

# Local Routing with Simultaneous Transmission Attempts to Several Adjacent Nodes

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## Abstract

*This study introduces an efficient algorithm for local packet routing using two-hop splitting of packet flows within a narrow (one hop away) routing corridor along a global end-to-end routing path. The main concept of the proposed algorithm is based on an attempt for simultaneous transmission of same packet from a local relaying node to two (or more) first neighbors within the routing corridor, which are connected to the global path to be followed by the packet flow. The transmission attempt is terminated as soon as the packet is successfully transmitted to one of the said first neighbors. Therefore, the fastest transmission at an instant of time allows one to speed up the local packet relaying.*

**Keywords:** Local routing, simultaneous transmission, adjacent nodes.

## Introduction

A wireless channel can be viewed as a black box with a multitude of uncertainties affecting the packet flow. Packets often follow a global path which usually has a minimal number of routing steps (hops), also called the shortest path. In mobile ad-hoc networks (MANET), due to rapid changes in topology and dynamic signal-to-noise ratio (SNR), it is not guaranteed that a shortest path will have a low latency continuously in all intermediate links. The shortest path that has been chosen initially may become the nosiest one in some links at certain time instants. Therefore, the research in local routing is not primarily based on the improvement of the global path but rather on the selection of alternative local paths for rerouting due to temporary link failures.

The problem statement of this study is to modify and improve an existing two-hop local routing approach (Batovski 2009) in ad-hoc networks. The main idea is to control the local routing along the global path by making instantaneous decisions at the relaying local node if the latency of the default link is increased temporarily.

The proposed algorithm requires each packet to be sent simultaneously to two (or more) adjacent nodes and the new local route to be chosen on the basis of the fastest transmission. The objective is to avoid packet loss, increased congestion and latency by offering the relaying local nodes more virtual channels for the implementation of local routing at the intermediate nodes. The new algorithm should be able to decrease the local two-hop delays along the global path from source to destination. Arbitrary SNR and mobility conditions can be represented statistically in the form of service time distributions at the wireless output ports. The performance evaluation then can be done by comparing the plain scheme of single path routing with the proposed algorithm for two-hop splitting which should result in reduced local delay. The initial concept of simultaneous transmission of a packet to two (or more) adjacent nodes comes from an analogy with satellite communications (Maral and Bousquet 1998) where two reference bursts (RBs) in a frame to two ground stations are used. However, this concept is extended in this study to the simultaneous transmission of same packet to two (or more) adjacent nodes.

### Theoretical Results

#### Traffic Splitting for a Single Hop with Two Output Ports

Consider two discrete service time distributions,  $T_1 = \{f_{i,T1}, t_i\}$  and  $T_2 = \{f_{i,T2}, t_i\}$ ,  $i = 1, 2, \dots, N$ , describing the transmission delays to two alternative adjacent neighbors from a statistical point of view, where  $t_i < t_j$  for  $i < j$ . Assume that the transmission approach is to send a packet to one of the two nodes having the fastest instantaneous response (shortest time). A comparison of the mean value and standard deviation (SD) of the initial distributions with the mean value and standard deviation of the resultant distributions is necessary for the evaluation of the proposed scheme.

**Theorem 1:** The resultant distributions  $R_1 = \{r_i, T_1, t_i\}$  and  $R_2 = \{r_i, T_2, t_i\}$  for two transmission links activated simultaneously are given by the formulae:

$$r_{i,T1} = \frac{f_{i,T1}[\frac{1}{2}f_{i,T2} + \sum_{j=i+1}^N f_{j,T2}]}{\sum_{j=1}^N r_{j,T1}}, i = 1, 2, \dots, N, \tag{1}$$

and

$$r_{i,T2} = \frac{f_{i,T2}[\frac{1}{2}f_{i,T1} + \sum_{j=i+1}^N f_{j,T1}]}{\sum_{j=1}^N r_{j,T2}}, i = 1, 2, \dots, N. \tag{2}$$

**Proof:** It is assumed that the initial service distributions are known on the basis of statistical accumulation of data over a certain period of time. A packet is sent through the faster link at a given time instant and the transmission through the slower link is terminated after the packet is successfully transmitted over the said faster link.

Therefore, for a given index  $i$  representing the transmission time over the faster link, the sums over all possible known

combinations are  $f_{i,T1} \sum_{j=i+1}^N f_{j,T2}$  and

$f_{i,T2} \sum_{j=i+1}^N f_{j,T1}$  for each link, correspondingly.

The illustration in Fig. 1 shows the underlying logic being used in the proof of Theorem 1.

