Relative Service Differentiation for Mobile Ad hoc Networks

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Abstract - **A relative bandwidth service differentiation scheme is proposed for Mobile Ad-hoc Networks (MANETs). The service profile for a traffic session is defined as a relative target rate, which is a fraction of the effective link capacity of nodes. To calculate the effective link capacity of nodes in a randomly moving topology MANET, two methods are presented: one is parameter based and the other is measurement based. Simulation results show that the parameter based and measurement based calculations work effectively to estimate the effective link capacity of nodes and the relative service differentiation is consistent. Furthermore, the differentiation is more consistent when nodes use the measurement based calculation of link capacity because it is more accurate.**

I. Introduction

Service differentiation categorizes traffic into a set of classes to which network nodes provide priority-based treatment without reserving resources exclusively. Because of its scalability and relative simplicity, service differentiation is an attractive approach in providing QoS in IP networks. For example, the Differentiated Service (DiffServ) [1] architecture has been defined for the Internet to provide Assured Service (AS) and Premium Service in addition to best-effort service. Research on service differentiation has also been extended to wireless networks. Mahadevan and Sivalingam [5] have proposed an enhanced DiffServ model after considering the specific characteristics of cellular wireless networks. Nandagopal et al. [6] have suggested an end-to-end rate control scheme to realize service differentiation. However, these solutions are aimed at cellular networks with only a one hop wireless link. Service differentiation in MANETs with multiple wireless hops has not been investigated in the literature.

Service differentiation can be categorized as absolute differentiation and relative differentiation. In absolute service differentiation, an admitted class is assured of its requested performance level, like packet delay, jitter, throughput and loss rate. In relative service differentiation, the assurance from the network is no longer an absolute metric to any class, but the relative relationship between/among classes. For example, relative queueing delay differentiation in [4] defines the QoS metric as the proportional queueing delay among classes. The advantage of relative service differentiation is the ability to keep service differentiation consistent regardless of network load changes.

Our previous work in [8] shows that differentiation is not consistent for TCP with AS in MANETs when absolute service differentiation is used. To achieve consistent differentiation, relative bandwidth service differentiation is proposed and illustrated with a simple *string* topology in [8]. This paper further refines the definition of the relative bandwidth service differentiation scheme and investigates its applicability in a randomly moving MANET environment. Service differentiation is also one of the features of the Flexible QoS Model for MANETs (FQMM) we have proposed in [7].

The rest of the paper is organized as follows. Section 2 defines the relative bandwidth service differentiation scheme. Section 3 analyzes how to calculate the effective link capacity in a randomly moving MANET. Performance evaluation of the relative service differentiation scheme is presented in Section 4 by simulation. Finally, Section 5 concludes the paper.

II. Relative Bandwidth Service Differentiation

The service profile is defined as γ, *a relative target rate of a traffic session, which is a fraction of the effective capacity of a link and ranges between 0 and 1.*

The effective link capacity, C_{eff}, is *the available bandwidth that a node can use to send out its own packets after considering the bandwidth used by its neighboring nodes.* The value of a node's effective link capacity depends on many factors, such as power constraints, node mobility, dynamic topology, routing and traffic load.

The relative target rate of a session is normalized over time as the session goes across a MANET according to the traffic distribution in the MANET. Assume session i is assigned a relative target rate γ_i. At a certain time instant, packets of session i arrive at a node N, which has altogether S sessions of traffic to send out. Some of these sessions may be originated by node N and some may be relayed by node N. The relative target rate of session i at node N is then normalized as:

$$\gamma_i^N = \frac{\gamma_i}{\sum_{j=1}^{S} \gamma_j} \tag{1}$$

where γ_j is the relative target rate of session j.

The above definition of normalized relative differentiation is suitable for the dynamics in MANET where the load distribution is dynamic and uneven because of node mobility and a time-varying topology. Some nodes may only forward one session, while others may have a lot of sessions to send out. For example, a congested node may have a large number of sessions to forward with total relative target rate (before normalization) greater than 1. In such a case, normalization is necessary to avoid the total sending rate of packets exceeding the available effective link capacity.

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To realize the relative bandwidth service differentiation, each node uses a token bucket profile meter whose token rate ρ and bucket length β are adaptively adjusted according to the instantaneous value of the effective link capacity. Each node also adopts Random Early Drop (RED) with In/Out (RIO) [3] as its buffer management scheme, and First In First Out (FIFO) as its scheduling scheme.

