Combined Routing & Scheduling for Spatial TDMA in Multihop Ad hoc Networks

Marvin Sánchez
Dept. of Signals, Sensors and Systems,
Royal Institute of Technology
SE-100 44 Stockholm, Sweden
marvins@radio.kth.se

Jens Zander
Dept. of Signals, Sensors and Systems,
Royal Institute of Technology
SE-100 44 Stockholm, Sweden
jens.zander@radio.kth.se

Tim Giles
Dept. of Signals, Sensors and Systems,
Royal Institute of Technology
SE-100 44 Stockholm, Sweden
Tim.Giles@radio.kth.se

Abstract

Spatial Time Division Multiple Access(STDMA) is a conflict free MAC protocol for multihop ad hoc networks where links or nodes are scheduled to transmit in periodical slots. This paper analyzes the performance of a novel routing and scheduling strategy to create the schedule in STDMA, named Reuse Adaptive Minimum Hop Algorithm (RA-MHA). RA-MHA uses the set of minimum hop paths between sources and destinations as well as previously suggested schedule strategies in order to assign link transmissions. The results show that when directional antenna patterns are used, RA-MHA produces substantial improvement in throughput and packet delay.

Keywords

Multihop, Ad hoc, Packet Radio, MAC, TDMA, STDMA, MHA, RA-MHA, schedule, routing, beam forming antennas.

INTRODUCTION

In many practical communications scenarios, simplicity and speed in setting up the network is of primary importance, hence multihop ad hoc networks are of interest. There are many potential applications of multihop ad hoc networks including Wireless LAN (WLAN), home networking, and personal area networking (PAN)[2]. Another application could be found in developing countries where long distances, difficult terrain, and poverty limit the availability of land-base communication infrastructure.

The term *ad hoc* is used to indicate that the network is self-configuring and set up without needing any central administration. The network is made up of communicating radio units (nodes) that send data packets via the wireless medium. As the term *multihop* suggests, the information is conveyed through the network using data packets that may be forwarded through a number of nodes between their source (S) and destination (D). Therefore, each node must perform routing, i.e. selection of a set of intermediate links (path) between every initial S and final D of a packet (denoted by an (S, D) pair), and flow control functions[7]. Routing influences the Multiple Access Interference (MAI) created by sharing the radio channel limiting the potential network throughput. This problem can be the result of limited network connectivity but also due to poor route selection that may arise when more than one path exists between a (S, D) pair. Spatial Time Division Multiple Access is a Medium Access Control (MAC) protocol that can be used to effectively share the radio channel and compensate the uneven traffic distribution created by routing. In STDMA systems, the problem that a node can not transmit and receive at the same time and neither can receive simultaneously from more than one of its neighbors [1] (nodes within its radio range at a single hop), is managed by assigning nodes or individual (unidirectional) links to transmit in periodical slots called *schedule*. Several links (nodes) are assigned to transmit in the same time-slot provided that their mutual MAI allows simultaneous reception, these links are said to be *compatibles*. To illustrate this, Fig.1 shows a simple 6 nodes network with all possible (bi-directional) radio links indicated by lines connecting the nodes. In this network it would, for example, seem feasible to reuse the time slots used for communication on the links $2 \rightarrow 3$ and $4 \rightarrow 6$, whereas $5 \rightarrow 4$ and $2 \rightarrow 1$ would probably not be able to share the same slot.

STDMA Schedule algorithms adapted to traffic patterns have been studied in [3, 9, 11] using omnidirectional antennas. The basic approach for constructing the schedule starts by creating the routing, then, the uneven traffic problem is alleviated by a procedure that assigns to each link a number of slots proportional to its relative traffic (referred as traffic sensitive or traffic controlled scheduling). However, earlier works revealed that when interference reduction techniques are used (e.g. Smart Antennas), construction of an efficient minimum length schedule is strongly dependent on route selections [13]. In this paper the authors propose a combined routing & scheduling procedure for STDMA, named Reuse Adaptive Minimum Hop Algorithm (RA-MHA), in order to create a more efficient schedule.

SYSTEM MODELS

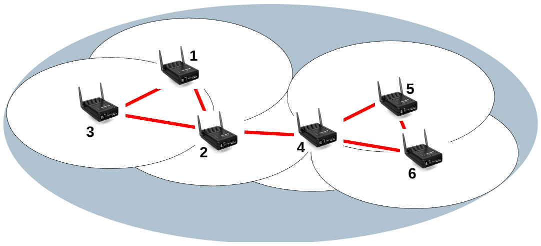

Figure 1. Multihop Ad hoc network example with 6 nodes.