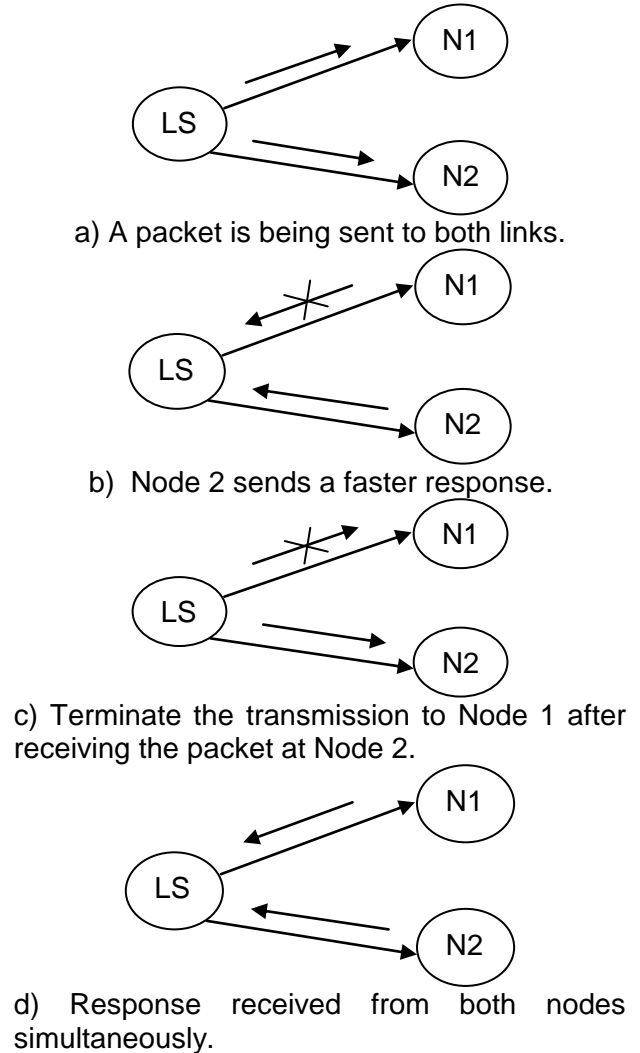


Fig. 1. Illustration of the proof of Theorem 1.

The illustration in Fig. 1 shows the private case when the relaying local source (LS) node receives a faster response from node N2. When the local source node completes the transmission to node N2, it cancels the transmission to node N1. Similarly, one can redraw the above scenario for the case of a faster transmission to node N1.

In the private case, when the same transmission times occur for both links as shown in Fig. 1(d), the link used to transmit the packet is chosen by throwing a fair coin

resulting in the additional terms  $\frac{1}{2} f_{i,T1} f_{i,T2}$  and  $\frac{1}{2} f_{i,T2} f_{i,T1}$  for each link, correspondingly.

The combination of both terms results in the following expressions for the two resultant distributions:

$$r_{i,T1} = f_{i,T1} \left[ \frac{1}{2} f_{i,T2} + \sum_{j=i+1}^N f_{j,T2} \right], i = 1, 2, \dots, N, \tag{3}$$

and

$$r_{i,T2} = f_{i,T2} \left[ \frac{1}{2} f_{i,T1} + \sum_{j=i+1}^N f_{j,T1} \right], i = 1, 2, \dots, N. \tag{4}$$

After normalization to unity by dividing Eqs. (3) and (4) by  $\sum_{j=1}^N r_{j,T1}$  and  $\sum_{j=1}^N r_{j,T2}$ , correspondingly, Eqs. (1) and (2) are obtained.

$$\lambda_1 = \lambda_{total} \frac{\sum_{i=1}^N \left( f_{i,T1} \left[ \frac{1}{2} f_{i,T2} + \sum_{j=i+1}^N f_{j,T2} \right] \right)}{\sum_{i=1}^N \left( f_{i,T1} \left[ \frac{1}{2} f_{i,T2} + \sum_{j=i+1}^N f_{j,T2} \right] \right) + \sum_{i=1}^N \left( f_{i,T2} \left[ \frac{1}{2} f_{i,T1} + \sum_{j=i+1}^N f_{j,T1} \right] \right)}, \tag{5}$$

and

$$\lambda_2 = \lambda_{total} \frac{\sum_{i=1}^N \left( f_{i,T2} \left[ \frac{1}{2} f_{i,T1} + \sum_{j=i+1}^N f_{j,T1} \right] \right)}{\sum_{i=1}^N \left( f_{i,T1} \left[ \frac{1}{2} f_{i,T2} + \sum_{j=i+1}^N f_{j,T2} \right] \right) + \sum_{i=1}^N \left( f_{i,T2} \left[ \frac{1}{2} f_{i,T1} + \sum_{j=i+1}^N f_{j,T1} \right] \right)}, \tag{6}$$

**Proof:** The splitting of the total rate  $\lambda_{total}$  is determined by the probabilities of packets relayed through the fastest link for a given service time. The determination of the joint probabilities to have the shortest service time for a given link together with other service times over the other link is shown in Theorem 1.

**Traffic Splitting for a Single Hop with More than Two Output Ports**

Consider three discrete service time distributions,  $T_1 = \{f_{i,T1}, t_i\}$ ,  $T_2 = \{f_{i,T2}, t_i\}$  and  $T_3 = \{f_{i,T3}, t_i\}$ ,  $i = 1, 2, \dots, N$ , describing the

One can choose arbitrary initial service distributions ( $T_1$  and  $T_2$ ) and apply Eqs. (1) and (2), which would result in virtual distributions with corresponding mean value and standard deviation. The mean value and standard deviation of  $T_1$  and  $T_2$  can be calculated with a custom program (Tayyab 2011) written in Mathematica (2004).