The token bucket profile meter marks each packet as IN or OUT according to tokens available. The parameters of the token bucket profile meter of a certain session i are as follows:

$$\rho_i = \gamma_i \times C_{eff} \times R \tag{2}$$

$$\beta_i = \gamma_i \times C_{eff} \times L \tag{3}$$

R and L are constants here.

From the definition in (2) and (3), the parameter that is difficult to decide is C_{eff}. Primarily we need to determine the value of C_{eff} in a randomly moving MANET in order to make the relative service differentiation scheme work in such an environment.

III. Effective Link Capacity

As mentioned earlier, many factors affect the value of the instantaneous effective link capacity of a node, like power constraints, node mobility, dynamic topology, routing and traffic load. Consider a mobile node N in a MANET environment as shown in Fig. 1. Nearby node N, there are 7 nodes, among which $N1$, $N2$, $N6$ are N's one hop away neighbors and $N5$ and $N7$ are N's two hop away neighbors. Assume N wants to send packets to $N1$.

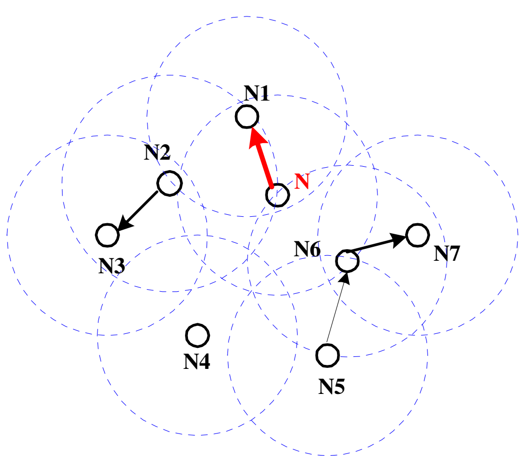


Fig. 1. Calculation of effective link capacity.

In Fig. 1, assume there are only three transmissions between nodes, viz., from $N2$ to $N3$, from $N6$ to $N7$ and from $N5$ to $N6$. $N2$ and $N6$ are N's one hop away neighbors and thus $N2$ / $N6$ and N share one common channel. When $N2$ / $N6$ is sending packets to the wireless channel, node N cannot send packets, otherwise a collision will happen at both nodes N and $N2$ / $N6$. In addition, when $N6$ is receiving packets from $N5$ (one of node N's two hop away neighbors), N cannot use the channel because a collision will happen at node $N6$. Therefore, the effective link capacity that node N can use is

$$C_{eff}^{N} = C^{N} - BW_{N2} - BW_{N6} - BW_{N5} \tag{4}$$

where C_{eff}^{N} is the effective link capacity of node N, C^{N} is the raw bandwidth of node N's link, BW_{N2} / BW_{N6} / BW_{N5} is the bandwidth that $N2$ / $N6$ / $N5$ occupies for transmission.

In general, for any node N in MANETs, its effective link capacity C_{eff}^{N} is

$$C_{eff}^{N} = C^{N} - \sum_{m} BW_m - \sum_{n} BW_n \tag{5}$$

where $m \in$\{N's 1 hop away neighbors\}, $n \in$\{N's 2 hop away neighbors\}, $\sum_m BW_m$ and $\sum_n BW_n$ are the total bandwidth occupied by N's 1 hop and 2 hops away neighbors, respectively.

The raw bandwidth of a physical channel C is a fixed value for the physical link. However, the bandwidth that each of node N's one / two hop neighbor node occupies, i.e., BW_m or BW_n, is time-varying. The key obstacle here is "how does node N know the values of BW_m and BW_n".

Consider how to decide BW_m for a common node m first. Generally, for a common node m, the bandwidth it occupies in a MANET depends on the traffic sessions it has at that time and the individual rate of those sessions. That is:

$$BW_m = \sum_{j} Avg\_rate_j^m \tag{6}$$

where $j \in$\{Sessions transmitted by node m\} and $Avg\_rate_j^m$ is the transmission rate of session j, i.e., the bandwidth used by session j.

In the following context we propose two methods to calculate $Avg\_rate_j^m$; one is parameter based and the other is measurement based.