Link Quality Modeling

The networks studied in this paper consist of a collection of N nodes spread randomly over a given area. For easy analysis of results, the received power P_{ij} at node j resulting from transmission of node i with power P_i is computed using a distance dependent propagation model,

$$P_{ij} = P_i G_{ij} A_i(\theta_{ij}) A_j(\theta_{ji}) = \frac{P_i A_i(\theta_{ij}) A_j(\theta_{ji})}{d_{ij}^{\alpha}} \ , \quad (1)$$

G_{ij} and d_{ij} are the path gain and distance between node i and j respectively, α is the path loss exponent, $A_i(.)$ denotes the (horizontal) antenna pattern of the antenna used by node i, and θ_{ij} denotes the angle to node j as seen from node i.

In the radio environment the probability of a packet arriving error free is dependent on the modulation, coding, MAI and background noise. In STDMA, MAI is controlled by scheduling only compatible links in the same time-slot. For a set of links L to be compatible, two condition must be met:

i) Nodes only appear once in the set L, i.e. nodes cannot transmit and receive simultaneously.

ii) The SIR in all receiving nodes is above a certain threshold γ_0. Assuming an interference limited system, the SIR Γ_{ij} for each link (i, j) in L must satisfy (2).

$$\Gamma_{ij} = \frac{P_i G_{ij} A_i(\theta_{ij}) A_j(\theta_{ji})}{\displaystyle\sum_{\substack{\forall \text{ link } (k,l) \in L \\ \text{link } (k,l) \neq \text{ link } (i,j)}} P_k G_{kj} A_k(\theta_{kj}) A_j(\theta_{jk})} \geq \gamma_0 \ . \quad (2)$$

Two nodes are connected if packets can be successfully transmitted between them while there is no interference from any other node. Fig.2 shows a network realization using this criteria.

Antenna Model and Adaptation Scheme

Adaptive beamforming antennas (BFA) can control the antennas radiation pattern electronically, thus reducing MAI and increasing the slot reusability. In our study, each node is equipped with a BFA controlled at the MAC sub-layer. In order to obtain easily analyzed and general results the flat-top model is adopted [[5], page 137]. The horizontal antenna pattern $A_i(\theta, j)$ used by node i while transmitting to node j is given by

$$A_i(\theta, j) = \begin{cases} \frac{2\pi}{\phi_h}; & \theta_{ij} - \frac{\phi_h}{2} \leq \theta \leq \theta_{ij} + \frac{\phi_h}{2} \\ \frac{2\pi}{\phi_h a_{sl}}; & Otherwise \ , \end{cases} \quad (3)$$

where ϕ_h is the horizontal antenna beamwidth and a_{sl} is the side lobe attenuation. The antenna radiation pattern of the receiving antenna in node j is computed in the same manner.

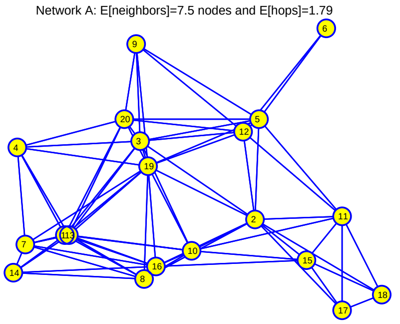

Figure 2. Sample networks A with N=20 nodes over an area of 100x100 km. Lines indicate feasible bi-directional links. The average number of neighbors and hops needed to reach any other node is indicated.

Traffic Model

It is assumed that the external traffic source attached to each node $i \{i = 1 \ldots N\}$, generates Poisson distributed packet arrivals with average traffic load $\lambda_i = \lambda/N$ (packets/slot); where λ is the total external traffic load. Packet destinations are assumed to be equally likely among nodes.

In a multihop ad hoc network a routing algorithm must be used to route packets between (S, D). Therefore, the average traffic load going through a link (i, j), λ_{ij}, is the result of external and internal traffic [12] (4).

$$\lambda_{ij} = \sum_{\substack{\forall (S,D) \text{routed} \\ \text{through link } (i,j)}} \frac{\lambda}{N(N-1)} = \frac{\lambda}{N(N-1)} T_{ij} \ , \quad (4)$$

where $T_{ij} = \sum (S, D)$ routed through link (i, j), this is called the relative traffic load over link (i, j). Hereby, route selections have a strong influence on the network performance. Commonly, while doing route search for a particular (S, D) pair, the number of hops are used to select between different possible paths. This may result in an uneven traffic distribution.

