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Delay Variation Optimized Traffic Allocation Based on Network Calculus for Multi-path Routing in Wireless Mesh Networks

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Abstract: This paper studies the traffic allocation in multi-path routing in consideration of the strict requirement for delay variation in the real-time applications. Firstly, the queuing delay is analyzed based on network calculus and the upper bounds of end-to-end delay and its variation in all paths are deduced. Then the transfer rate of data flowing into each path should be used as constraint for satisfying end-to-end delay requirement, and the Maximum Allowed Rate (MAR) for each path is calculated. Based on MAR, a traffic allocation algorithm named as TADVO is proposed for delay variation optimization, in which the traffic is allocated proportional to MAR of each path. Finally, TADVO is integrated into AOMDV. The simulation shows that the new protocol outperforms the other two in terms of delay and delay variation.

Keywords: Wireless mesh network, multi-path routing, traffic allocation, network calculus

Wireless Mesh Network (WMN) is an emerging technology for future broadband wireless access. In the architecture of WMNs, the middle layer is wireless backbone, which consists of mesh routers and gateways. As the communication bridges between the wireless backbone and the Internet, the gateways are always performance bottlenecks [1]. In order to provide the guaranty of the quality of service (QoS) to mesh clients, the performance of wireless backbone is concerned. This paper focuses on the optimization of delay variation in multipath transmission in wireless backbone.

The wireless backbone is similar to an ad hoc network in nature, but with static nodes, no energy constraints, and relative stable topology. Some routing protocols in ad hoc can be used in wireless backbone directly with little modification. However, the performance of these protocols is much worse than what expected. In recent years, a lot of research works have been done with attention to the characteristics of WMNs, and new routing protocols such as [2,3,4,5] are presented. These protocols can be classified into single-path and multipath routing protocols. Single-path routing protocol is simple to implement and easy to manage and configure. However, excessive traffic on a particular path may lead to the formation of "hot spots" of network traffic, resulting in the decrease of network performance and QoS. In multipath routing, multiple paths are established and used to transmit data streams, and network traffic is distributed among multiple paths. Therefore, the throughput and traffic balance on the network can be improved, with lower packet loss rate and end-to-end delay. In general, contrasting to single-path routing, a better QoS can be obtained with the use of multi-path routing [6]. Therefore, the multi-path routing is a better solution for real-time data transmission.

In the research, some researchers have proposed the multi-path routing protocols [3,5] for the WMNs, and the research work mostly focuses on how to discover multiple paths, how to select the transmit paths, and how to mainten the paths. However, the problem of traffic allocation and distribution in multi-path routing should not be ignored, which have an important impact on the QoS.

For real-time applications, the end-to-end delay is strictly constrained. Moreover, when multiple paths are used for data transmission, the variation of end-to-end delay among all paths should satisfy the requirement of

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different applications such as audio, video, and network games.

In this paper, we emphasize on the traffic allocation problem in multi-path routing. We propose the traffic allocation algorithm for delay variation optimization based on network calculus.

1 Related Works

From the above analysis, gateways often become the bottleneck of network performance in WMNs. To improve end-to-end QoS, gateways should distribute the traffic among multiple paths instead of routing all traffic along one path, which can balance the network traffic and efficiently avoid the traffic aggregation in "hot spots". Therefore, multi-path routing in WMNs has become a hot research area [7]. Many multi-path routing protocols are proposed in the past research, and these protocols mainly focus on the mechanism of routing discovery, paths selection, and routing maintenance.

Long Le [8] presented a multi-path routing design for WMNs, and the key idea was a QoS-aware algorithm for multi-path computation that took channel load and interference on wireless links into consideration. Bedi and Gupta [9] proposed a geographic multi-path routing protocol which used virtual coordinate for packet transmission. The hop-count metric in the protocol can recognize congestion and location of its immediate neighbors. Qu, Ren, and Wang [10] proposed a node-disjoint multi-path routing protocol, which was based on AOMDV, and added the routing sequence number, i.e., something like the source routing sequence in DSR. The new multi-path routing algorithm had less computational complexity and routing overhead than AOMDV. Li [11] had studied the cooperation problem among mesh routers in multi-path routing, and proposed a reputation-based system in multi-path routing to stimulate each node in different paths to forward packets from others. Hu and his partners [12] has studied how to maintain forwarding paths in the routing, and proposed a multi-path routing protocol MGMP with multiple gateways supported. Simulation result showed that MGMP outperforms HWMP, AODV, and OLSR.