Theorem 1 provides information about the resultant service distributions for traffic splitting with two output ports. However, the analysis of the delay requires the knowledge of the resultant output rates of serviced packets through the said output ports.

**Theorem 2:** The resultant splitting of the total rate  $\lambda_{total}$  of serviced packets into two flows  $\lambda_1$  and  $\lambda_2$  is given by the formulae:

transmission delays to two alternative adjacent neighbors from a statistical point of view, where  $t_i < t_j$  for  $i < j$ . Assume that the transmission approach is to send a packet to one of the three nodes having the fastest instantaneous response (shortest time).

**Theorem 3:** The resultant distributions  $R_1 = \{r_{i,T1}, t_i\}$ ,  $R_2 = \{r_{i,T2}, t_i\}$  and  $R_3 = \{r_{i,T3}, t_i\}$ ,  $i = 1, 2, \dots, N$ , for three transmission links activated simultaneously are given by the formulae:

$$r_{i,T1} = \frac{f_{i,T1}[\frac{1}{3} f_{i,T2} f_{i,T3} + \frac{1}{2} (f_{i,T2} \sum_{j=i+1}^N f_{j,T3} + f_{i,T3} \sum_{j=i+1}^N f_{j,T2}) + \sum_{l=i+1}^N \sum_{j=i+1}^N f_{j,T2} f_{l,T3}]}{\sum_{j=1}^N r_{j,T1}}, \tag{7}$$

$$r_{i,T2} = \frac{f_{i,T2}[\frac{1}{3} f_{i,T1} f_{i,T3} + \frac{1}{2} (f_{i,T1} \sum_{j=i+1}^N f_{j,T3} + f_{i,T3} \sum_{j=i+1}^N f_{j,T1}) + \sum_{l=1}^N \sum_{j=i+1}^N f_{j,T1} f_{l,T3}]}{\sum_{j=1}^N r_{j,T2}}, \tag{8}$$

$$r_{i,T3} = \frac{f_{i,T3}[\frac{1}{3} f_{i,T1} f_{i,T2} + \frac{1}{2} (f_{i,T1} \sum_{j=i+1}^N f_{j,T2} + f_{i,T2} \sum_{j=i+1}^N f_{j,T1}) + \sum_{l=1}^N \sum_{j=i+1}^N f_{j,T1} f_{l,T2}]}{\sum_{j=1}^N r_{j,T3}}, \tag{9}$$

**Proof:** It is assumed that the initial service distributions are known on the basis of statistical accumulation of data over a certain period of time.

A packet is sent through the fastest link at a given time instant and the transmissions through the slower links are terminated after the packet is successfully transmitted over the said fastest link. Therefore, for a given index  $i$  representing the transmission time over the fastest link, the sums over all possible known combinations are:

$$f_{i,T1} \sum_{l=i+1}^N \sum_{j=i+1}^N f_{j,T2} f_{l,T3},$$

$$f_{i,T2} \sum_{l=1}^N \sum_{j=i+1}^N f_{j,T1} f_{l,T3}, \text{ and}$$

$$f_{i,T3} \sum_{l=1}^N \sum_{j=i+1}^N f_{j,T1} f_{l,T2} \text{ for each link,}$$

correspondingly.

In the private case when the same transmission times occur for all three links, the link used to transmit the packet is chosen by

throwing a fair coin resulting in the additional terms  $\frac{1}{3} f_{i,T1} f_{i,T2} f_{i,T3}$ ,  $\frac{1}{3} f_{i,T2} f_{i,T1} f_{i,T3}$ , and  $\frac{1}{3} f_{i,T3} f_{i,T1} f_{i,T2}$  for each link, correspondingly.

Also, in the private case, when the same transmission times occur for any two of the three links, the link used to transmit the packet is chosen by throwing a fair coin resulting in the additional

terms:  $\frac{1}{2} f_{i,T1} (f_{i,T2} \sum_{j=i+1}^N f_{j,T3} + f_{i,T3} \sum_{j=i+1}^N f_{j,T2})$ ,

$\frac{1}{2} f_{i,T2} (f_{i,T1} \sum_{j=i+1}^N f_{j,T3} + f_{i,T3} \sum_{j=i+1}^N f_{j,T1})$ , and

$\frac{1}{2} f_{i,T3} (f_{i,T1} \sum_{j=i+1}^N f_{j,T2} + f_{i,T2} \sum_{j=i+1}^N f_{j,T1})$  for each link, correspondingly.