ROUTING & STDMA SCHEDULING

The uneven traffic problem can be alleviated with STDMA since the capacity C_{ij} of a particular link (i, j) is up to some extend controlled yet limited by the spatial reuse of time slots. The capacity is related to the schedule's period N_f (slots) and the number of slots assigned to the link n_{ij} by $C_{ij} = n_{ij}/N_f$ (packet/slot). The values for C_{ij} and the relative traffic load can be used to estimate the maximum end-to-end throughput λ^*. Assuming infinite buffer length, if the average traffic load routed through link (i, j) is $\lambda_{i,j}$, for stable condition $\lambda_{i,j}$ must be lower than C_{ij} [4]. Consequently, the maximum end-to-end throughput is given by

$$\lambda < \lambda^* = N(N-1) \min_{\forall \text{ link } (i,j)} \left\{ \frac{n_{ij}}{N_f T_{ij}} \right\} \ . \quad (5)$$

Equation (5) reveals that assigning a number of slots proportional to the relative traffic load of a link improves λ^*. Therefore traffic controlled algorithms aim to maximize the end-to-end throughput. In [11, 3] the Minimum hop algorithm (MHA) is used as the routing method and the uneven

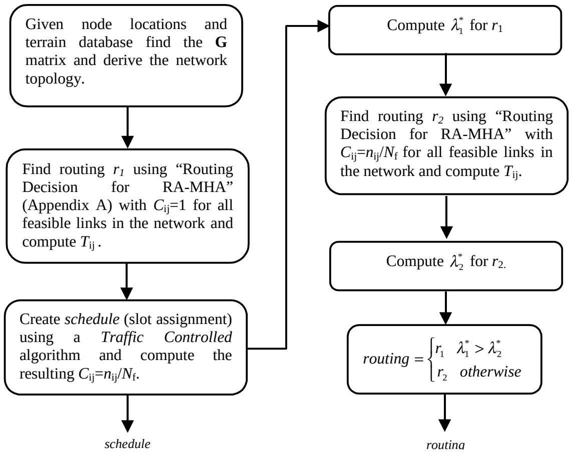

Figure 3. Reuse Adaptive Minimum Hop Algorithm.

traffic distribution is then compensated through the schedule. MHA minimize the number of hops in a multihop "connection". When setting the routing table a decision has to be made if several paths with the same minimum number of hops are found. If only the number of hops is used as decision criteria, a random selection seems to be a reasonable choice (we will refer to this as random MHA). Compensating the uneven traffic load after route selection is not an optimal solution since the capacity that can be assigned to a given link is limited not only by interference but also by the fact that a node can not receive from more than a single node and neither can transmit simultaneously. This is better understood if we consider the case where all the interference has been removed (e.g. narrow beamforming antennas). In this case, route selection becomes a limiting factor. In the intermediate case, both interference and route selection are important. Therefore, the authors propose a new procedure referred as Reuse Adaptive Minimum Hop Algorithm (RA-MHA) illustrated by the flow diagram in Fig.3. Similar to the previous method the algorithm starts by computing the **G** matrix (composed by links path gain G_{ij}) to find the routing topology based on the link quality. In a real system, this information can be collected when the network is started and could be periodically updated, a method to do this can be found in [8] .The second step aims to spread the traffic with the objective of spreading the MAI by considering that all links have the same capacity ($C_{ij} = 1$) and using the routing decision for RA-MHA (Appendix A), that takes into account the set of minimum hop paths and capacity assigned to each link for route selection. The generated routing table is labelled r_1 and is stored for later use. The relative traffic load produced by r_1 is used in the next step to find the schedule by applying a Traffic controlled schedule (TCS) algorithm, like the one by Robertazzi and Shor in [9] or the one by Grönkvist in [3]. From the schedule the actual capacity of each link can be computed by $C_{ij} = n_{ij}/N_f$. T_{ij} and C_{ij} are used to find the maximum throughput achieved with routing r_1 using (5). In the next step , C_{ij} can be used to find a new routing table r_2 with the routing decision for RA-MHA. Next, the maximum throughput achieved with r_2 and C_{ij} is computed. Finally, the routing to be used is the one that produces the highest throughput.

