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

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Abstract - **Multihop ad hoc radio networks can potentially provide low cost, reliable and easily deployed wireless communications for both civilian and military applications. Using a store and forward procedure, with half-duplex transceivers, communication between nodes that are beyond direct radio range is enabled. There are a variety of multiple access protocols applicable to this type of system. Spatial Time Division Multiple Access (STDMA) is a conflict free MAC protocol where links or nodes are scheduled to transmit in periodical slots. This paper analyze the performance of a novel routing and scheduling strategy to create the link transmission *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 behavior of RA-MHA is compared against the classical STDMA approach through simulations using omnidirectional and Adaptive Beam Forming Antennas. The use of directional antenna patterns reduces the Multiple Access Interference and RA-MHA produces substantial improvement in throughput and packet delay.**

I. INTRODUCTION

In many practical communications scenarios, simplicity and speed in setting up the network is of primary importance, hence Multihop Ad hoc networks are interesting. There are many potential applications of *Multihop Ad hoc* networks including Wireless LAN (WLAN), home networking, and personal area networking (PAN) [1]. Another application could be found in developing countries where long distances, difficult terrain, and poverty limit the availability of land-base communication infrastructure and the deployment of Multihop Ad hoc rural-area networks could provide a cost-effective solution.

The term Ad hoc is used to indicate that the network is self-configuring and setup without needing any central administration. Communicating radio units (nodes) that send data packets via the wireless medium compose the network. As the term multihop suggest, the information is conveyed through the network using data packets that may be forwarded through a number of nodes between their source and destination meaning that each node must perform routing and flow control functions[2]. An additional problem in Multihop Ad hoc is created by access to the shared radio channel. A Medium Access Control (MAC) protocol must be used to deal with conflicts, 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 [3] (nodes within its radio range at a single hop). This paper focuses on the Spatial Time Division Multiple Access (STDMA)[4] MAC protocol where smart antennas can be directly applied. The use of antenna arrays or smart antennas increases the cost but promises to significantly increase throughput [5].

In STDMA systems, nodes or individual (unidirectional) links are assigned to transmit in periodical slots called *schedule.* Several links (nodes) are assigned to transmit in the same time-slot provided that their mutual Multiple Access Interference (MAI) allows simultaneous reception. 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→3 and 4→6, whereas 5→4 and 2→1 would probably not be able to share the same slot.

STDMA *Schedule* algorithms adapted to traffic patterns to produce low delay have been studied in [6][7][8] using omnidirectional antennas. The basic approach for constructing the schedule starts by creating the routing, i.e. selection of a particular path between every initial source (S) and final destination (D) of a packet denoted by an (S,D) pair. As expounded in section III, the MAI is influence by traffic and routing. Routing may produce uneven traffic distributions reducing the potential network throughput. This problem can

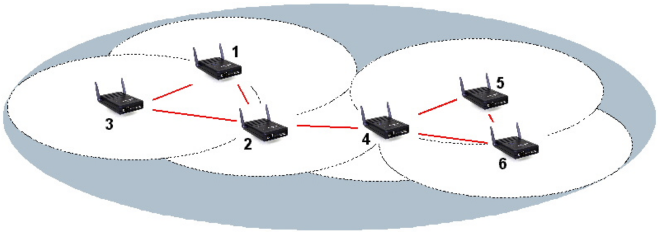

Fig. 1: Multihop Ad hoc network example with 6 nodes.

be the result of limited network connectivity but also due to poor route selection, this may arise when more than one path exists between a (S, D) pair and the one with lower capacity (or more congested) is selected. In references [6][7][8] the unbalanced traffic problem is alleviated by assigning more time-slots to links that are heavily loaded. However, earlier works revealed that when interference reduction techniques are used (e.g. Smart Antennas), construction of a efficient minimum length *schedule* is strongly dependent on route selections[9]. In this paper the authors propose a combined routing and scheduling strategy for STDMA, named Reuse Adaptive Minimum Hop Algorithm (RA-MHA), in order to create a more efficient *schedule*.

II. SYSTEM MODELS

A. 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,

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

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 power P_{Noise}. In STDMA control of the MAI is done by constructing the *schedule*. The *link schedule* is created adding each link at a time to test its *compatibility* with previous added links. A set of links L is said to be compatible if nodes in each link in the set do not appear more than once (nodes cannot receive and transmit at the same time) and that the SIR in all receiving nodes is above a certain threshold γ_0. The SIR Γ_{ij} for each link (*i, j*) in *L* must satisfy (2).

$$\Gamma_{ij} = \frac{P_i G_{ij} A_i(\theta_{ij}) A_j(\theta_{ji})}{\sum\limits_{\substack{\forall\, \mathrm{link}(k,l) \in L \\ \mathrm{link}(k,l) \neq \mathrm{link}(i,j)}} P_k G_{kj} A_k(\theta_{kj}) A_j(\theta_{jk}) + P_{Noise}} \geq \gamma_0, \qquad (2)$$

Two nodes are *connected* if packets can be successfully transmitted between them while there is no interference from any other node. Using this criterion the connectivity diagram for three sample networks used for performance evaluation are shown in Fig. 2. This three samples can be seen as the nomadic behavior of nodes within the given area (that can remain for several minutes in a real network) or three different networks in the static case.

