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Delay minimisation in multipath routing using intelligent traffic distribution policies

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Abstract: A key component of an efficient multipath routing is the optimal traffic allocation strategy that deals with how the traffic should be distributed among the multiple paths. In this study, two intelligent traffic distribution policies that minimise the experienced delay by the end user are proposed. For such delay minimisation, the authors investigate and compare average delay minimisation and maximum delay minimisation (MDM) over all the paths. It will be shown that MDM is a more efficient strategy for end-to-end delay minimisation. Based on this fact, an intelligent algorithm that can minimise the maximum delay of all paths is proposed using an adaptive traffic sharing scheme.

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1 Introduction

Multipath routing has become a major ingredient for enhancing functionality, performance and flexibility of networks of computational resources. Thanks to its ability to provide load balancing, fault tolerance and higher aggregation of available bandwidth. Although many routing metrics have been proposed as the basis of traffic sharing policy, minimum delay is a suitable metric for most of today's real-time internet applications such as voice over IP and video conferencing. In addition, multipath routing is becoming an essential part of reliable routing protocols in *ad hoc* networks where nodes should fully exploit the rich connectivity of the network to improve the reliability of packet delivery at the destination. A key component of an efficient multipath routing is the optimal resource allocation strategy that deals with how the portions of traffic should be distributed among the multiple paths from one source to a destination. This is why a large amount of research had been conducted on devise efficient traffic allocation strategy for obtaining better quality of service (QoS). In [1], a distributed computation framework for multipath routing that specifies the fraction of traffic for each link based on the observed delay of the link has been proposed. The algorithm is applied independently at each node and successively updates the routing table at that node based on information communicated between adjacent nodes about the marginal delay to each destination. In [2] a near optimal routing algorithm is proposed which establishes multiple loop free paths using long-term end-to-end delay information using short-term local delay information. Multipath routing algorithms that optimally split the traffic between a given set of paths have been also studied in the context of flow control and intelligent traffic allocation. In [3] the problem of congestion-aware multipath routing in the internet has been considered. Using minimal congestion feedback signals from the routers, a class of algorithms have been implemented at the sources to stably and optimally split the flow between each source–destination pair. In addition, the congestion of the most utilised link in multipath routing has been minimised in [4], however, they did not consider the quality of the selected paths. The study in [5] also considered multipath routing as an optimisation problem with an objective function that minimises the congestion of the most utilised link in the network; however, they did not consider the quality of the selected paths. The study in [6] investigates multipath routing in wireless networks using simulation and based on the assumptions that the packet delays along all used paths between source and destination are the same and the delay along used paths is smaller than or equal to the delays along unused paths. Gill *et al.* [7] have shown that the optimal routing problems for unicast, multiple unicasts and multicast can all be formulated as convex optimisation problems. As a proof of concept, mathematical programs that compute optimal routes for network flows in the network of the queues based on minimising average delay for the flows have been developed in the paper. Although the paper provided a model for minimising average delay, the analytical solution for the delay minimisation has not been presented and the result has been obtained through simulations. In [8] a solution for the average delay minimisation (ADM) of [7] in the heterogeneous network of computational resources that follow M/M/1 queuing model [9] has been proposed. Nevertheless, the proposed solution is dependent on the parameter ϕ_0 which takes a long computational time to be numerically calculated.

Despite all the above efforts, to the best of our knowledge there is a lack of analytical analysis of the issue of delay minimisation in multipath routing. The most closely related work in this area is the work in [7, 8] which have addressed the issue of ADM. However, the authors in [7] have formulated the problem that there is no closed-form analytical solution for route selection and traffic allocation given in the paper. Furthermore, the solution in [8] is dependent on the parameter that needs to be calculated through long numerical simulation. As in the real network the traffic is changing over the time, and the traffic distribution for the path needs to be obtained through a faster algorithm. In addition, no other related work has taken into account the issue of bottleneck path delay minimisation. Thus further research should be needed to provide delay minimisation in multipath routing for enhancing the QoS performance of the real time and multimedia streaming application through delay minimisation. In this paper, we will address this issue through the following strategies:

1. ADM of the data packets sent over the available paths.
2. Maximum delay minimisation (MDM) of the data packets sent over the available path.

Similar to assumptions made in [8], to perform the above studies, we first model the delay of a disjoint multipath network with several resources and service characteristics that follow the M/M/1 queuing model [9]. We should note that this model has been widely used for modelling delay in scenarios where the processing delay is a dominant factor compared to the propagation delay. Based on the derived delay model, the paper proposes two different traffic allocation strategies to achieve the ADM and MDM targets. Then it will be shown that MDM (i.e. bottleneck path delay minimisation) is a more efficient strategy for end-to-end delay minimisation. It will be then proved MDM can be achieved through delay synchronisation. Based on this fact, an adaptive algorithm called synchronised traffic distribution policy (SynDTC) is proposed and validated.

The organisation of the rest of this paper is as follows: in Section 2, we model the delay characteristics of a disjoint multipath network. Sections 3 and 4 calculate and compare the traffic distribution policies that minimise the average delay and maximum delay, respectively. In Section 5, the details of synchronised delay traffic controller (SynDTC) will be studied and validated. Finally Section 6 concludes the paper and outlines the future potential improvement works in this area.