The previous research work maimly emphasize on the construction of routing paths, the increase of network throughput, and the decrease of routing overhead. However, in real-time applications, we need take the end-to-end delay into consideration. Rong and the co-authors [13] had studied the multi-path routing for video delivery over wireless mesh networks. To meet the strict delay requirements, they developed an optimized algorithm for packet scheduling to shorten packet delay of video communication in multi-path routing. Unfortunately, the delay variation among the multiple paths was not studied in their work. For the end-to-end delay in a single path, the delay variation among the transmission paths has an important impact on QoS in the video systems.

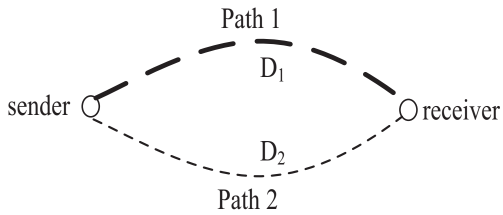

Fig. 1 Traffic Allocation for Two Paths Routing.

In multi-path routing, the traffic allocation algorithm is sensitive to the path delay and its variation, as shown in Fig. 1. In the figure, there are two paths between the sender and receiver, with path 1 having the better transmission capability than path 2. It is assumed that two back-to-back packets travel through path 1 and path 2 from the sender to receiver with the experienced delay as D_1 and D_2, respectively. To real-time applications, the necessary QoS requires that (1) D_1 and D_2 cannot exceed the delay upper bound Δ, and (2) $|D_1 - D_2|$, the variation of D_1 and D_2, should be as small as possible.

Addition to end-to-end bandwidth of two paths, the strategy of traffic allocation is related to D_1 and D_2. Due to less transmission capacity of path 2, a little more traffic assigned to path 2 will result in the sharp increase of D_2. However, path 1 can carry much more traffic than path 2 with little impact on D_1. Therefore, traffic allocation between path 1 and path 2 should be taken into account in two-path routing as shown in Fig. 1.

This paper focuses on the traffic allocation among the multiple routing paths, and proposes the allocation algorithm for the reduction of the delay variation among the paths, while end-to-end delay of each path satisfies the requirement.

2 Problem Description

In multi-path routing, there exist many routing paths between the source and the destination, and the source node should share the forwarding traffic of all paths for parallel transmission. This paper studies the strategy of traffic allocation, taking into account the end-to-end delay of each path and delay variation among all paths.

Definition 1: Delay Constraint

To any packet P_i, if it leaves the source node at the time T_s, and reaches the destination at the time T_r, the transmission delay is $D_i = T_r - T_s$. In real-time system, D_i should be bounded by Δ, which is related to the system.

Definition 2: Delay Variation

Assume that there be m paths between the source and destination, m packets are sent from the source node at the same time through the m paths, respectively, and the transmission delays of each packet are D_1, D_2, ..., and D_m. The delay variation of these m paths is defined as:

$$V_m = \underset{1\le i<j\le m}{MAX} |D_i - D_j|.$$

In video transmission applications, to ensure the clarity of the video image, we should reduce V_m as much as possible, while the transmission delay of each path satisfies the requirement of real-time system.

This paper, by adjusting the allocation scheme of the traffic, optimizes the delay variation V_m, therefore, the problem studied in this paper can be described as a linear programming problem.

$$\begin{aligned} &\min V_m \\ &s.t. \\ &D_i \le \Delta(1 \le i \le m). \end{aligned}$$

It is a NP-Hard problem to get the optimal solution for the above LP problem. In the next section, based on network calculus, a further analysis is carried out on the delay and its variation in multi-path routing, and a traffic allocation algorithm is proposed for reduction of the delay variation among the routing paths.

3 Analysis of Delay and Its Variation

In this section, delay and its variant in multi-path routing are analyzed based on network calculus, and the direction for delay variant optimization is given.

3.1 Network Calculus

Network Calculus (NC) is an efficient framework or theory for performance evaluation of QoS-based queuing networks. The previous work shows that it is a useful tool for the analysis of performance bounds such as delay, jitter, backlog, and so on. Recently, NC is also used for link-layer modeling and TCP performance improvement in wireless network.