B. *Antenna Model and Adaptation Scheme*

In our study, each node is equipped with a Beam Forming Antenna (BFA) controlled at the MAC sub-layer. In order to obtain easily analyzed and general results we adopted the *flat-top* model [10][page 137]. The horizontal antenna pattern $A_i(\theta,j)$ used by node *i* while transmitting to node *j* is given by (3).

$$A_i(\theta, j) = \begin{cases} \dfrac{2\pi}{\varphi_h} & ;\ \theta_{ij} - \dfrac{\varphi_h}{2} \leq \theta \leq \theta_{ij} + \dfrac{\varphi_h}{2}, \\ \dfrac{1}{a_{sl}} & ;\ \text{Otherwise,} \end{cases} \qquad (3)$$

φ_h is the horizontal antenna beamwidth (BW) 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.

C. *Traffic model*

It is assumed that packets are of constant length and arrive according to a Poisson process with *total external traffic*

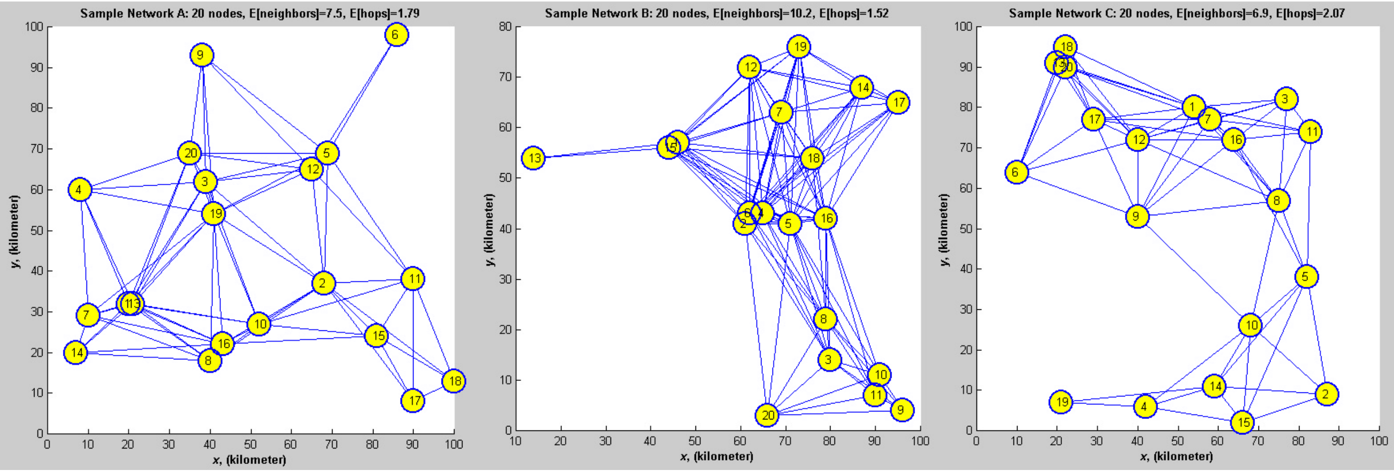

Fig. 2. Typical networks samples (Network A, B, and C) with N=20 nodes. Nomadic behavior is simulated by random location over an area of 100x100 km^2. Lines indicate possible bi-directional communication links in absence of MAI. The average number of neighbors and hops needed to reach every other node is indicated in each sample.

load of λ packets per packet duration. Furthermore, it is assumed that the traffic load is evenly distributed (4).

$$\lambda_i = \lambda / N \qquad i \in \{1, 2, \ldots N\}. \tag{4}$$

λ_i is the external traffic load on node *i*.

Due to the store-and-forward mechanism, packets between (*S, D*) pairs may travel through intermediate nodes. It is assumed that packet destination is uniform distributed among nodes. Therefore, the traffic load λ_{ij} going through a link (*i,j*) is the result of external and internal traffic [5, page 25] (5).

$$\lambda_{ij} = \sum_{\substack{\forall (S,D) \text{ routed} \\ \text{through link } (i,j)}} \frac{\lambda}{N(N-1)} = \frac{\lambda}{N(N-1)} T_{ij}, \tag{5}$$

where

$$T_{ij} = \sum (S,D) \text{ routed through link } (i,j). \tag{6}$$

T_{ij} is called the *relative traffic load* for link (*i,j*). As revealed by this equation, route selections have a strong influence on the network performance.