2 Network model

In order to obtain the solution for ADM and MDM policies, let us characterise the disjoint multipath network as follows:

1. The heterogeneous network with n disjoint path resources is characterised by the set of values $\boldsymbol{\mu} = (\mu_1, \mu_2, \mu_3, \ldots, \mu_i, \ldots, \mu_n)$ for the individual resources. A resource could be the data transmission capacity of the given communication channel (e.g. in bits/s).
2. The set $\boldsymbol{\lambda} = (\lambda_1, \lambda_2, \lambda_3, \ldots, \lambda_i, \ldots, \lambda_n)$ represents the distribution of the load across the set of the resources $\boldsymbol{\mu}$ and the total traffic sent from the source is $\lambda = \sum_{i=1}^{n} \lambda_i$.
3. The set $\boldsymbol{D} = (D_1, D_2, D_3, \ldots, D_i, \ldots, D_n)$ represents the delay values experienced on each of the n paths when the distribution of the traffic along the paths is $\boldsymbol{\lambda}$, and the distribution of the resources along the paths is $\boldsymbol{\mu}$. We should note that if a particular path has the form of M/M/1 delay function characteristic, then D_i can be calculated as follows

$$D_i = \frac{1}{\mu_i - \lambda_i} \tag{1}$$

4. The set $\boldsymbol{P} = (P_1, P_2, \ldots, P_i, \ldots, P_n)$ represents the proportion of traffic shares on each of the n paths assuming the total traffic sent from the source is λ. The traffic share of particular path i (P_i) can be calculated as below

$$P_i = \frac{\lambda_i}{\lambda} \tag{2}$$

3 Average delay minimisation

Our objective in this section is to find the set of traffic load proportion $\boldsymbol{P}^{\mathbf{ADM}} = (P_1^{\mathrm{ADM}}, P_2^{\mathrm{ADM}}, P_3^{\mathrm{ADM}}, \ldots, P_i^{\mathrm{ADM}}, \ldots, P_n^{\mathrm{ADM}})$ and its corresponding set of delay $\boldsymbol{D}^{\mathbf{ADM}} = (D_1^{\mathrm{ADM}}, D_2^{\mathrm{ADM}}, D_3^{\mathrm{ADM}}, \ldots, D_i^{\mathrm{ADM}}, \ldots, D_n^{\mathrm{ADM}})$ to minimise the average delay. Using (1) and (2), the corresponding value of the average or expected delay ($E[D]$) is obtained as follows

$$E[D] = \sum_{i=1}^{n} P_i D_i \tag{3}$$

Our objective in ADM is to minimise the $E[D]$ in (3) subject to the $\sum_{i=1}^{n} P_i = 1$. To this aim, let us define D_ϕ as follows

$$\begin{aligned} D_\phi &= \sum_{i=1}^{n} P_i^{\mathrm{ADM}} D_i^{\mathrm{ADM}} - \phi\left(\sum_{i=1}^{n} P_i^{\mathrm{ADM}} - 1\right) \\ &= \sum_{i=1}^{n} \frac{P_i^{\mathrm{ADM}}}{\mu_i - P_i^{\mathrm{ADM}}\lambda} - \phi\left(\sum_{i=1}^{n} P_i^{\mathrm{ADM}} - 1\right) \end{aligned} \tag{4}$$

where ϕ is Lagrange multiplier. To find the $\boldsymbol{P}^{\mathbf{ADM}}$, the conditions given in both (5) and (6) must be satisfied for all the paths

$$\frac{\partial D_\phi}{\partial P_i^{\mathrm{ADM}}} = \frac{1}{\mu_i - \lambda P_i^{\mathrm{ADM}}} + \frac{\lambda P_i^{\mathrm{ADM}}}{(\mu_i - \lambda P_i^{\mathrm{ADM}})^2} - \phi = 0, \quad \forall 1 \le i \le n \tag{5}$$

$$\frac{\partial D_\phi}{\partial \phi} = \sum_{i=1}^{n} P_i^{\mathrm{ADM}} - 1 = 0 \tag{6}$$

To solve this system of equations, let us rewrite (5) as below

$$\frac{\mu_i - \lambda P_i^{\mathrm{ADM}} + \lambda P_i^{\mathrm{ADM}}}{(\mu_i - \lambda P_i^{\mathrm{ADM}})^2} = \phi, \quad \forall 1 \le i \le n \tag{7}$$

Therefore we have

$$\mu_i - \lambda P_i^{\mathrm{ADM}} = \sqrt{\frac{\mu_i}{\phi}}, \quad \forall 1 \le i \le n \tag{8}$$

By summing up (8) for all values of i, we have

$$\sum_{i=1}^{n} \left((\mu_i - \lambda P_i^{\mathrm{ADM}}) = \sum_{i=1}^{n} \left(\sqrt{\frac{\mu_i}{\phi}} \right) \right) \tag{9}$$

or

$$\sum_{i=1}^{n} \mu_i - \lambda \sum_{i=1}^{n} P_i^{\mathrm{ADM}} = \frac{1}{\sqrt{\phi}} \sum_{i=1}^{n} \sqrt{\mu_i} \tag{10}$$