In NC, arrival curves and service curves are used to express the properties of network flows, and deduce the performance bounds. In the following paragraphs, the basic knowledge of NC for performance analysis is given. For more detail about NC theory, readers can refer to [14].

In the network, from the viewpoint of QoS, every node should take the control of the input traffic, and provide the QoS with guaranteed service for the input data flows. Similar to the leaky bucket controller shown in Fig. 2, for any time t, the data in the bucket denoted as $x(t)$ should not exceed a constant σ, which is the maximum capacity of the leaky bucket. Therefore, for a given output rate ρ, the input traffic $R(t)$ must be constrained. For any input traffic $R(t)$, if $x(t)$ is always below the maximum capacity σ for any time t, it is considered that R satisfies the controller of (σ, ρ) leaky bucket.

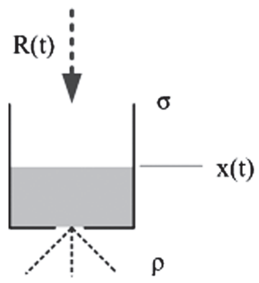

Fig. 2 Leaky Bucket Controller.

Definition 3: Cumulative Function

The cumulative function $R(t)$ is defined as the number of bits on the flow in the time interval $[0,t]$, and $R(0) = 0$. Function R is always wide-sense increasing.

Definition 4: Arrival Curve

Given a wide-sense increasing function α for $t \ge 0$, if a flow R (its cumulative function) satisfies one of two equivalent conditions: (1) $R(t) - R(s) \le \alpha(t-s)$ and (2) $R \le R \otimes \alpha$ for all $s \le t$, it is said that α is the arrival curve of the flow R. In the second condition, $\otimes$ stands for the operation of min-plus convolution.

Definition 5: Min-Plus Convolution

Let f and g be two wide-sense increasing functions. The min-plus convolution between f and g is:

$$(f \otimes g)(t) = \inf_{0\le s\le t} [f(t-s) + g(s)].$$

Theorem 1: If a flow R is under the control of (σ, ρ) leaky bucket, $R(t)$ is constrained by the arrival curve $\alpha(t) = \sigma + \rho t$.

In consideration of QoS, the queuing delay of any packet in a node is limited, and supposed to be bounded by T. That is to say that any packet has the maximum queuing delay of T. To a node, for any time t, it is assumed that the input and output traffic are denoted by $R(t)$ and $R^*(t)$, respectively. For any $s \ge T$, R and R^* must satisfy

$$R^*(s) \ge R(s-T). \quad (1)$$

From the above inequality, we can find that, for a given input function R, the nodes should provide needed processing capacity to ensure that packets queuing delay satisfies the QoS requirement, and the output function R^* is related to the processing capacity of the node. In NC, the processing capacity of a node is expressed as the service curve.

Definition 6: Service Curve

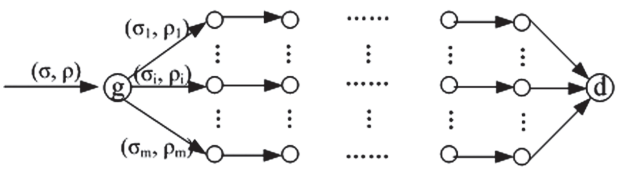

Fig. 3 Multi-path Transmission.

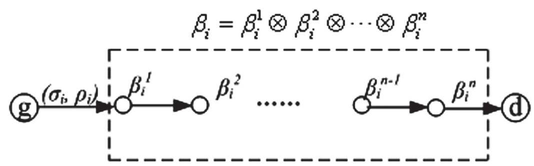

Fig. 4 Concatenation of Service Curves.

To a wide-sense function $\beta(t)$ with $\beta(0) = 0$, considering a system S and a flow through S with the input function R and output function R^*, if the inequality (2) is satisfied, it is said that S offers a service curve β to the flow.

$$R^* \geq R \otimes \beta \tag{2}$$

In a communication network, a flow often goes through many nodes. Therefore, it should be considered that the nodes as a whole provide a service curve for the flow.