Even though more iterations could be used, in the algorithm, the performance improvement was considered to be insignificant when compared to the extra computational effort.

NUMERICAL RESULTS

Two parameters have been used to evaluate performance, the upper bound for stable end-to-end throughput λ^* given by (5) and the average end-to-end packet delay. The end-to-end packet delay is defined as the time between the arrival of a packet at the buffer of the source node and its successful reception at the destination node. Three different sample networks, A, B and C were used for performance evaluation [10]. Each node transmits with constant power that produces a maximum radio range of 40 km with $\alpha = 3, \gamma_0 = 10$ dB and antenna sidelobe attenuation $a_{sl} = 20$ dB. Fig.4 shows the CDF of the maximum end-to-end throughput for network A in Fig.2 with RA-MHA and random MHA with 100 independent trials. The maximum throughput using RA-MHA (indicated with *) occurs with probability one, therefore the CDF is a unitary step function. Fig.5 summarizes the maximum throughput improvement obtained by RA-MHA compared with the mean value achieved with random MHA. Furthermore, Fig.6 shows the end-to-end packet delay versus the external total traffic load, λ, (a single snapshot in random MHA was used in this case).

Fig.4 and 5 show that when narrow antenna beamwidth are used RA-MHA may produce significant higher throughput than random MHA. The level of improvement is also dependent on the network topology. For instance, the throughput improvement applying RA-MHA with 60 degrees antennas

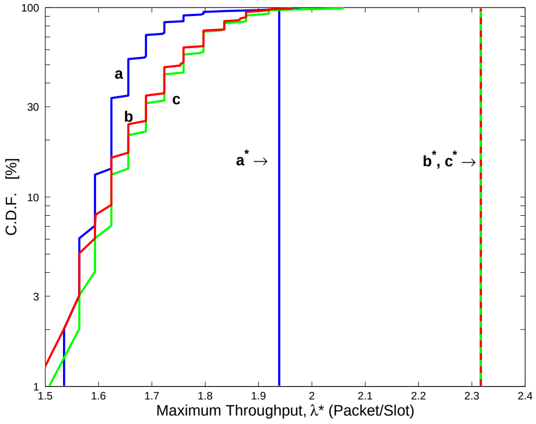

Figure 4. CDF of Maximum Throughput using adaptive BFAs (Network A). Letters a, b, and c correspond to MHA with $\phi_h = 120^o, 60^o$ and 10^o respectively. The use of RA-MHA is indicated with a*, b*, and c*.

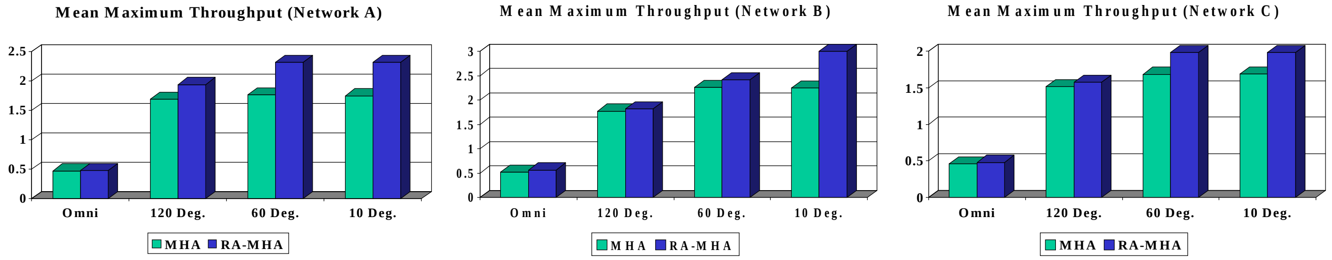

Figure 5. Maximum throughput (λ^* in packet/slot) for different antenna beamwidth.