A. Parameter Based Calculation

This method estimates $Avg\_rate_j^m$ as follows:

$$Avg\_rate_j^m = C_{eff}^{m} \times \gamma_j^m \tag{7}$$

B. Measurement Based Calculation

This method estimates $Avg\_rate_j^m$ based on measurement. A rate estimator is used to smooth out the burstiness of traffic in each session as well as to be sensitive to the instantaneous sending rate. We adopt the Time Sliding Window (TSW) algorithm [3] with slight changes. The design of TSW is as follows. Three state variables are maintained by TSW: Win_length, which is measured in units of time, Avg_rate, the rate estimate upon each packet arrival, and T_last, which is the time of the last packet arrival. Among them, Avg_rate and T_last are updated once a packet is received, but Win_length is fixed from the time the TSW estimator is installed for each session.

The TSW algorithm we use works as follows. Initially, the state variables are:

$$\begin{aligned} Win\_length &= \text{A constant} \\ Avg\_rate_j^m &= C_{eff}^m \times \gamma_j^m \\ T\_last &= 0 \end{aligned} \tag{8}$$

Upon each packet arrival, the state variables are updated as:

$$\begin{aligned} Bytes\_in\_TSW &= Avg\_rate_j^m \times Win\_length \\ New\_bytes &= Bytes\_in\_TSW + pkt\_size \\ Avg\_rate_j^m &= \frac{New\_bytes}{T\_now - T\_last + Win\_length} \\ T\_last &= T\_now \end{aligned} \tag{9}$$

where $Bytes\_in\_TSW$ is the number of bytes in the TSW, New_bytes is the sum of bytes in the TSW and the new arriving packet, pkt_size is the packet size of the arriving packet, and T_now is the time of current packet arrival.

From (8), (9) and (7), it is obvious that the parameter based calculation is simpler than the TSW measurement based calculation. However, its flaw is also obvious: it depends heavily on the accuracy of the rate control token bucket profiler (see (7)). The TSW measurement based calculation mitigates the dependency by only taking the rate control value of the token bucket profiler as its initial value (see (8)). Later the TSW algorithm adjusts the estimated rate according to the real packet transmissions of that session.

After proposing the above two methods for determining BW_m, the bandwidth occupied for a common node m, we now tackle the question of "how does node N decide BW_m and BW_n", i.e., how a node determines the bandwidth occupied by its one hop away and two hops away neighbors.

C. Bandwidth Occupied by One Hop Away Neighbors

We assume that a node's network interfaces can be set to the *promiscuous* mode so that the node can listen to all packets on the wireless channel. These packets include broadcast and multicast packets, as well as those with someone else's Media Access Control (MAC) address in the destination field. Over time, the node can calculate the bandwidth its one hop away neighbors use based on the packets it listens to.

Take the scenario in Fig. 1 as an example. When node N's network interface works at promiscuous mode, it can overhear the transmissions of its one hop away neighbors, e.g., from $N2$ to $N3$ and from $N6$ to $N7$. In order to calculate the bandwidth that $N2$ / $N6$ uses to send packets, N identifies the transmissions sessions it hears from one hop away neighbors by five fields together in the packet headers, viz., source MAC address, source IP address, destination IP address, source transport port, and destination transport port. Packets belong to the same session only if they have the identical values of the above five fields. Thus, we have

$$\sum_m BW_m = \sum_m \sum_j Avg\_rate_j^m \tag{10}$$

where $m \in$ {N's 1 hop away neighbors}, $j \in$ {Sessions transmitted by node m} and $Avg\_rate_j^m$ is the transmission rate of session j (see (6)).

D. Bandwidth Occupied by Two Hops Away Neighbors

Even if a node works in the *promiscuous* mode, it cannot hear the transmissions of its two hop away neighbors. To let a node have this knowledge, additional control messages have to be introduced. In the current stage of our work, we do not consider complex procedures, so a heuristic is used here.

Intuitively, the bandwidth occupied by node N's two hop away neighbors can be calculated separately in the bandwidth occupied by other nodes' one hop away neighbors. Therefore, we approximately let,

$$\sum_n BW_n = \xi_N \sum_m BW_m \tag{11}$$

where $m \in \{N$'s 1 hop away neighbors$\}$, $n \in \{N$'s 2 hops away neighbors$\}$, ξ_N is a parameter to help calculate $\sum_n BW_n$.