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Considering the constraint $\sum_{i=1}^{n} P_i^{\mathrm{ADM}} = 1$ from (6) and given that $\mu = \sum_{i=1}^{n} \mu_i$, ϕ can be calculated as

$$\sqrt{\phi} = \frac{\sum_{i=1}^{n} \sqrt{\mu_i}}{\mu - \lambda} \tag{11}$$

By substituting the value of $\sqrt{\phi}$ from (11) into (8), P_i^{ADM} can be calculated as follows

$$\begin{aligned} P_i^{\mathrm{ADM}} &= \frac{1}{\lambda}\left(\mu_i - \frac{\sqrt{\mu_i}(\mu - \lambda)}{\sum_{j=1}^{n} \sqrt{\mu_j}}\right) \\ &= \frac{1}{\lambda}\left(\mu_i - \frac{\sqrt{\mu_i}(\sum_{j=1}^{n} \mu_j - \lambda)}{\sum_{j=1}^{n} \mu_j}\right) \end{aligned} \tag{12}$$

Finally using (12) the traffic distribution under ADM policy can be solved as follows

$$\lambda_i^{\mathrm{ADM}} = \left(\mu_i - \frac{\sqrt{\mu_i}(\sum_{j=1}^{n} \mu_j - \lambda)}{\sum_{j=1}^{n} \sqrt{\mu_j}}\right) \tag{13}$$

We should note that the solution to the above equation is valid if $\lambda_i^{\mathrm{ADM}} \geq 0$. In practice, this means that only paths that satisfy the following inequality should be selected for traffic allocation (i.e. the rest of paths should be evicted from the list of paths to be used by ADM)

$$\mu_i \geq \left[\frac{(\sum_{j=1}^{n} \mu_j - \lambda)}{\sum_{j=1}^{n} \sqrt{\mu_j}}\right]^2 \tag{14}$$

Therefore ADM provides two stages for average delay minimisation. At first stage, it selects the paths with enough resources to satisfy the above inequality (Path Selection). Then, it allocates traffic among chosen paths in order to minimise the average delay over them (Traffic Allocation).

Having found the P_i^{ADM} and λ_i^{ADM} using (1) and (13), the value of delay for each path under ADM policy can be calculated as

$$D_i^{\mathrm{ADM}} = \frac{\sum_{j=1}^{n} \sqrt{\mu_j}}{\sqrt{\mu_i}(\mu - \lambda)} = \frac{\sum_{j=1}^{n} \sqrt{\mu_j}}{\sqrt{\mu_i}(\sum_{j=1}^{n} - \lambda)} \tag{15}$$

3.1 Discussion

Although the ADM scheme gives us the minimum average delay in multipath routing, it is important to note that the experienced delay by the user is the maximum delay of all the paths in (15). This is because the end-to-end delay experienced by the user is measured from the time the packet leaves the source to the time when all the fragments from different routes arrive at the destination. Hence, the experienced delay specified by the path with the minimum resources (and therefore the highest delay) can be calculated as follows

$$\mathrm{Delay}_{\mathrm{E2E}}^{\mathrm{ADM}} = \mathrm{Max}[D_i^{\mathrm{ADM}}] = \frac{\sum_{j=1}^{n} \sqrt{\mu_j}}{\sqrt{\mu_i^{\min}}(\mu - \lambda)}, \quad \forall i,\ 1 \leq i \leq n \tag{16}$$

where $\mu_i^{\min}$ represents the path with minimum resources. In the following section, MDM will be introduced to minimise the maximum delay of the paths.

4 Maximum delay minimisation

The second strategy for delay minimisation is to minimise the maximum delay of data over different paths from a source to a destination. One heuristic approach to achieve this target is to divert the traffic from the path with the least resource (and therefore the highest delay) to the other paths. By using this policy continuously, the delay of other paths will increase and the delay of the worst paths will decrease until they become equal. Based on the above explanation, it is natural that minimisation of the maximum delay can be achieved through 'delay synchronisation' where the objective is to minimise the $\sigma_D^2 = (\sum_{i=1}^{n} (D_i - \bar{D})^2/n)$ for all the n paths.

Therefore with the assumption that D_i^{MDM} has the form of M/M/1 and it has to be equal for all the paths, we have

$$D_i^{\mathrm{MDM}} = \frac{1}{\mu_i - \lambda_i^{\mathrm{MDM}}} = \frac{1}{\mu_j - \lambda_j^{\mathrm{MDM}}} = c, \quad \forall i, j \tag{17}$$

where c is a constant and the value of λ_i^{MDM} can be obtained by solving the above equation

$$\lambda_i^{\mathrm{MDM}} = \mu_i - \frac{\mu - \lambda}{n} \tag{18}$$

where $\mu = \sum_{i=1}^{n} \lambda_i^{\mathrm{MDM}}$ and $\lambda = \sum_{i=1}^{n} \lambda_i^{\mathrm{MDM}}$. We should note that the solution to the above equation is valid if $\lambda_i^{\mathrm{MDM}} \geq 0$. Similar to ADM, this in practice means that only paths that satisfy the following inequality should be selected for traffic allocation (i.e. the rest of paths should be evicted from the list of paths to be used by MDM)

$$\mu_i \geq \frac{\mu - \lambda}{n} \tag{19}$$

Therefore similar to ADM, MDM also consists of Path Selection and Traffic Allocation policies.