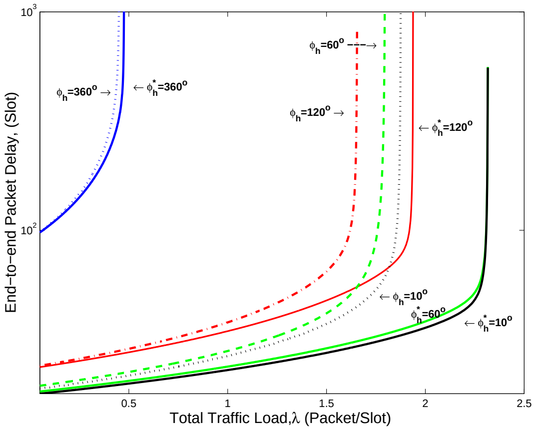

Figure 6. Packet Delay vs. traffic load (Network A). ϕ_h^* indicates the use of RA-MHA.

was 31.8%, 6.2% and 18.3% higher throughput, for network A, B and C respectively, when compared to the mean value achieved with random MHA. The lowest improvement in network B is produced because nodes were very close to each other. Hence, in scenarios where nodes are close to each other higher improvement requires the use of very narrow antenna beamwidth. Note that in networks A and B the same throughput is achieved with 60 and 10 degrees antennas with RA-MHA indicating that the MAI is neutralized by spatial filtering.

The results in Fig.6 demonstrate that lower delays for almost all traffic conditions were obtained using RA-MHA respect to random MHA. Note that the gain with omnidirectional antennas is very small suggesting that the traffic controlled schedule algorithm effectively manage the uneven traffic problem created by the routing. Furthermore, the results demonstrate that smart antennas can produce a tremendous capacity improvement with respect to omnidirectional antennas with relatively simple antennas array (a big improvement with only 120 degrees antenna's beamwidth was achieved).

CONCLUSIONS

In this paper a novel combined routing & scheduling strategy called Reuse Adaptive Minimum Hop Algorithm (RA-MHA) for Spatial - TDMA in multihop ad hoc networks was introduced. When designing Spatial TDMA multihop ad hoc networks two factors need to be considered, firstly the multiple access interference (MAI) and secondly the half-duplex operation of the nodes. When beam forming antennas are used the MAI is reduced and the second factor becomes the most significant. Routing to balance the traffic can be used to improve performance when limited by the half-duplex capacity of a few links in the network. However, routing and scheduling are inter-related. The algorithm presented does routing and scheduling iteratively in order to improve performance. A significant improvement of up to 32% in throughput was observed in the simulation examples using 60 degrees beamwidth antennas.

REFERENCES

[1] Chou, A., Li, V.O.K., "Fair Spatial TDMA Channel Access Protocols for Multihop Radio Network", INFOCOM '91, Bal Harbour, FL, April 1991.

[2] Frodigh, M., Johansson, P. and Larsson, P., "Wireless Ad hoc Networking - The art of networking without a network". Ericsson Review, no. 4, 2000.

[3] Grönkvist, J., "Traffic Controlled Spatial TDMA in multihop radio networks". PIMRC 98, October 1998.

[4] Kleinrock, L., "Queueing Systems", vol. I. Jhon Wiley & Sons, 1975.

[5] Liberti, J.C. Jr., Rappaport, T.S., "Smart Antennas for Wireless Communications: IS-95 and Third Generation CDMA Applications". Prentice Hall, ISBN: 0-7803-4736-6.

[6] Nelson, R., Kleinrock, L., "Spatial- TDMA, A collision-free multihop channel access protocol". IEEE Trans. Comm., vol. COM-33, no. 9, Sept 1985.

[7] Perkins, Ch. E., "Ad hoc Networking". Addison-Wesley, 2001. ISBN 0-201-30976-9.

[8] Robertazzi, T. G., and Sarachik, P. E., "Self-Organizing Communication Networks". IEEE Comm. Magazine, vol. 24, p. 28-33, January 1986.

[9] Robertazzi, T., Shor, J., “Traffic Sensitive Algorithms and Performance Measures for the generation of Self-Organizing Radio Network Schedules”. IEEE Trans. Comm., vol. COM-41, no. 1, Jan 1993.

[10] Sánchez, M., Zander, J. and Giles, T. , “Combined Routing & Scheduling for Spatial TDMA in Multihop Ad Hoc Networks”. In Proc. of the 2nd. Swedish workshop on ad hoc networks , March 2002.

[11] Somarriba, O., “Multihop Packet Radio Systems in Rough Terrain”. Licentiate Thesis, Radio Communication Systems, Dept. of S3, Royal Institute of Technology, Stockholm, Sweden, Oct. 1995.