The usage of ξ_N simplifies the way to calculate the effective link capacity of a node; however, it also makes the calculation less accurate. ξ_N's value depends on the load distribution, size of the network, topology formation and routing path choice in MANETs. We will discuss the choice of ξ_N later in the performance evaluation.

Thus, (5) is modified to

$$C_{eff}^N = C^N - \sum_m BW_m - \xi_N \sum_m BW_m \tag{12}$$

IV. Performance Evaluation

A. Determination of ξ_N

We first determine the value of ξ_N considering a simple traffic load comprising traffic between a single pair of source and destination nodes. Consider the scenario in Fig. 2. Sessions $1, 2, 3$ and 4 originate from $N3$, pass by $N2$, $N6$ and N and arrive at the destination $N5$. N is taken as the node of interest in this analysis. $N6$ is N's one hop away neighbor. Thus, N calculates the bandwidth that $N6$ occupies to send the packets of these sessions to N, i.e., BW_{N6}, by working in promiscuous mode. $N2$ is N's two hop away neighbor; the following observation helps to determine BW_{N2}, the bandwidth that it occupies.

Since all sessions are between the same pair of source and destination (from $N3$ to $N5$), $N6$, as a relay node in between, forwards all the packets it receives from node $N2$ (the previous relay node) to node N (the next relay node) for these sessions. Consequently,

$$BW_{N2} = BW_{N6} \tag{13}$$

Therefore, when all the traffic in the network are between the same pair of source and destination, we have

$$\xi_N = 1 \tag{14}$$

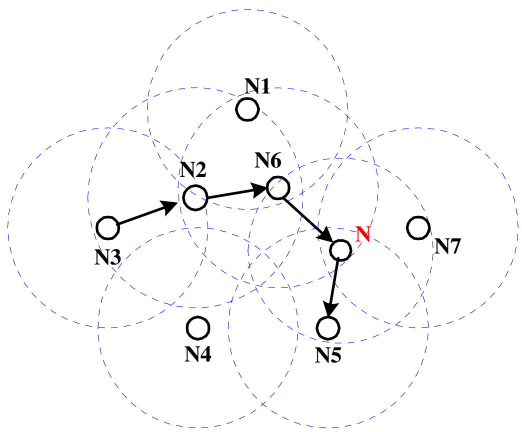


Fig. 2. Calculation of ξ_{MN}

B. Simulation

We simulate by using 10 nodes to form a small MANET in a 800×800 square meter area. Each node moves according to the *random waypoint* mobility model and run the Dynamic Source Routing (DSR) protocol [2]. The transmission range of each node is 250 meters. The maximum number of hops among nodes is thus 5, i.e., $[800 \times \sqrt{2} \div 250] + 1$. Four TCP sessions are introduced among the same pair of source and destination; two of the sessions have a relative target rate of 0.15 each and the other two have a relative target rate of 0.35 each. We run simulations over many randomly generated mobility patterns and choosen the representative results from one typical simulation to present here.

Fig. 3 demonstrates the absolute throughput of the four TCP sessions. The simulation is run for 900 seconds and the instantaneous throughput is measured every 10 seconds. Results in Fig. 3a and 3b are obtained when nodes use the parameter based method and the measurement based method to calculate their effective link capacity, respectively. Fig. 3a and Fig. 3b show that the instantaneous throughputs of TCP sessions vary over time when the nodes move around and the topology changes. TCP throughput of sessions belonging to the two groups with different target rates are differentiated for most of the time. In general, the two figures present similar trend of variation although the instantaneous values of TCP throughputs of the same session at the same time may be different.

Although the movement of nodes during the simulation is not shown, we can tell the distance between the source and the destination easily from Figs. 3a and 3b. Packet transmission of the four sessions start at 100s. From 100s to 120s, the four sessions achieve 0 throughput, which means the source and destination are separate from each other. From 120s to 160s, the four sessions achieve a small throughput (totally about 200kbps) without differentiation. This period corresponds to a distance of 5 hops between the source and destination. From 160s to 260s, the source and the destination are separated again. From 260s to 390s, throughputs of the four sessions are differentiated and this period corresponds to a distance of 2 hops between the source and the destination.