The combination of all terms results in the following expressions for the three effective distributions:

$$r_{i,T1} = f_{i,T1}[\frac{1}{3} f_{i,T2} f_{i,T3} + \frac{1}{2} (f_{i,T2} \sum_{j=i+1}^N f_{j,T3} + f_{i,T3} \sum_{j=i+1}^N f_{j,T2}) + \sum_{l=i+1}^N \sum_{j=i+1}^N f_{j,T2} f_{l,T3}], \tag{10}$$

$$r_{i,T2} = f_{i,T2}[\frac{1}{3} f_{i,T1} f_{i,T3} + \frac{1}{2} (f_{i,T1} \sum_{j=i+1}^N f_{j,T3} + f_{i,T3} \sum_{j=i+1}^N f_{j,T1}) + \sum_{l=1}^N \sum_{j=i+1}^N f_{j,T1} f_{l,T3}], \tag{11}$$

$$r_{i,T3} = f_{i,T3}[\frac{1}{3} f_{i,T1} f_{i,T2} + \frac{1}{2} (f_{i,T1} \sum_{j=i+1}^N f_{j,T2} + f_{i,T2} \sum_{j=i+1}^N f_{j,T1}) + \sum_{l=1}^N \sum_{j=i+1}^N f_{j,T1} f_{l,T2}]. \tag{12}$$

After normalization to unity by dividing Eqs. (10), (11) and (12) by  $\sum_{j=1}^N r_{j,T1}$ ,  $\sum_{j=1}^N r_{j,T2}$ , and  $\sum_{j=1}^N r_{j,T3}$ , correspondingly, Eqs. (7), (8) and (9) are obtained.

**Note:** The generalization of this proof for more than 3 output ports ( $P > 3$ ) is straightforward and not shown here due to the increased complexity of the formulae.

Theorem 3 provides information about the resultant effective service distributions for traffic splitting with three output ports. However, an eventual calculation of the delays would require the knowledge of the resultant output rates of serviced packets through all output ports.

**Theorem 4:** The resultant splitting of the total rate  $\lambda_{total}$  of serviced packets into multiple flows  $\lambda_1, \lambda_2, \dots, \lambda_p$ ,  $p = 1, 2, \dots, P$ , where  $P$  is the number of output ports in the local node used for traffic splitting, is given by the formula:

$$\lambda_p = \lambda_{total} \frac{\sum_{i=1}^N r_{i,Tp}^{beforenormalization}}{\sum_{k=1}^P \sum_{i=1}^N r_{i,Tp}^{beforenormalization}}. \quad (13)$$

**Proof:** The splitting of the total rate  $\lambda_{total}$  is determined by the probabilities of packets going through the fastest link for a given service time.

Here the values *before normalization to unity* must be used. The sum of said non-normalized values divided by the total sum of probabilities for all the links together results in Eq. (13).

**Note:** For three links, the exact determination of the joint probabilities to have the shortest service time for a given link together with other service times over all other links is shown in Theorem 3.

Theorem 4 provides the general expressions for the resultant effective service distributions and the packet rates after splitting over more than two output ports ( $P > 2$ ), if the initial (plain) service distributions are known *a priori*. This case ( $P > 2$ ) is less likely to be used for the practice although it is interesting from a fundamental point of view.

**Theorem 5:** After traffic splitting with an instantaneous transmission over the fastest link for a given packet, the mean value and standard deviation of the resultant service distributions are *always* lower than the initial ones.

**Proof:** The proof follows directly from the selection of the probabilities  $\sum_{j=i+1}^N f_{i,T1} f_{j,T2}$  since by definition:  $t_i < t_j$ . For more than two output ports, similar inequalities apply:  $t_i < t_j, t_i < t_l, \dots$

**Theorem 6:** At a local relaying node, the total node utilization after traffic splitting over the fastest link is lower than utilization of the plain scheme without splitting.

**Proof:** Considering all other traffic as background traffic, the total node utilization is given, as follows:

$$\rho_{node} = \rho_{background} + \sum_{j=1}^P \rho_j^{aftersplitting}. \quad (14)$$

Since  $\rho_j^{aftersplitting} < \rho_j^{plainscheme}$ ,  $j = 1, 2, \dots, P$ , which follows from Theorem 5, the total node utilization after splitting will be reduced compared to the plain scheme.

**Corollary 1:** For M/M/1 queues, for which all the coefficients of time variation (CoV) are equal to 1, the node delay after splitting is always lower compared to the plain scheme.

A statement similar to Corollary 1 can also be assumed for GI/G/1 queues, although an exact proof is more difficult to obtain.

## Computational Results and Analysis

### Traffic Splitting for Two Hops

Local routing can effectively be used for traffic relaying among several connected nodes in a preferred direction (Inthawadee and Batovski 2008) or in alternative two-path two-hop configurations (Batovski 2009). Consider the following local routing scenario (Batovski 2009) as shown in Fig. 2, which includes a relaying local source node (LS), local destination node (LD) and two intermediate nodes N1 and N2. After splitting the chosen traffic into two local flows in the selected preferred direction, the reduction of the delay during the first hop can be insufficient if the delay during the second hop for the second alternative local path within the routing corridor increases.