Theorem 2: Concatenation of Nodes

Assume a flow $R(t)$ traverse n nodes, which offers the service curves $\beta_1(t)$, $\beta_2(t)$, ..., $\beta_n(t)$, respectively. Then, the path defined by the concatenation of these nodes offers the following service curve β to the flow.

$$\beta = \beta_1 \otimes \beta_2 \otimes \cdots \otimes \beta_n \tag{3}$$

Based on the arrival and service curve, the queuing delay bounded in a node for any packet can be calculated.

Theorem 3: Delay Bound

Assume a flow $R(t)$, constrained by arrival curve $\alpha(t)$, traverse a system S that offers a service curve $\beta(t)$. For any time t, the delay $d(t)$ satisfies the inequality (4), in which the $h(\alpha,\beta)$ is the horizontal deviation between $\alpha(t)$ and $\beta(t)$.

$$\begin{aligned} d(t) &\leq \sup_{t\geq 0}\{\inf\{d \geq 0; \alpha(t) \leq \beta(t+d)\}\} \\ &= h(\alpha,\beta) \end{aligned} \tag{4}$$

3.2 Delay Variation Analysis in Multi-Path Routing

There are multiple paths between the source and the destination in multi-path routing and network traffic is distributed on those paths. The m paths are used to distribute the input flow R between gateway g and mesh router d as shown in Fig. 3, and R is constrained by the arrival curve $\alpha(t) = \sigma + \rho t$, in which σ is the instantaneous burst of traffic, and ρ is the long-term average rate for data transmission.

In multi-path routing, the flow would be divided into m sub-flows with the input functions $R_1(t)$, $R_2(t)$, ..., and $R_m(t)$. For the i^{th} path, the input function is R_i, and

$$R(t) = R_1(t) + R_2(t) + \cdots + R_m(t).$$

In consideration of end-to-end delay, the input function R_i should be constrained. Assume R_i be under the control of leaky bucket (σ_i, ρ_i), that is, the arrival curve of the i^{th} sub-flow of $\alpha_i(t) = \sigma_i + \rho_i t$ and the Equation (5) are satisfied.

$$\begin{cases} \alpha(t) = \alpha_1(t) + \alpha_2(t) + \cdots + \alpha_m(t) \\ \sigma = \sigma_1 + \sigma_2 + \ldots + \sigma_m \\ \rho = \rho_1 + \rho_2 + \ldots + \rho_m \end{cases} \tag{5}$$

Take a path of anyone as an example, based on the status of wireless channel, each node in the path provides the variable capacity of service. As shown in Fig. 4, the nodes in the i^{th} path have the service curves β_i^1, β_i^2, ..., and β_i^n, respectively. Based on the Theorem 2, the path with n nodes as a whole has the service curve $\beta_i = \beta_i^1 \otimes \beta_i^2 \otimes \cdots \otimes \beta_i^n$.

For any node in the network, no matter what scheduling algorithm is adopted, its service curve can be described as rate-delay service curve [14]. Thus, in the i^{th} path, the service curve provided by the j^{th} node can be denoted as Equation (6), in which r_i^j is the long-term average rate of data transmission in the j^{th} node, and T_i^j is the packet delay caused by the node.

$$\beta_i^j(t) = r_i^j\left[t - T_i^j\right]^+ = \begin{cases} r_i^j(t - T_i^j) & \text{if } t > T_i^j \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

From the properties of rate-delay function, the service curve provided by the i^{th} path can be deduced as the following equations:

$$\begin{cases} \beta_i(t) = \beta_i^1 \otimes \beta_i^2 \otimes \cdots \otimes \beta_i^n(t) = r_i[t - T_i]^+ \\ r_i = \min\left\{r_i^1, r_i^2, \cdots, r_i^n\right\} \\ T_i = T_i^1 + T_i^2 + \cdots + T_i^n \end{cases} \tag{7}$$

It is known that a packet delay of a path has relation with the processing capacity of the path, and the higher processing capacity, the less packet delay it has in the path.