TABLE I

DISTANCE BETWEEN THE SOURCE AND DESTINATION DURING THE SIMULATION FOR A TYPICAL MOBILITY PATTERN

Time (second)	Distance between the source and the destination (hops)	Throughput differentiation (Yes/No)
$120 \sim 160$	5	No
$260 \sim 390$	2	Yes
$390 \sim 730$	1	Yes
$740 \sim 770$	3 or 4	Yes
$810 \sim 880$	2	Yes
Other times	∞ (separated)	Not applicable

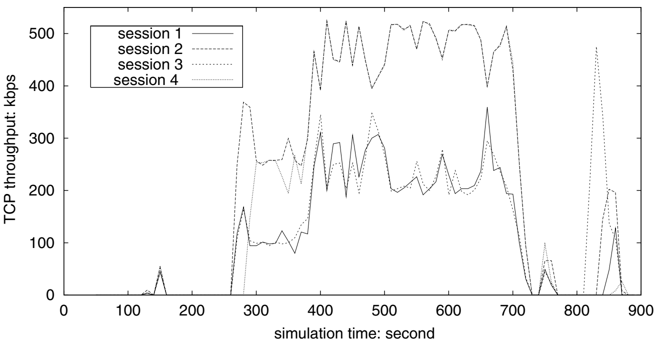
Similarly, the distance between the source and the destination over other simulation time is derived and listed in Table I.

Fig. 4 shows the instantaneous relative throughputs of the four TCP sessions. Values in the figure are calculated from the corresponding values of the instantaneous absolute throughputs. Assume at time t, the absolute throughputs of the four sessions are AbT_i, where $i \in \{1, 2, 3, 4\}$. The total absolute throughput is $AbTT = \sum_{i=1}^{4} AbT_i$. Thus the relative throughputs of the four sessions are calculated as $ReT_i = AbT_i/AbTT$, where $i \in \{1, 2, 3, 4\}$.

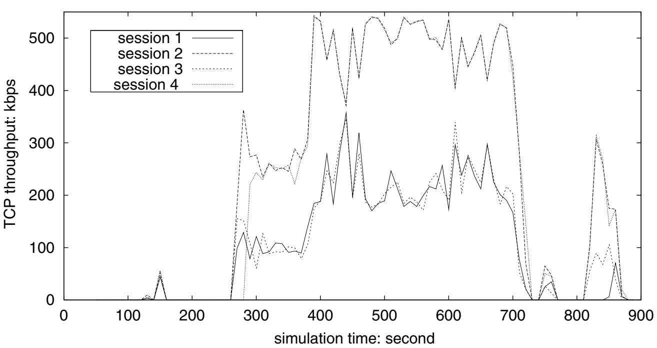
When the parameter based method is used to calculate the effective link capacity of nodes, Fig. 4a demonstrates that for most of the time (from 260s to 770s), the relative throughput is differentiated consistently with variation around the target rate of each session (0.35 for sessions 2 and 4, and 0.15 for sessions 1 and 3). This observation also exists in Fig. 4b when the measurement based method is used to calculate the effective link capacity of nodes. This proves that the two methods we propose in the previous subsection for nodes to calculate the effective link capacity work well in the relative bandwidth differentiation scheme with dynamic topology in MANETs.

Comparing Fig. 4a and Fig. 4b, it is noticed that the relative throughputs of sessions achieved in Fig. 4b when the measurement based method is used to calculate nodes' effective link capacity are more centered at their target rates than in Fig. 4a. In addition, during the period from 810s to 880s, the throughput differentiation is not consistent in the parameter-based calculation of the effective link capacity. These observations are explained in the following context of the examination of the effective link capacity of nodes.

Figs. 5 and 6 show the instantaneous effective link capacity of the source node and an intermediate node by using the parameter based calculation (Fig. 5a and Fig. 6a) and the measurement based calculation (Fig. 5b and Fig. 6b). We observe that the value of effective link capacity of nodes, either it be the source, the destination or an intermediate node, changes with the same trend at most of the time in the parameter and measurement based calculations. The changing trend over time actually relates to the absolute TCP throughput shown in Fig. 3. For example, consider the two periods in the simulation: one is from time 260s to 390s, during which the absolute TCP throughput corresponds to a distance of 2 hops between the source and the destination; the other is from time 390s to 690s,