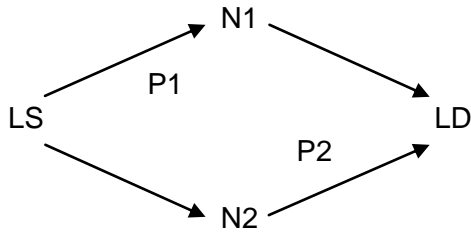


Fig. 2. A sample rhombic configuration of four connected nodes and two alternative paths (Batovski 2009).

After splitting the plain pair  $(\lambda_{LS}, c_{LS,\lambda}^2)$  into two pairs:  $(\lambda_{LS \rightarrow N1}, c_{LS \rightarrow N1,\lambda}^2)$  and  $(\lambda_{LS \rightarrow N2}, c_{LS \rightarrow N2,\lambda}^2)$ , where  $\lambda_{LS} = \lambda_{LS \rightarrow N1} + \lambda_{LS \rightarrow N2}$ , one should evaluate whether the proposed splitting technique is *suboptimal* compared to the ideal splitting (Batovski 2009). Mathematica source code for the proposed splitting technique is used in this study (Tayyab 2011). A additional Mathematica code for GI/G/1 queues is used to evaluate the two-hop performance in terms of the average rate-delay product over two paths after splitting (Tayyab 2011).

The rate-delay product  $\lambda_{LS \rightarrow N1} D_{P1} + \lambda_{LS \rightarrow N2} D_{P2}$  of ideal standard splitting (Batovski 2009) and the proposed splitting are compared for different scenarios. The standard splitting is

based on rate-delay equalization (Inthawadee and Batovski 2008; Batovski 2009) using the rate-delay ( $\lambda D$ ) product of each path  $P_1$  and  $P_2$  as given by the following equations:

$$\lambda_{LS \rightarrow N1} D_{P1} = \lambda_{LS \rightarrow N1} (D_{LS \rightarrow N1} + D_{N1 \rightarrow LD}), \quad (15)$$

$$\lambda_{LS \rightarrow N2} D_{P2} = \lambda_{LS \rightarrow N2} (D_{LS \rightarrow N2} + D_{N2 \rightarrow LD}). \quad (16)$$

During the rate-delay equalization process, the following system of two equations is solved:

$$\lambda_{LS \rightarrow N1} D_{P1}(\lambda_{LS \rightarrow N1}) = \lambda_{LS \rightarrow N2} D_{P2}(\lambda_{LS \rightarrow N2}), \quad (17)$$

$$\lambda_{LS} = \lambda_{LS \rightarrow N1} + \lambda_{LS \rightarrow N2}, \quad (18)$$

which reduces to a nonlinear equation after substituting Eq. (18) in Eq. (17):

$$\lambda_{LS \rightarrow N1} D_{P1}(\lambda_{LS \rightarrow N1}) = (\lambda_{LS} - \lambda_{LS \rightarrow N1}) D_{P2}(\lambda_{LS} - \lambda_{LS \rightarrow N1}). \quad (19)$$

For the most general case of GI/G/1 queuing at the individual nodes, Eq. (19) can be rewritten in a more explicit form (Batovski 2009):

$$\begin{aligned} & \lambda_{LS \rightarrow N1} \left[ \rho_{LS \rightarrow N1} + \frac{\rho_{LS \rightarrow N1}}{1 - \rho_{LS,T}} \frac{c_{LS \rightarrow N1,\lambda}^2 + c_{LS \rightarrow N1,\mu}^2}{2} \right. \\ & \times \phi(\rho_{LS,T}, c_{LS \rightarrow N1,\lambda}^2, c_{LS \rightarrow N1,\mu}^2) \\ & + \rho_{N1 \rightarrow LD} + \frac{\rho_{N1 \rightarrow LD}}{1 - \rho_{N1,T}} \frac{c_{N1 \rightarrow LD,\lambda}^2 + c_{N1 \rightarrow LD,\mu}^2}{2} \\ & \left. \times \phi(\rho_{N1,T}, c_{N1 \rightarrow LD,\lambda}^2, c_{N1 \rightarrow LD,\mu}^2) \right] \\ & = (\lambda_{LS} - \lambda_{LS \rightarrow N1}) \left[ \right. \\ & \rho_{LS \rightarrow N2} + \frac{\rho_{LS \rightarrow N2}}{1 - \rho_{LS,T}} \frac{c_{LS \rightarrow N2,\lambda}^2 + c_{LS \rightarrow N2,\mu}^2}{2} \\ & \times \phi(\rho_{LS,T}, c_{LS \rightarrow N2,\lambda}^2, c_{LS \rightarrow N2,\mu}^2) \\ & + \rho_{N2 \rightarrow LD} + \frac{\rho_{N2 \rightarrow LD}}{1 - \rho_{N2,T}} \frac{c_{N2 \rightarrow LD,\lambda}^2 + c_{N2 \rightarrow LD,\mu}^2}{2} \\ & \left. \times \phi(\rho_{N2,T}, c_{N2 \rightarrow LD,\lambda}^2, c_{N2 \rightarrow LD,\mu}^2) \right]. \quad (20) \end{aligned}$$

The Mathematica implementation of this approach for GI/G/1 queues (Tayyab 2011) allows one to estimate the range where certain changes in the splitting process do not affect significantly the performance which is sub-optimal compared to the ideal splitting (Batovski 2009).