A packet delay in the end-to-end transmission includes two parts, i.e., fixed delay and variant delay. A fixed delay includes transmission delay and propagation delay, and a variant delay comes from queuing. To the i^{th} path, assume a fixed delay denoted as f_i, and the variant delay as v_i for any time t, then the delay in the path can be represented by Equation (8).

$$d_i(t) = f_i + v_i(t) \quad (8)$$

In a stable queuing system, the research work in [15, 16] shows that the upper bound of queuing delay must be the maximum busy period. Thus, to the flow R_i constrained by the arrival curve $\alpha_i(t) = \sigma_i + \rho_i t$, the upper bound of queuing delay can be expressed as:

$$\begin{aligned} v_i^{bound} &= \inf\{t \geq 0 : \alpha_i(t) - r_i t \leq 0\} \\ &= \frac{\sigma_i}{r_i - \rho_i}. \end{aligned} \quad (9)$$

Thus, the variant delay in the i^{th} path satisfies the inequality (10),

$$v_i(t) \leq \frac{\sigma_i}{r_i - \rho_i}. \quad (10)$$

In addition, transmission delay and propagation delay in a single hop depend on wireless channel, and are mostly unchanged part. Assume that h_i is the hop count in the i^{th} path, and c is the sum of transmission delay and propagation delay in a single hop, the fixed delay would be

$$f_i = h_i c. \quad (11)$$

Based on (8), (9), (10), and (11), the delay bound D_i in the i^{th} path can be represented by

$$D_i = h_i c + \frac{\sigma_i}{r_i - \rho_i}. \quad (12)$$

For any two paths, the delay variation satisfies the inequality (13):

$$|d_i - d_j| \leq |f_i - f_j| + \max\left(\frac{\sigma_i}{r_i - \rho_i}, \frac{\sigma_j}{r_j - \rho_j}\right) \quad (13)$$

From the definition 2 and the inequality (13), the delay variation upper bound V_m in Fig. 3 should be

$$\begin{aligned} V_m &= \max_{1 \leq i \leq j \leq m} |d_i - d_j| \\ &\leq \max_{1 \leq i,j \leq m and i \neq j} |f_i - f_j| + \max_{1 \leq k \leq m}\left(\frac{\sigma_k}{r_k - \rho_k}\right) \\ &= \max_{1 \leq i,j \leq m and i \neq j} |h_i - h_j| c + \max_{1 \leq k \leq m}\left(\frac{\sigma_k}{r_k - \rho_k}\right). \end{aligned} \quad (14)$$

As shown in inequality (14), the former part of V_m is fixed, and the latter one is variable. Therefore, we should pay attention on the latter part for the decrease of delay variation among these m paths.

4 Traffic Allocation for Delay Variation Optimization

In multi-path routing, for the real-time application, the delay in each path should be less than the maximum allowed delay, and the delay variation among all paths should be as small as possible. To the given maximum allowed delay Δ, the delay in any path should satisfy:

$$h_i c + \frac{\sigma_i}{r_i - \rho_i} \leq \Delta \quad (1 \leq i \leq m). \quad (15)$$

The inequality (15) can be converted to the inequality (16), in which ρ_i is the constrained rate for the input flow, also called the Maximum Allowed Rate (MAR) of the input flow in the path.

$$\rho_i \leq r_i - \frac{\sigma_i}{\Delta - h_i c} \quad (1 \leq i \leq m). \quad (16)$$

As shown inequality (16), the larger of service rate r_i, the larger MAR satisfying the delay requirement is.

Combining (5) and (16), the following inequality is derived.

$$\rho = \sum_{1 \leq i \leq m} \rho_i \leq \sum_{1 \leq i \leq m} r_i - \sum_{1 \leq i \leq m} \frac{\sigma_i}{\Delta - h_i c} \quad (17)$$

Inequality Equation (17) shows that the rate of input flow is constrained by some conditions. If the rate is larger than the given threshold, the excessive amount of packets should be backlogged at some nodes, and the end-to-end delay would fail to satisfy the QoS requirement.

In consideration of QoS in multi-path routing, the delay of each path must satisfy the given requirement. Furthermore, delay variation among all paths has an important impact on the routing performance, and should be optimized as far as possible. Thus, the problem studied in this paper can be converted to the following linear programming problem.

$$\begin{aligned} &\min \max_{1 \leq k \leq m}\left(\frac{\sigma_k}{r_k - \rho_k}\right) \\ &s.t. \\ &\begin{cases} \rho_i \leq r_i - \frac{\sigma_i}{\Delta - h_i c} (1 \leq i \leq m) \\ \rho_1 + \rho_2 + \cdots + \rho_m = \rho \\ \sigma_1 + \sigma_2 + \cdots + \sigma_m = \sigma \end{cases} \end{aligned}$$

4.1 Algorithm Description

Considering the complexity of the mathematic solution, a simple greedy algorithm is proposed to find the efficient solution. For simplicity, we assume that all nodes in a WMN be homogeneous. In detail, all node-to-node links in a path have the same transmission delay and propagation delay with $\sigma_1 = \sigma_2 = \cdots = \sigma_m = \sigma/m$.