Using (1) and (17), the delay obtained from MDM (i.e. D_i^{MDM}), can be obtained as follows

$$D_i^{\mathrm{MDM}} = \frac{1}{\mu_i - \lambda_i^{\mathrm{MDM}}} = \frac{n}{(\mu - \lambda)}, \quad \forall i \tag{20}$$

We should note that similar to discussion given in Section 2, the end-to-end delay experienced by the user in MDM scenario is $\mathrm{Max}[D_i^{\mathrm{MDM}}]$. As the delay for all the paths is equal in this policy, the end-to-end delay experienced by the user ($\mathrm{Delay}_{\mathrm{E2E}}^{\mathrm{MDM}}$) can be calculated as follows

$$\mathrm{Delay}_{\mathrm{E2E}}^{\mathrm{MDM}} = \mathrm{Max}[D_i^{\mathrm{MDM}}] = \frac{n}{\mu - \lambda}, \quad \forall i,\ 1 \leq i \leq n \tag{21}$$

The comparison of (16) and (21) shows that $\mathrm{Delay}_{\mathrm{E2E}}^{\mathrm{ADM}} \geq \mathrm{Delay}_{\mathrm{E2E}}^{\mathrm{MDM}}$ since $\sum_{j=1}^{n} \sqrt{\mu_j} \geq n\sqrt{\mu_i^{\min}}$. Therefore the maximisation of the minimum delay (MDM) policy achieved through the delay synchronisation is the key policy in order to minimise the experienced delay by the end user.

Fig. 1 illustrates the accuracy of the above finding for a random network of $N = 10^4$ resources which are uniformly distributed in the interval [0, 1]. As it can be seen in this figure, for different values of traffic, the end-to-end delay of MDM policy is always less than the end-to-end delay value of the ADM policy.

Furthermore, Fig. 2 compares the average delay obtained from the ADM and MDM policies. As it can be observed,

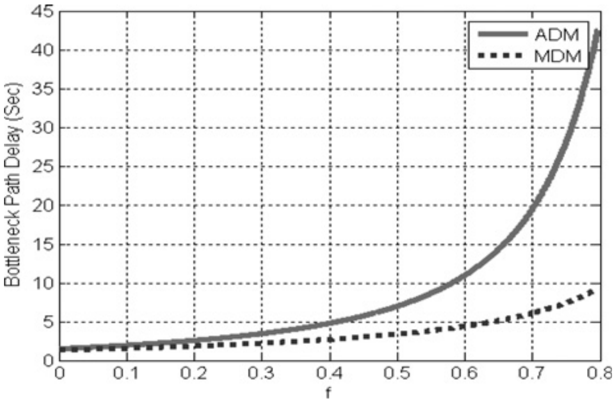

Fig. 1 *Comparison of MDM and ADM policies in a heterogeneous network of N = 10 000 nodes with uniformly distributed resources*

End-to-end delay (bottleneck path delay) is depicted as a function of $f = \lambda/\mu$, the ratio of total traffic to total computational resource

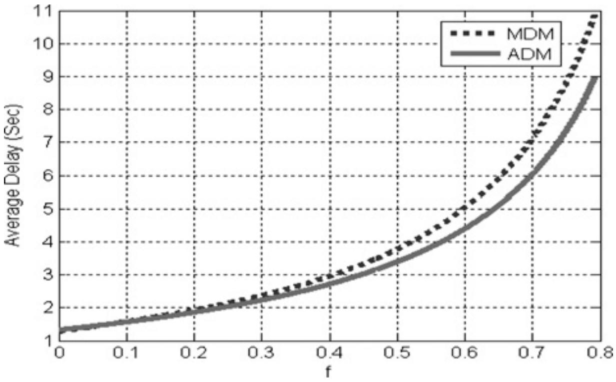

Fig. 2 *Comparison of MDM and ADM policies in a heterogeneous network of N = 10 000 nodes with uniformly distributed resources*

Average delay is depicted as a function of $f = \lambda/\mu$

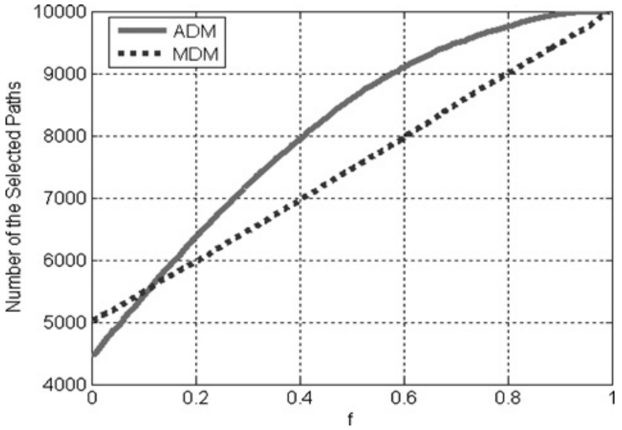

Fig. 3 *Comparison of MDM and ADM policies in a heterogeneous network of N = 10 000 nodes with uniformly distributed resources*

