we study scenario II in Fig. 1 and the parameters has been explained in Section 3.1. Suppose there is a multihop flow traveling through links L_1, L_2, L_3, and L_4, and requires the same throughput over these four links, i.e.,

$$f = y_1 = y_2 = y_3 = y_4$$

where f is the end-to-end throughput of the flow, and $y_i (1 \leq i \leq 4)$ is the throughput over link L_i.

The optimization problem generates the following link scheduling S,

$$S = \begin{cases} (\lambda_1 = 0.1, E_1 = \{L_1, 54\}), \\ (\lambda_2 = 0.3, E_2 = \{L_2, 54\}), \\ (\lambda_3 = 0.3, E_3 = \{L_3, 54\}), \\ (\lambda_4 = 0.3, E_4 = \{(L_1, 36), (L_4, 54)\}) \end{cases}, f = 16.2$$

The throughput f can be supported by the following two rate vectors $\overrightarrow{R_1}$ and $\overrightarrow{R_2}$, their corresponding supported throughput vectors $\overrightarrow{f_1}$ and $\overrightarrow{f_2}$, and their time shares γ_1 and γ_2:

$$\begin{aligned} &\overrightarrow{R_1} = \{54, 54, 54, 54\}, \gamma_1 = 0.1, \overrightarrow{f_1} = \{54, 0, 0, 0\} \\ &C_1 = \{(L_1, 54), (L_2, 54), (L_3, 54), (L_4, 54)\} \\ &\overrightarrow{R_2} = \{36, 54, 54, 54\}, \gamma_2 = 0.9, \overrightarrow{f_2} = \{12, 18, 18, 18\} \\ &C_2 = \{(L_1, 36), (L_2, 54), (L_3, 54)\} \\ &y_i = \gamma_1 f_{1i} + \gamma_2 f_{2i} = f = 16.2 \end{aligned}$$

It is not difficult to show the clique with the maximum clique transmission time share are the above C_1 and C_2 for R_1 and R_2, respectively, whose clique constraints are valid for

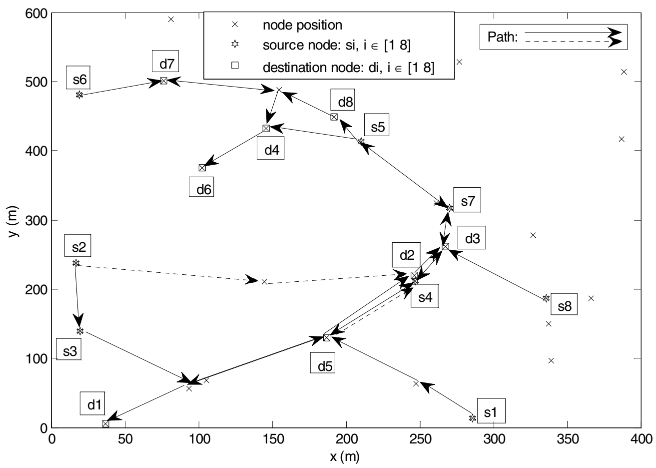

Figure 2. Random topology

individual throughput vector f_1 and f_2, respectively, but not for the maximum end-to-end throughput f:

$$\sum_{L_i \in C_1} \frac{f_{1i}}{R_{1i}} = 1, \sum_{L_i \in C_2} \frac{f_{2i}}{R_{2i}} = 1$$
$$\sum_{L_i \in C_1} \frac{y_i}{R_{1i}} = 1.2 > 1, \sum_{L_i \in C_2} \frac{y_i}{R_{2i}} = 1.05 > 1$$

Notice that the upper bounds of end-to-end throughput provided by cliques for either $\overrightarrow{R_1}$ or $\overrightarrow{R_2}$ (refer to Equation (7)) is less than $f = 16.2$:

$$\overrightarrow{R_1} : s_1 \leq \frac{1}{\sum_{L_i \in C_1} \frac{1}{R_{1i}}} = \frac{1}{\frac{4}{54}} = 13.5 < 16.2$$
$$\overrightarrow{R_2} : s_2 \leq \frac{1}{\sum_{L_i \in C_2} \frac{1}{R_{1i}}} = \frac{1}{\frac{1}{36} + \frac{2}{54}} = \frac{108}{7} \approx 15.43 < 16.2$$

It clearly shows that the maximum feasible throughput vector does not satisfy any clique constraint in this example, and hence clique constraints cannot directly provide an upper bound any more.

Apparently, achieving the optimum end-to-end throughput $f = 16.2$ requires some appropriate link adaptation algorithm, which allows L_1 to transmit data with different data rates at different time to obtain higher end-to-end throughput than any fixed rate vectors.

5.2. Compare Distributed QoS Routing Metrics

In this subsection, we study performance of different QoS routing metrics.