Figure 3 shows a sample comparison between the plain scheme (default single path), ideal standard splitting assuming an explicit knowledge about the statistics during the second hop, and the proposed splitting for the two sample service distributions (Tayyab 2011) used as an illustration ( $\lambda_{LS} = 0.1, \mu_{LS \rightarrow N1} = 2.5, \mu_{LS \rightarrow N2} = 1.6, \mu_{N1 \rightarrow LD} = 3.0, \mu_{N2 \rightarrow LD} = 3.0$ ).

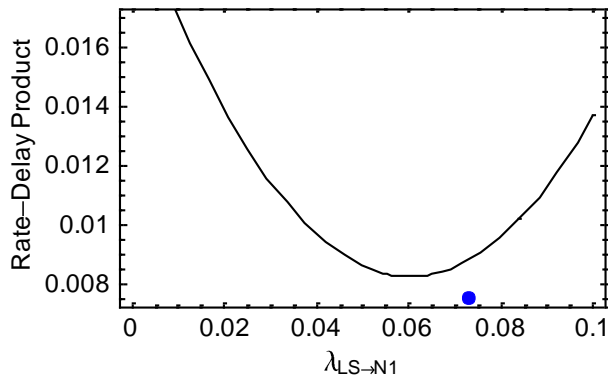


Fig. 3. Sample graphical comparison of the proposed splitting (the single point) compared to the plain scheme (the right-most point of the curve) and ideal standard splitting assuming an explicit knowledge about the statistics during the second hop (the minimum point of the curve).

The sample result demonstrates that for intermediate nodes N1 and N2 for which the service distributions do not differ significantly and the node utilizations are also similar, a performance which is even better than the ideal standard splitting can be obtained with the proposed splitting algorithm which uses simultaneous attempts to transmit same packets to both N1 and N2.

The horizontal rate location of the single point representing the proposed splitting algorithm in Fig. 3 is determined by Theorem 2. Note that if the sample service distributions exchange places in this private case, the single point will appear at the left side of the

alternative graph as shown in Fig. 4 and the performance of the proposed algorithm will be slightly worse than the ideal standard splitting.

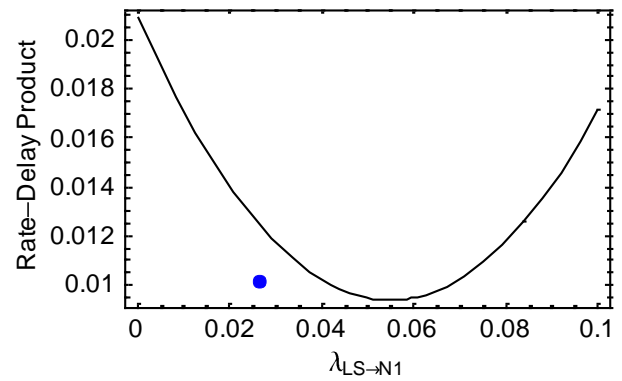


Fig. 4. Sample graphical comparison of the proposed splitting (the single point) compared to the plain scheme and ideal standard splitting if the sample service distributions exchange places.

If eventually the service distributions and background traffic for both paths during the first and second hops coincide, the location of the single point of the proposed splitting will be below the minimum of the curve for ideal standard splitting as shown in Fig. 5.

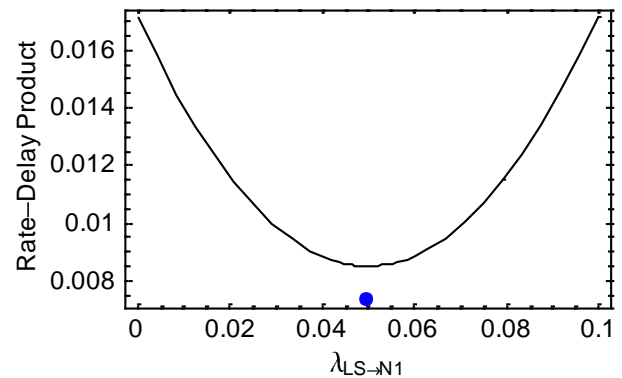


Fig. 5. Sample graphical comparison of the proposed splitting (the single point) compared to the plain scheme and ideal standard splitting if the service distributions and background traffic for both paths during the first and second hops coincide.

The following scenarios illustrate the strengths and limitations of the proposed splitting which does not use any prior statistical knowledge to relay packets locally over two-hop rhombic topological configurations to the intermediate adjacent nodes.

Consider the first scenario with increased mean packet rate  $\lambda_{LS} = 1.0$  and mean service rates during the second hop which are much lower than the mean service rates of the splitting during the first hop, as follows:  $\mu_{LS \rightarrow N1} = 2.5$ ,  $\mu_{LS \rightarrow N2} = 1.6$ ,  $\mu_{N1 \rightarrow LD} = 1.0$ ,  $\mu_{N2 \rightarrow LD} = 1.0$ . The result is shown in Fig. 6. In this case, *suboptimal* performance is observed.