[12] Tobagi, F. A., “Modeling and Performance Analysis of Multihop Packet Radio Networks”. In Proc. of the IEEE, Vol.75, no.1, p.135-155 , January 1987.

[13] Wieseltier, J., Wang, J., Ephremides, A.,“A Neural Network Approach to Routing without Interference in Multihop Radio Networks”. IEEE Trans. Comm., vol.42, no.1, Jan. 1994.

APPENDIX A

Routing Decision for Reuse Adaptive Minimum Hop Algorithm

In the following the relative links capacity C_{ij} and the network topology are input parameters for routing decision. Priority is given to paths with longer distance since this will affect a higher number of links. Every time a route is selected the relative traffic load is updated adding one to all links within the selected path to influence the next routing decision but it can be modified to include differences in traffic between (S, D) pairs. The resulting routing table used by each node is a matrix (rather than a vector as in MHA), where row and column indexes correspond to sources and destinations respectively, and the value held is the index of the relaying node to be used to deliver the packet.

Algorithm

I. Using the network topology, collect the set of paths with shortest distance between all (S, D) pairs in the network. MHA can be used for this.

II. Put (S, D) pairs in a list in ascending order according to the number of possible paths; i.e. (S, D) pairs with less number of choices are considered first. If several (S, D) pairs have equal number of possible paths, order them according to the number of hops in descending order.

III. Set the relative traffic load $T_{ij} = 0$; ∀ links (i, j).

IV. Consider the (S, D) pair at the start of the list:

   i. Take the first path in the set for this (S, D) pair as the $Best\text{-}Path$.

   ii. Store relative traffic load matrix: $BestT_{ij} = T_{ij}$; ∀ links (i, j)

   iii. Update the relative traffic load matrix: $BestT_{ij} = (T_{ij}+1)$; ∀ links (i, j) in $Best\text{-}Path$.

   iv. Compute the relative flow vector: $BestFlow = \{\frac{C_{ij}}{BestT_{ij}}$; ∀ links (i, j) in $Best\text{-}Path\}$.

   v. While there are paths remaining to be considered for this (S, D) pair:

      a) Take the next path in the set as the $New\text{-}Path$ and store the relative traffic load matrix: $NewT_{ij} = T_{ij}$; ∀ links (i, j)

      b) Update the relative traffic load matrix: $NewT_{ij} = (T_{ij} + 1)$; ∀ links (i, j) in $New\text{-}Path$.

      c) Compute the relative flow vector for this path: $NewFlow = \{\frac{C_{ij}}{NewT_{ij}}$; ∀ links (i, j) in $New\text{-}Path\}$.

      d) If Better($NewFlow, BestFlow$) /*Fig. 7*/ then
         $Best\text{-}Path = New\text{-}Path$;
         $BestT_{ij} = NewT_{ij}$; ∀ links (i, j) ;
         $BestFlow = NewFlow$.

   vi. Update Traffic load and routing tables

      a) $T_{ij} = BestT_{ij}$; ∀ links (i, j)

      b) Update table of relaying nodes: put in routing table of node i, (S,D)=j , ∀ nodes i in links (i, j) in $Best\text{-}Path$.

   vii. Remove this (S, D) pair from the list and repeat step IV until the list of (S, D) pairs is empty.

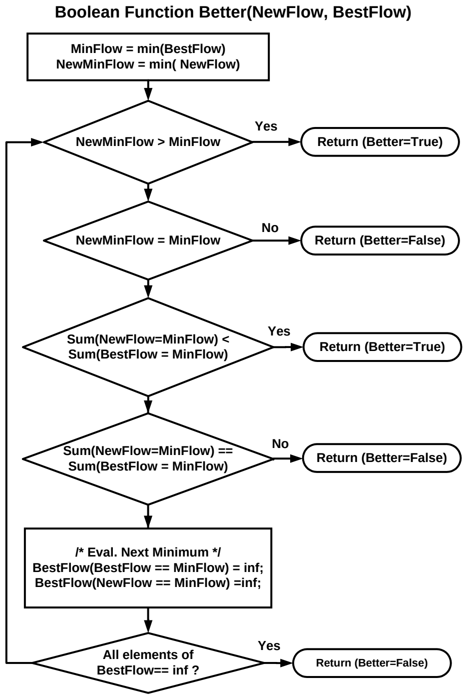

Figure 7. Function to decide if the traffic flow over a selected path is better that the previously selected.