Number of the selected paths is depicted as a function of $f = \lambda/\mu$

the average delay for all the selected paths obtained from MDM policy is close to the corresponding delay obtained from ADM policy. This shows that the MDM policy that aims to minimise the delay of the bottleneck path can also achieve an average delay close to the theoretical bound obtained from ADM policy. Finally, Fig. 3 illustrates the Path Selection stage of ADM and MDM described in Sections 3 and 4, respectively. As it can be seen, in low saturated network nearly half of the paths with lowest resources will not be selected for traffic allocation. However, as the network becomes saturated, the number of selected paths for traffic allocation will increase to utilise all the available network resources.

5 Synchronised delay traffic controller

In previous section, we showed that delay synchronisation is the key element in minimising end-to-end delay in multipath routing. Based on this result, the following traffic distribution and its end-to-end delay were derived

$$\begin{cases} \lambda_i^{\text{syn}} = \mu_i - \dfrac{\sum_{j=1}^{n}\mu_j - \lambda}{n} \\ \text{Delay}_{\text{E2E}}^{\text{syn}} = \text{Max}[D_i^{\text{syn}}] = \dfrac{n}{\mu - \lambda} \end{cases} \tag{22}$$

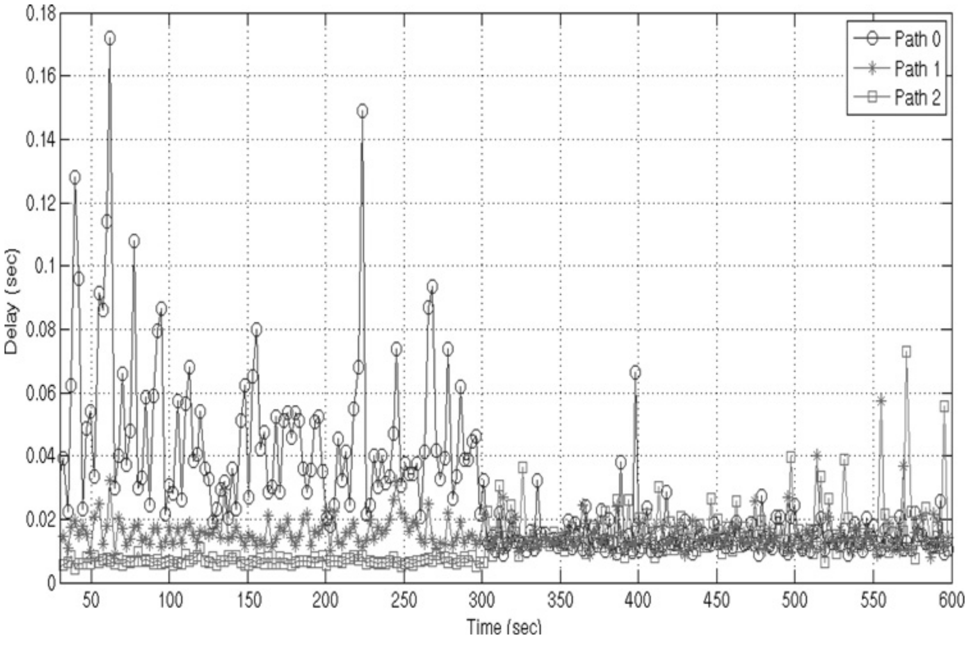

Fig. 4 *Observed delay at sink before and after using SynDTC in a M/M/1-based network*

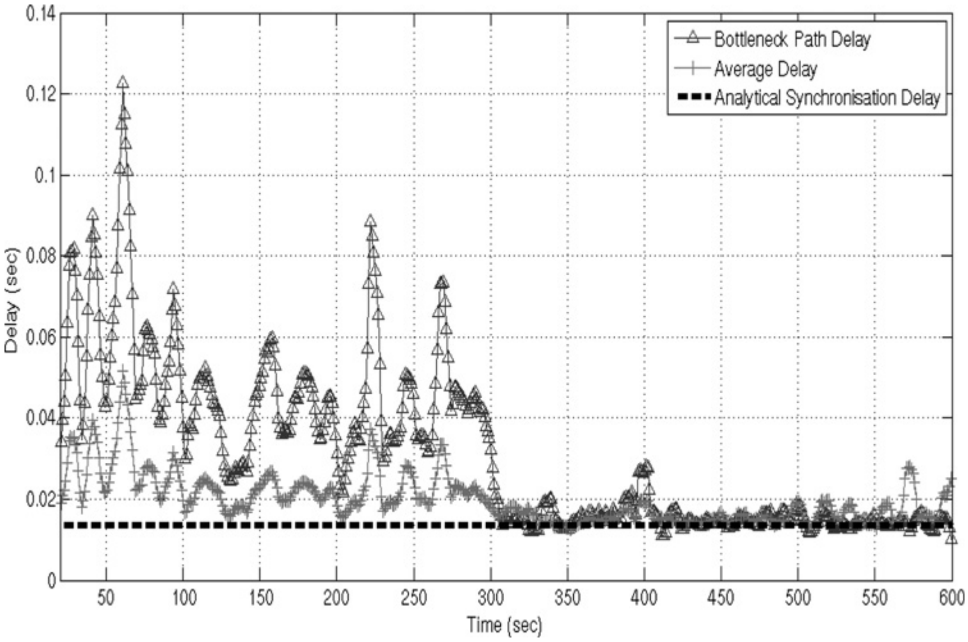

Fig. 5 *Comparison of average delay, bottleneck path delay and analytical value of synchronised delay before and after using SynDTC in a M/M/1-based network*