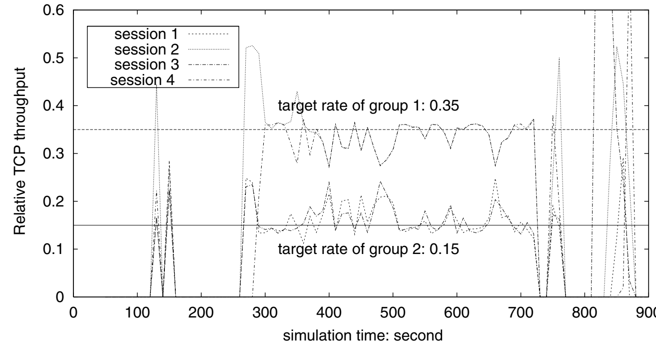


a. Parameter based method is used to calculate the effective link capacity of nodes.

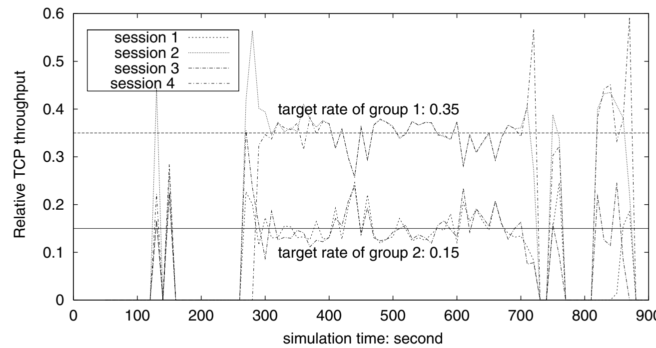


b. Measurement based method is used to calculate the effective link capacity of nodes.

Fig. 3. Absolute throughputs of TCP sessions.



a. Parameter based method is used to calculate the effective link capacity of nodes.



b. Measurement based method is used to calculate the effective link capacity of nodes.

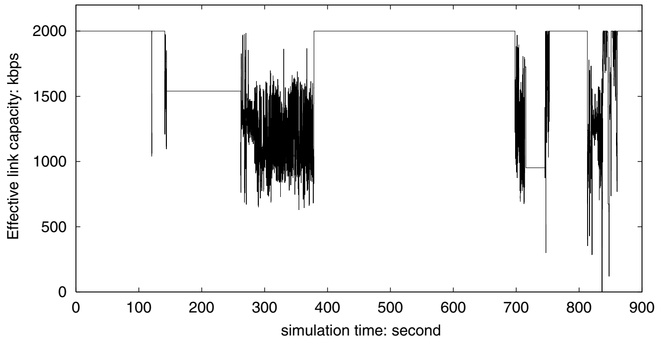
Fig. 4. Relative throughput of TCP sessions.

during which the absolute TCP throughput corresponds to a distance of 1 hop between the source and the destination. The effective link capacity of the source node (see Fig. 5) during 2 hops away period is lower than that during the 1 hop away period. This proves that the calculation of the effective link capacity is correct with the dynamics of network topology and the mobility of nodes.

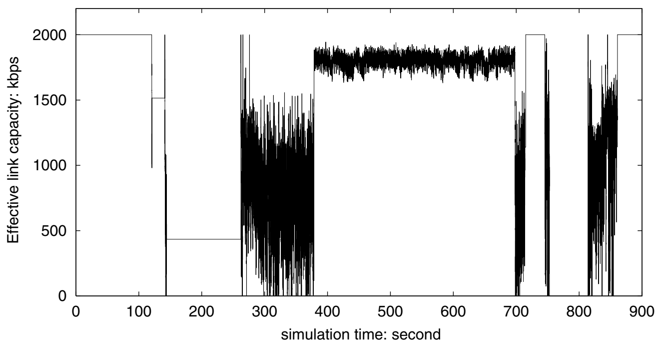
Secondly, the measurement based calculation has a lower estimate of the effective link capacity of the source node than the parameter based calculation. And the effective link capacity fluctuates around a lower mean value in the measurement based calculation than in the parameter based calculation (e.g., see period from 270s to 390s in Fig. 5 in the source node). We attribute this result to the different degrees of accuracy of the two methods of calculation. The parameter based calculation does not consider the bandwidth consumed by the MAC layer control packets, its estimation of session rate is only determined by the target rate of a session and the effective link capacity of node (see (7)). In contrast, the measurement based calculation takes into consideration the consumption of MAC layer control packets by measuring the real sending rate of sessions. As a result, the estimation of the effective link capacity is higher in parameter based calculation than in the measurement based calculation.