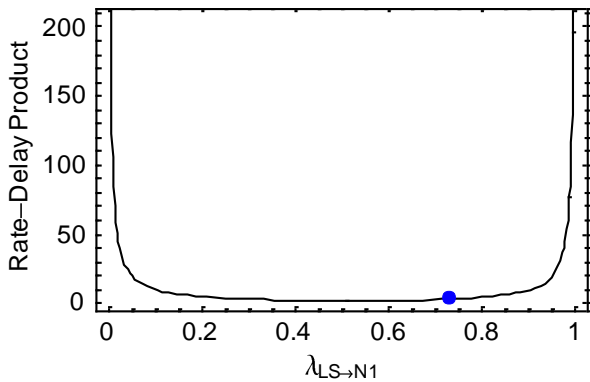


Fig. 6. Sample graphical comparison of the proposed splitting (the single point) compared to the plain scheme and ideal standard splitting when the mean service rates during the second hop are much lower than the mean service rates of the splitting during the first hop.

If the service conditions in the path of the plain scheme during the second hop are better than that of the second path ( $\lambda_{LS} = 1.0$ ,  $\mu_{N1 \rightarrow LD} = 4.0$ ,  $\mu_{N2 \rightarrow LD} = 2.0$ ), then the proposed splitting has better performance than that of the standard splitting as shown in Fig. 7.

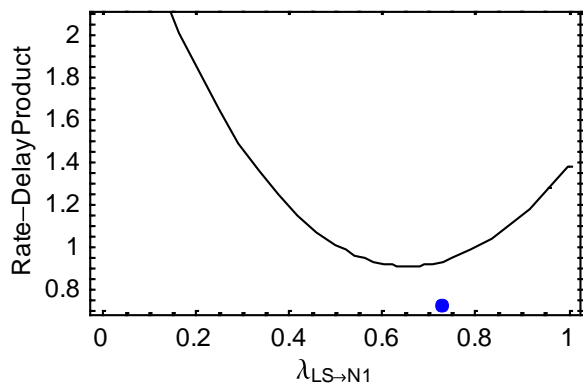


Fig. 7. Sample graphical comparison of the proposed splitting (the single point) compared to the plain scheme and ideal standard splitting when the service conditions in the path of the plain scheme during the second hop are better than that of the second path.

On the contrary, if the service conditions in the path of the plain scheme during the second hop are worse than that of the second path ( $\lambda_{LS} = 1.0$ ,  $\mu_{N1 \rightarrow LD} = 2.0$ ,  $\mu_{N2 \rightarrow LD} = 4.0$ ), then the proposed splitting has similar or worse performance than that of the standard splitting as shown in Fig. 8.

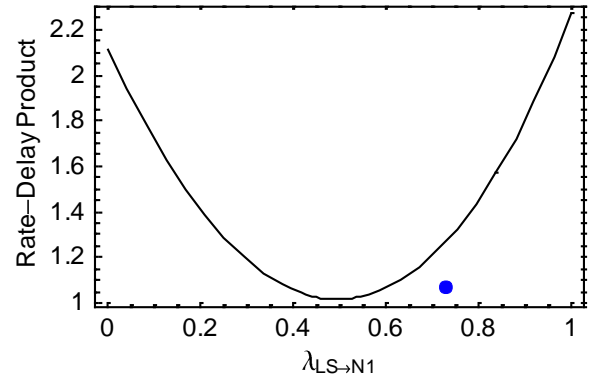


Fig. 8. Sample graphical comparison of the proposed splitting (the single point) compared to the plain scheme and ideal standard splitting when the service conditions in the path of the plain scheme during the second hop are worse than that of the second path.

As the proposed splitting technique does not use prior knowledge about the conditions during the second hop, then with  $\mu_{LS \rightarrow N1} = 2.5 > \mu_{LS \rightarrow N2} = 1.6$  if node N2 for the alternative path 2 offers much better relaying conditions than node N1 for the default (plain) path 1 ( $\lambda_{LS} = 1.0$ ,  $\mu_{N1 \rightarrow LD} = 1.2$ ,  $\mu_{N2 \rightarrow LD} = 4.0$ ), then the suboptimal performance is not observed as shown in Fig. 9.

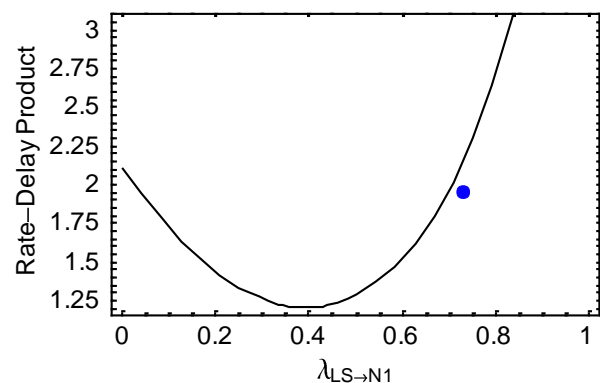


Fig. 9. Sample graphical comparison of the proposed splitting (the single point) compared to the plain scheme and ideal standard splitting with  $\mu_{LS \rightarrow N1} > \mu_{LS \rightarrow N2}$  if node N2 for the alternative path 2 offers much better relaying conditions than node N1 for the default (plain) path.