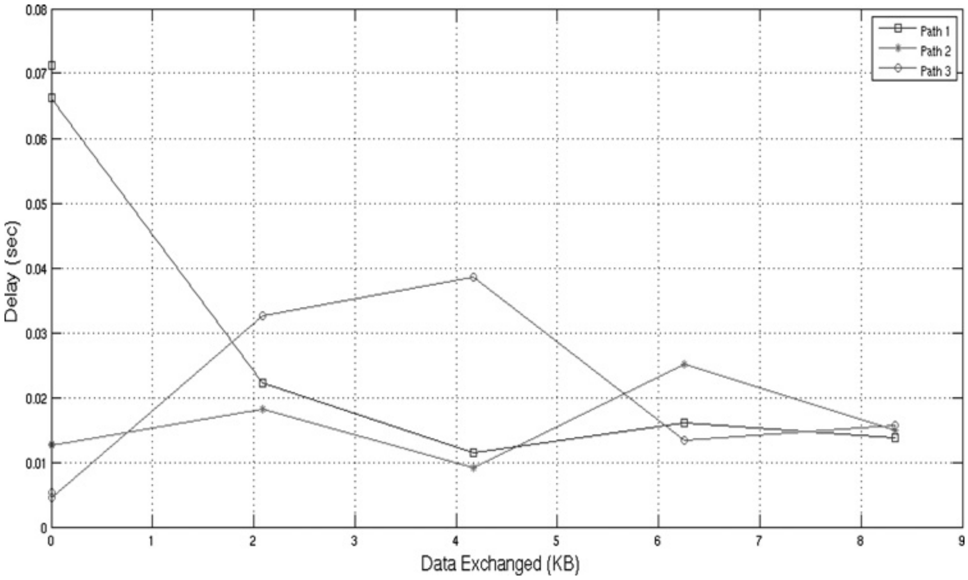

Fig. 6 *Convergence speed of SynDTC in delay synchronisation*

In this section, we propose an adaptive algorithm called SynDTC which can be used in multipath routing to achieve delay synchronisation and therefore minimise observed delay at the receiver.

The main idea behind SynDTC is to estimate the resources on each path based on the observed delay at the receiver and adjust the traffic on each path using (22). In particular, by assuming that there exist n paths the SynDTC has the following stages:

1. *Initial stage:* At the first step the traffic distribution will be set equally for all the paths and the resource will be estimated based on the observed delay at the receiver.
2. *Path selection stage:* The suitable paths for traffic allocation will be selected according to (19).
3. *Traffic allocation stage:* The traffic will be allocated to each selected path based on (22) to synchronise the delay of the path.

To evaluate and analyse the performance of SynDTC, we define a network of three parallel paths with different delay characteristics between a single source and a destination using OPNET simulator. To model the delay characteristic of each path, we first use M/M/1 queues with the processing rates of $\mu_1 = 75\,00$ bits/s, $\mu_2 = 9600$ bits/s and $\mu_3 = 14\,000$ bits/s, for paths 1, 2 and 3, respectively. The traffic rate at the source is set to $\lambda = 20$ Kb/s with Poisson characteristics. At time 300 s, SynDTC is applied to the system by averaging the delay of every 1000 packets at the sink node and estimating the resources of each path.