Lastly, it is noticed that the parameter based calculation and the measurement based calculation have different trends for some short durations, e.g., from 710s to 810s in the source node (see Fig. 5), and from 750s to 810s in the intermediate node (see Fig. 6). From the relative TCP throughput in Fig. 4, the measurement based calculation of the effective link capacity of nodes achieves more consistent differentiation (see Fig. 4b) than the parameter based calculation of the effective link capacity of nodes (see Fig. 4a) during the period from 710s to 880s. Therefore, we would say that the lower accuracy of the parameter based calculation causes the (short time) different trends of the effective link capacity from the measurement based calculation. This is also the reason why the relative throughputs of sessions achieved in Fig. 4b when the measurement based method is used to calculate nodes' effective link capacity are more centered at their target rates than in Fig. 4a when the parameter based method is used to calculate nodes' effective link capacity.

Overall, the simulation results show that the parameter based and measurement based calculations work well to estimate the effective link capacity of nodes in a MANET environment. The relative service differentiation is consistent with a randomly moving topology in MANETs. Furthermore, the differentiation is more consistent when nodes use measurement based calculation of link capacity than parameter based calculation because the former is more accurate than the latter.

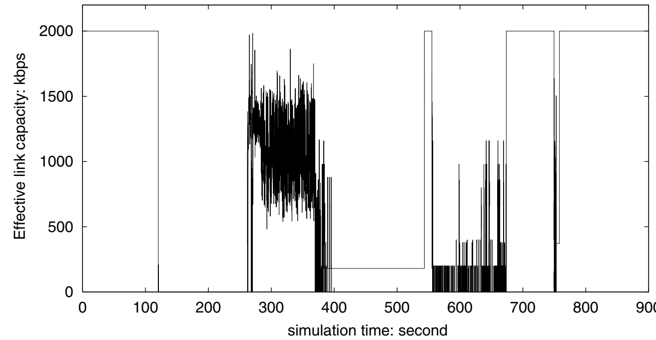


a. Parameter based method is used to calculate the effective link capacity of nodes.

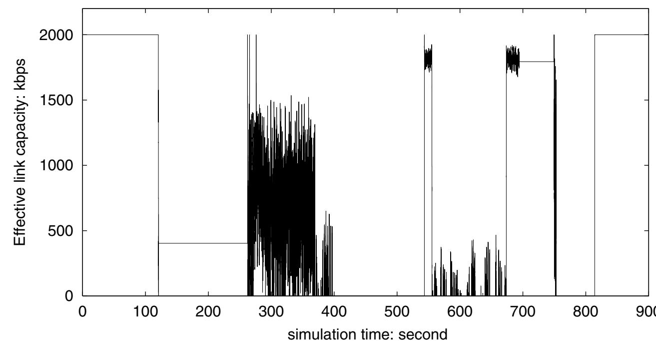


b. Measurement based method is used to calculate the effective link capacity of nodes.

Fig. 5. Effective link capacity of the source node.



a. Parameter based method is used to calculate the effective link capacity of nodes.



b. Measurement based method is used to calculate the effective link capacity of nodes.

Fig. 6. Effective link capacity of an intermediate node.

V. Conclusion and Future Work

A relative bandwidth service differentiation scheme is proposed to provide consistent differentiation considering the time-varying capacity of the wireless link due to high error rates, collisions and topological changes due to node mobility in MANETs. In order to let the relative differentiation scheme work with the randomly moving topology of MANETs, two methods are proposed for nodes to calculate the effective link capacity: one is parameter based and the other is measurement based. Simulation results show that the parameter based and measurement based calculations work well to estimate the effective link capacity of nodes in a MANET environment. The relative service differentiation is consistent. Furthermore, the differentiation is more consistent when nodes use measurement based calculation of link capacity than parameter based calculation because the former is more accurate than the latter.

For service differentiation, there is scope to investigate the performance of the relative service differentiation scheme with a more complex traffic load. To do this, the problem of how a node knows the bandwidth occupied by its two hop away neighbors must first be solved. Some protocols may be introduced to let nodes have such knowledge to avoid use of the promiscuous mode which may have security concerns.

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