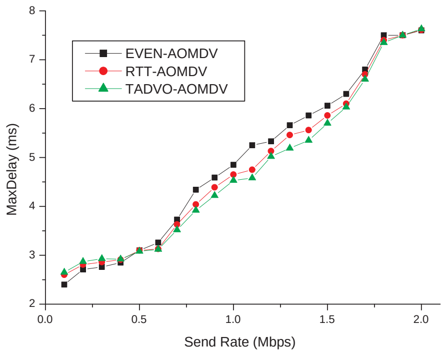

Fig. 5 MaxDelay.

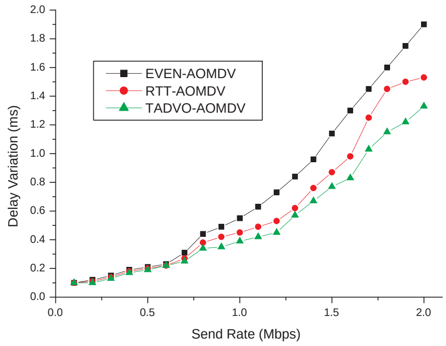

Fig. 6 Delay Variation.

Then, a greedy algorithm TADVO (Traffic Allocation for Delay Variation Optimization) is presented as follows:

Input: ρ, σ, Δ, m, $r_i(1 \leq i \leq m)$
Output: the MARs of all paths $(\rho_1, \rho_2, \ldots\ldots, \rho_m)$
Step 1: Computing the upper bounds of ρ_1, ρ_2, ..., and ρ_m based on the inequality (16), and the results are denoted as B_1, B_2, ..., and B_m, respectively.
Step 2: Computing the initial allocation result $(\rho_1$, ρ_2, ..., $\rho_m)$ based on the Equation (18):

$$\rho_i = \rho \frac{B_i}{\sum\limits_{1 \leq j \leq m} B_j} \quad (1 \leq i \leq m) \tag{18}$$

Step 3: For the current allocation result $(\rho_1$, ρ_2, ..., $\rho_m)$, based on Equation (9), computing the queuing delay upper bounds of all paths.
Step 4: For paths with the minimum and maximum queuing delay upper bounds, their constrained rate is denoted as $\rho_{\max}$ and $\rho_{\min}$ with decreasing $\rho_{\max}$ and increasing $\rho_{\min}$ by a probing value in order to reduce the delay variation among all paths, that is, to minimize $\max_{1 \leq k \leq m}\left(\frac{\sigma_k}{r_k - \rho_k}\right)$.
Step 5: If $\max_{1 \leq k \leq m}\left(\frac{\sigma_k}{r_k - \rho_k}\right)$ is never reduced, the algorithm stops. Otherwise, go to Step (4).

4.2 Algorithm Implementation

TADVO algorithm should be run on the source node, and the needed data and parameters can be collected from routing information. In algorithm implementation, the following methods are used.

(1) The hop count $h_i(1 \leq i \leq m)$ of each path can be obtained from the information of routing protocol.

(2) For the parameter c in inequality (16), an idle path with h hops is used to end-to-end delay measurement. Assume the delay be D_h, then c is near to D_h/h because the queuing delay in an idle path can be negligible.

(3) Each node sets up a timer to estimate the average service rate recently, and the scheme of routing request and reply will tell the source of minimal service rate of the nodes in a given path. From Equation (7), the service rate $r_i(1 \leq i \leq m)$ of each path is the minimal service rate of the nodes in the path. Thus, the approximate service rate of each path can be found out.

(4) To the parameters, ρ can be considered as the long-term average rate of the input flow, and σ is the instantaneous burst of traffic. Both parameters can be obtained through setting up timers for traffic counting in the source node.

Once the source node gets needed data and parameters, TADVO algorithm will be used to calculate the constrained MAR for each path. Then, the source node transmits the packets forward to each path proportional to its MAR. The data collection, parameter generation, and TADVO algorithm will be scheduled periodically for reflecting the new change of network status.