The performance of the proposed splitting is still better than that of the plain scheme. Therefore, the two-hop evaluation can be used in making a decision whether to use the proposed path splitting or not. As a result, the proposed two-hop splitting can be used for local two-hop local routing in reducing the node utilization in congested local nodes.

It is also important to know the coefficients of variation (CoV) of real-time traffic and service distributions. The limited knowledge of the said CoV parameters due to the limited time to collect statistical data about the traffic patterns and the wireless service distributions affects the decision-making process. For instance, if the squared CoV of the service distribution in the second hop of the path of the plain scheme for the example shown in Fig. 3 is substantially increased ( $c_{\mu, N1 \rightarrow LD}^2 = 10.0$ ), then the optimal performance is reduced to *suboptimal* due to the increased uncertainty in relaying packets as shown in Fig. 10.

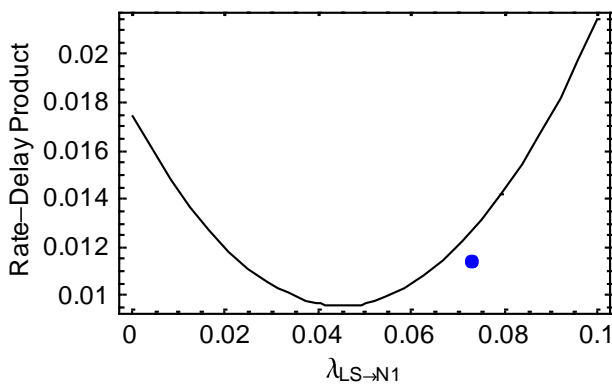


Fig. 10. Sample graphical comparison of the proposed splitting (the single point) compared to the plain scheme and ideal standard splitting if the CoV of the service distribution in the second hop of the path of the plain scheme is substantially increased.

In summary, the existence of a region of sub-optimal performance around the ideal optimization point allows one to successfully reduce the delay in local nodes for a substantial number of scenarios, especially for adjacent nodes having similar traffic and service distributions. If a significant packet flow can be locally redirected to an adjacent underutilized node, the node delay of the default node is decreased due to the decreased node utilization.

The utilization in the adjacent node will increase. However, the average node-delay performance will remain suboptimal.

Whenever the performance estimation obtained with the proposed algorithm indicates that the simple splitting during the first hop is far from a *suboptimal* performance, the packet relaying will continue according to the plain scheme. It is important to note that the proposed splitting is activated on a case-by-case basis in certain local nodes of the network depending on the traffic patterns and the wireless conditions. Therefore, the proposed local splitting technique can be considered as a local upgrade of the existing global path algorithms, which would allow the local nodes to resolve congestion issues on-the-fly depending on their ability to achieve a *suboptimal* performance for a given situation.

Note: In Figs. 3-10, the packet rate  $\lambda_{LS \rightarrow N1}$  is measured in thousand packets/sec for the sample distributions used (Tayyab 2011).

## Conclusion

A hybrid algorithm for local two-hop path splitting among first neighbors (whenever it is topologically possible) is proposed. The algorithm attempts to send every packet to two (or more) first neighbors simultaneously where the transmission is completed as soon as one of the neighbors receives the said packet. It should be noted that a drawback of the algorithm is the increased transmission power required for the simultaneous transmissions. An analytic method for evaluation of the expected average delay of splitting a packet flow into two (or more) two-hop local paths is also presented. The method is based on a priori knowledge of service time distributions for packets waiting in the two queues in the two first neighbors for the second hop after splitting in order to make a decision in favor of path splitting. The main advantage of the hybrid algorithm assisted by the decision-making analytic method is that it has a better performance when compared to the plain scheme. The simplification of the analytic method comes from the exact knowledge of the

instantaneous number of waiting packets in the first neighbors (broadcast by each local node in a short control packet with a time to live of only one hop) at the time of path splitting. Therefore, the uncertainty of decision making is limited to the service distributions at the output ports and does not depend of the traffic distributions. This allows one to estimate the average delay after local path splitting much better than with the known standard queuing techniques. The quantitative comparison between the plain scheme and the proposed two-hop path splitting demonstrates that typically a twofold reduction of the average local two-hop delay is possible where the exact improvement varies depending on the number of waiting packets in the first neighbors and the service distributions. From fundamental point of view, the algorithm can be applied for local two-hop splitting among more than just two first neighbors. Theoretically, with the increase of the number of first neighbors involved in path splitting (whenever topologically possible), the improvement of the average delay may only increase after forming several rhombic two-hop topological configurations.

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