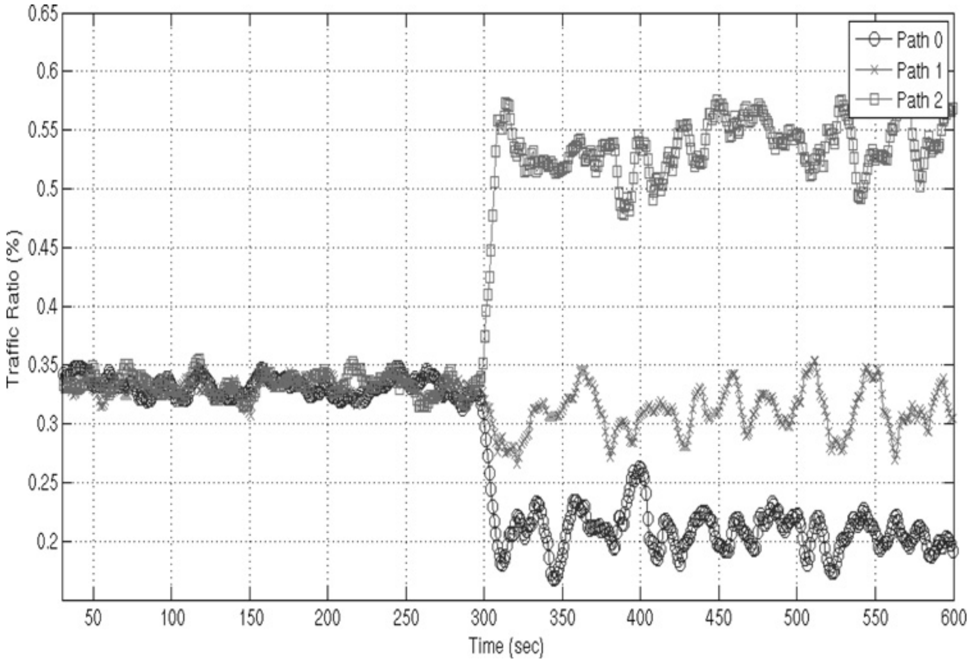

Fig. 7 *Traffic ratio of each path before and after SynDTC in a M/M/1-based network*

The sink then propagates back the estimated resources of each path to the source. Finally, the source sets the proportion of the traffic for each individual path according to the estimated resource received from the sink.

The result depicted in Figs. 4 and 5 clearly shows that after applying SynDTC at time 300 s, the delay observed from different paths become synchronised and converge to the delay given in (20).

Furthermore, Fig. 5 shows an important consequence of using SynDTC which is the elimination of the impact of bottleneck path delay in a multipath route network. In addition, the average delay of the network is reduced substantially when the delays of all the paths get synchronised by using SynDTC.

Fig. 6 depicts the convergence speed of SynDTC (i.e. the amount of packet exchange required before delay synchronisation is reached in SynDTC). It is interesting to note that the SynDTC is fairly quick in estimating the path resources and setting their traffic accordingly. This can be especially important for short life applications that do not last long and still can benefit from the algorithm.

To further show the underlying operation of SynDTC, Fig. 7 shows the traffic ratio of the traffic sent on each path before and after applying SynDTC. The figure illustrates how SynDTC intelligently adjusts the traffic ratio of each path according to its available resources.

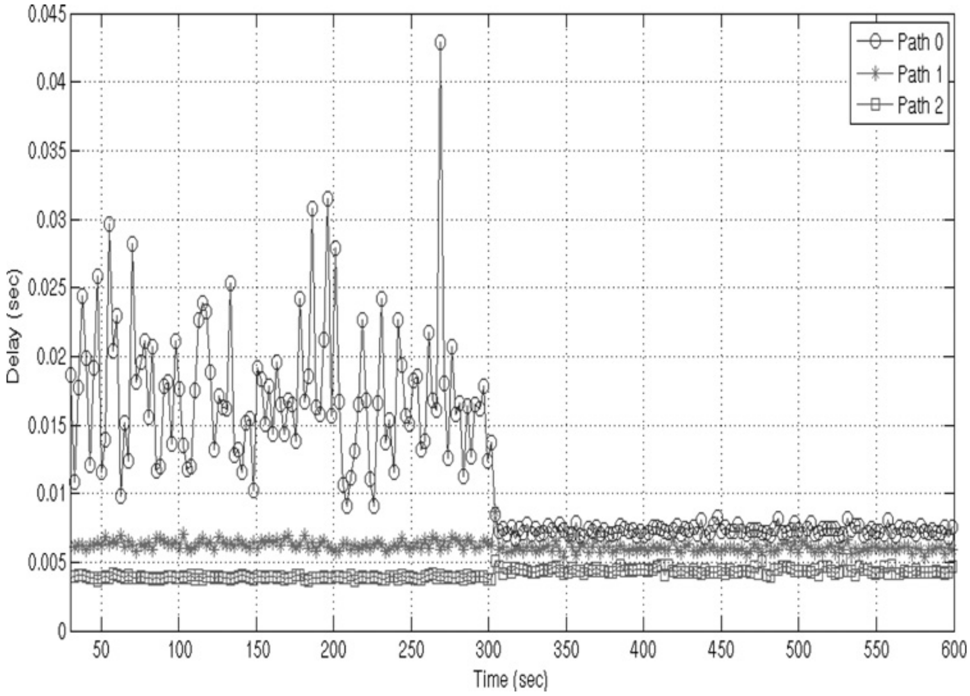

Fig. 8 *Observed delay at sink before and after using SynDTC in a non-M/M/1-based network*