5 Simulations

In the simulation, TADVO algorithm and the related scheme are implemented in the NS-2 [17], and joined with AOMDV routing protocol. The new multi-path routing protocol is called TADVO-AOMDV, which will be in comparison with EVEN-AOMDV and RTT-AOMDV on the performance in terms of delay, delay variation among the paths, and network throughput. EVEN-AOMDV is an AOMDV based multi-path routing with the traffic evenly allocated among the paths, and RTT-AOMDV allocates the traffic in proportion of the Round-Trip Time (RTT) on the paths.

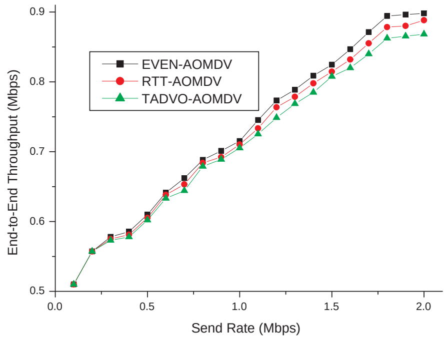

Fig. 7 Network Throughput.

5.1 Simulation Environment

First of all, the WMN with 50 nodes is generated, in which 10 CBR flows are running with the variant rate. Then, TADVO-AOMDV, EVEN-AOMDV and RTT-AOMDV will be employed respectively. Finally, the simulation result will be collected and analyzed for both protocols.

In the simulation, some testing packets are sent for the measurement of end-to-end delay and its variation. In the header of testing packet, a field of "sendTime_" is used to record the start time for the sender. When the destinations receive a testing packet, the end-to-end delay of this packet can be calculated through the arrival time minus the "sendTime_". In this paper, we care the maximum delay of these routing paths. For the measurement of delay variation, some back-to-back packets are delivered through the different routes, and the maximum delay variation of these packets will be obtained at the destination side.

In the NS-2, IEEE 802.11 is used as the MAC and physical layer protocol. The network contains 50 nodes located randomly in the field of 1500m$\times$1500m; the nominal bit rate is 2Mbps; transmission range is 250m; the number of CBR flows is 10; the length of interface queue is set to 50, and the type of queue is CMUPriQueue; the total running time is 100 seconds.

5.2 Simulation Results

Under the different network conditions, the measurement of Maximum Delay (MaxDelay) of the paths and the variation is carried out for the three protocols, respectively, and the result is shown in Figs. 5 and 6.

As shown in Fig. 5, when the network is lightly loaded, due to less complexity, EVEN-AOMDV has the less MaxDelay than RTT-AOMDV and TADVO-AOMDV. However, with the increasing of data transmission rate, TADVO-AOMDV outperforms the other two in the term of MaxDelay. When the sending rate is 1.8Mbps or 2.0 Mbps, the three protocols have almost the same results. In our opinion, when the network is at its maximum capacity at that time, there will be no room for performance optimization.

As far as the delay variation is concerned, TADVO-AOMDV performs better than the other two, as is shown in Fig. 6. The result shows that TADVO algorithm plays an efficient role in traffic allocation.

On the other hand, the traffic allocation algorithm TADVO adds the complexity to TADVO-AOMDV routing protocol, and TADVO-AOMDV has higher overhead than the other two. As shown in Fig. 7, for TADVO-AOMDV, the improvement of the delay and its variation is at the cost of little decrease of throughput.

6 Conclusion

In multi-path routing, traffic allocation scheme among all paths has an important impact on end-to-end delay and its variation. In this paper, based on network calculus, the upper bounds of end-to-end delay and delay variation in all paths are deduced. For end-to-end delay satisfying the requirement and delay variation optimization, the constrained input rate for each path is analyzed, and a traffic allocation TADVO is proposed. The simulation shows that the TADVO-AOMDV outperforms the other two AOMDV based protocols in terms of maximum delay of the multiple paths and delay variation. In short, TADVO is an efficient scheme for delay variation optimization in multi-path routing.

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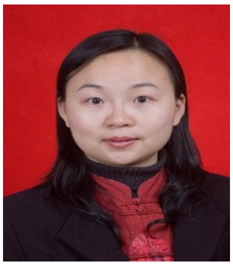

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