In the simulation, 30 nodes are randomly located in a 400m × 600m rectangle area as shown in Fig. 2. Four 802.11a rates are used, i.e., 54, 36, 18, and 6Mbps. The propagation exponent is set as 4. The transmission distances of these four rates are 59, 79, 119, 158m, respectively. Their SNR requirement are 24.56, 18.80, 10.79, 6.02dB, respectively ([14]). 8 sources and their destinations are

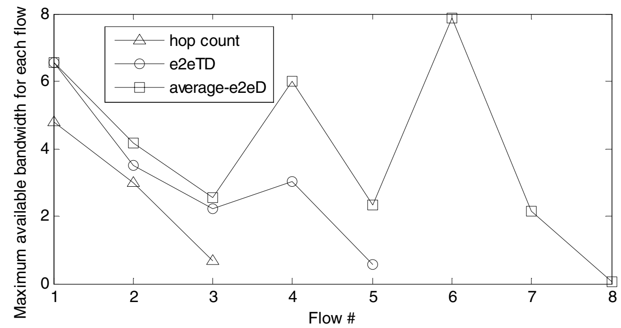

Figure 3. Available bandwidth

randomly chosen and each flow's demand is 2Mbps. Due to space limitation, we only compare three routing metrics, hop count, end-to-end transmission delay (e2eTD), and average end-to-end delay (average-e2eD) (refer to Equation (14)).

In the simulation, we assume that flows join the network one by one. The simulation stops when the demand of one flow is not satisfied. Fig. 2 also shows the paths found by the routing metric average-e2eD, which are illustrated by solid arrows. The e2eTD finds different paths for some flows, and the dotted arrows show some different links used by e2eTD. Fig. 3 shows the available bandwidth of each flow's path found by different routing metrics. Apparently, the average-e2eD can find paths with the largest available bandwidth among these three metrics, and it fails to find a path to satisfy the demand for the 8th flow. The e2eTD fails to find a path to satisfy the demand for the 5th flow, and it is the 3rd flow for the hop count.

5.3. Estimation of Path Available Bandwidth

In this subsection, we evaluate metrics studied in Section 4 including "clique constraint (Equation 11)", "bottleneck node bandwidth (Equation 10)", "min of the above two (Equation 12)", "conservative clique constraint(Equation 13)", "expected clique transmission time (Equation 15)". We apply these metrics to the paths found by the routing metric average-e2eD in the above subsection.

From Fig. 4, we can observe that "clique constraint" underestimates the available bandwidth when the background traffic is light due to the ignore of the advantages of link adaptation, and overestimates the available bandwidth when the background traffic is heavy due to the ignore of background traffic. "bottleneck node bandwidth" considers the effect of background traffic but ignores the interference among traffic along the new path, and hence overestimates the available bandwidth especially when the background traffic is light. "conservative clique constraint" considers both clique constraints and background traffic, and performs the best among these metrics. "expected clique transmission time" obtains lower values of available bandwidth and

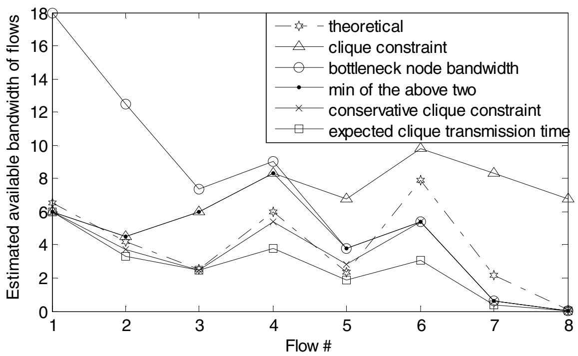

Figure 4. Estimated available bandwidth

performs a little worse than "conservative clique constraint". Furthermore, all metrics except "clique constraint" underestimate the available bandwidth when background traffic is heavy. This demonstrates the shortage of using channel idle time to estimate the available bandwidth and verifies the previous results in the paper.

6. Conclusions

In this paper, we have developed a theoretical model to calculate available path bandwidth by extending independent sets and cliques in mulirate and mulithop networks where link adaptation is allowed. Upper and lower bounds have been studied using cliques and independent sets. The model has also been extended to a joint design of QoS routing and link scheduling. Furthermore, several QoS routing metrics and metrics to estimate available path bandwidth have also been studied and compared.

From the theoretical model and performance evaluation results, we further have the following key observations in multirate and multihop networks:

- The clique constraint, a widely used condition to construct upper and even lower bounds of throughput, becomes invalid in mulitrate networks where links are allowed to transmit with different rates at different time;
- Channel idle time, a widely used metric, is not always effective to estimate nodes', links', and path's available bandwidth;
- End-to-end throughput can be improved by allowing links to transmit with different rates at different time, i.e., link adaptation works, but requiring sophisticated coordination;
- "Average-e2eD" could be a good QoS routing metric;
- The proposed "conservative clique constraint" performs the best among several studied metrics to estimate available path bandwidth by considering both the impact of background traffic and interference among the traffic along the path.

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