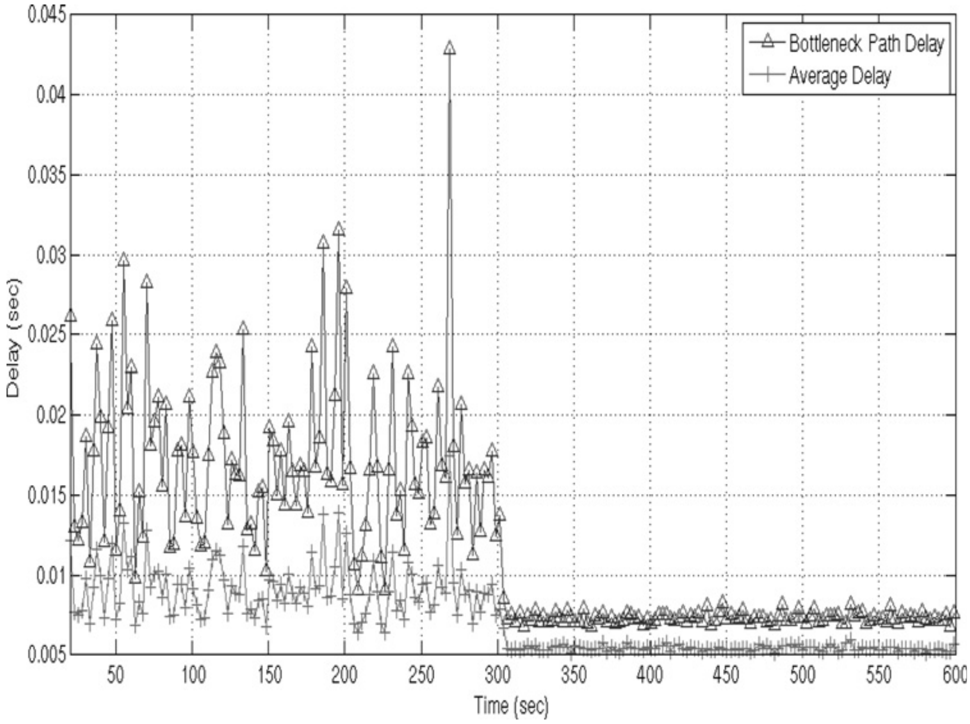

Fig. 9 *Average delay and bottleneck path delay before and after SynDTC in a non-M/M/1-based network*

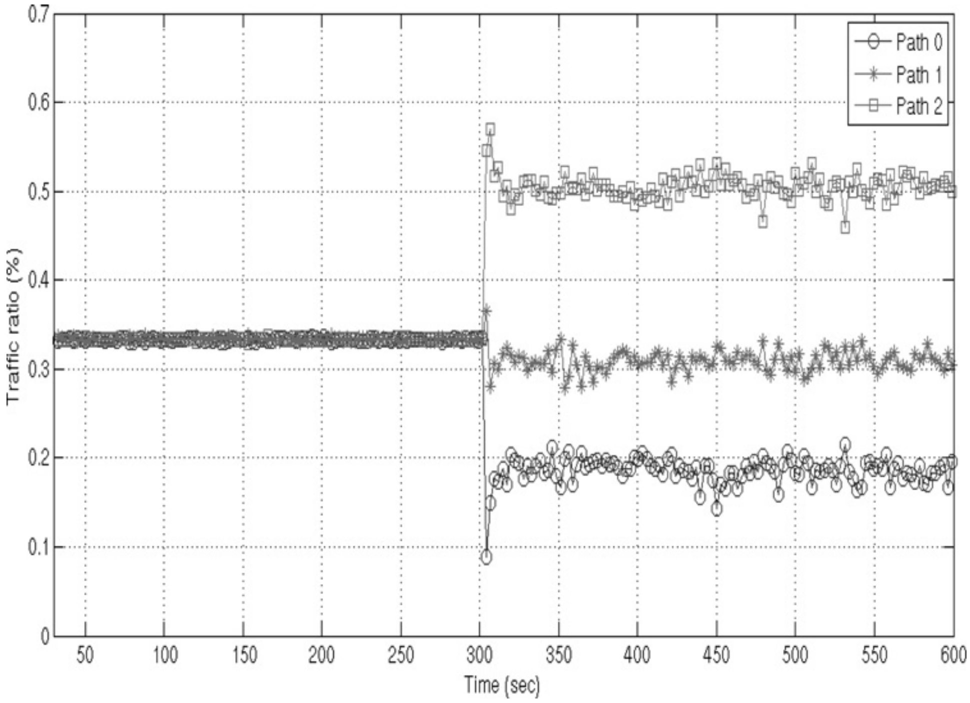

Fig. 10 *Traffic ratio of each path before and after SynDTC in a non-M/M/1-based network*

In the next set of simulations, SynDTC is deployed in a more generic scenario where the traffic and delay characteristic of the network follows a lognormal distribution that matches the delay and traffic in the internet [10].

The results given in Figs. 8–10 show that the SynDTC performs well even if the network resources do not follow the M/M/1 queuing characteristics. However, we should note that due to non-M/M/1 characteristic of the delay in the LogNormal traffic, it is not feasible to analytically calculate the value of synchronised delay.

6 Conclusion

This paper for the first time investigated the issue of delay minimisation through MDM and ADM in multipath routing by developing a closed-form theoretical framework. Using this analytical model, intelligent path selection and traffic distribution policies were proposed to achieve ADM and MDM. It was discussed that MDM is more important strategy for end-to-end delay minimisation as such scheme minimises the delay of the bottleneck path while keeping the average delay close to the theoretical bound obtained in the paper. Furthermore, it was proved that MDM can be achieved through delay synchronisation. Based on these facts, SynDTC was proposed to achieve delay synchronisation through an adaptive traffic distribution scheme. Although SynDTC showed to be an efficient way of providing synchronisation, it is only one of many possible implementations of the delay synchronisation. In future, we plan to investigate algorithms that can provide delay synchronisation for services that require shorter convergence time.

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