III. ROUTING & STDMA SCHEDULING

In STDMA the capacity C_{ij} of a particular link (*i,j*) is dependent on the equipment's capabilities as well as the proportion of time slots allotted to the link. This is related to the schedule's period N_f (Time slots) and the number of slots assigned to the link n_{ij} by $C_{ij} = n_{ij} / N_f$ (packet/ Time-slot). Hence, using (5) the upper bound for the stable *end-to-end throughput* λ^* can be found,

$$\lambda < \lambda^* = \min(\lambda \,\forall\, \lambda_{ij} : \lambda_{ij} = C_{ij}) = N(N-1) \min_{\forall \text{link } (i,j)} \left\{ \frac{n_{ij}}{N_f T_{ij}} \right\}. \tag{7}$$

Equation (7) reveals that assigning a number of slot proportional to the relative traffic load of a link improves λ^*. This strategy has been used in the *Traffic Controlled schedule* algorithms proposed in [6][7] and [8]. Something that is not explicitly clear in (7) is that 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 source. This is better explained if we think in the case of been able to remove all the interference (e.g. narrow beam Smart antennas). In this case the only problem that remains is which links must be activated during a time slot, so routing becomes the critical problem. In the intermediate case, both interference and route selection are important.

In[7][8] the Minimum hop algorithm (MHA) is used as the routing method. MHA minimize the number of hops in a multihop "connection" and is independent of the access schedule and the actual traffic flows. 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).

As the numerical results show in this paper, when smart antennas are used, spatial filtering of interference can effectively reduce the MAI. The system is then limited by the constraint that a node may only receive from one neighbor at a time. The authors propose a new procedure referred as *Reuse Adaptive Minimum Hop Algorithm* (RA-MHA) illustrated by the flow diagram in Fig. 3. The algorithm starts by computing the G matrix (composed by links path gain G_{ij}) based on node locations, and the terrain database. The second step aims to spread the traffic with the objective of spreading the MAI. This was achieved by employing the routing decision, RA-MHA (Appendix A), that takes into account the set of minimum hop paths and capacity assigned to each link for route selection. In this step, it is assumed that all links have the same capacity (C_{ij}=1) and the generated routing table is labeled r_1 for later decision. The relative traffic load (T_{ij}) produced by r_1 for every link can be computed and it is used in the next step to find the *schedule* (output) by applying a *Traffic controlled (TC) schedule* as proposed by Grönkvist in [8]. From the schedule, the resulting assigned capacity to each link is computed by $C_{ij} = n_{ij}/N_f$. Next, the maximum throughput achieved by routing r_1 and the *schedule* is computed using (7). The capacity assigned to each link by the *schedule* is used to find a new routing table r_2 with routing decision RA-MHA. Next, the maximum throughput achieved by routing r_2 and the *schedule* is computed. Finally, the routing to be used is the one that produces the highest throughput.

The main idea of routing decision RA-MHA is described here and a detailed step by step algorithm can be found in appendix A. The required inputs are the network topology and link capacity C_{ij}. The algorithm could be summarized by,

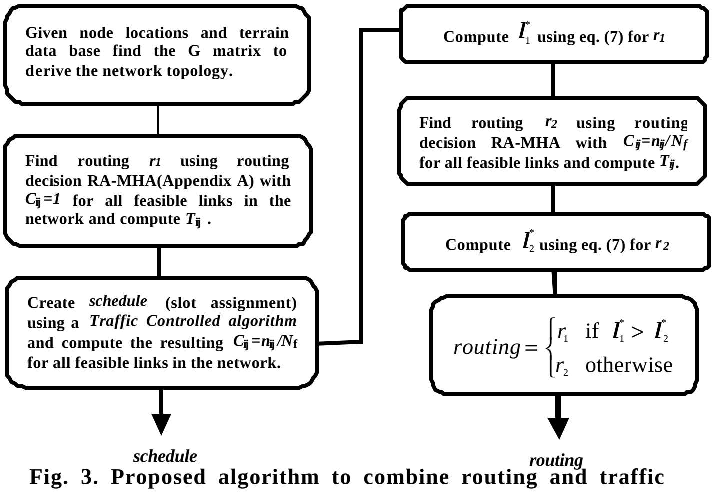

Fig. 3. Proposed algorithm to combine routing and traffic controlled scheduling in STDMA.

I. Collect the *set of paths with shortest distance* between all (*S,D*) pairs in the network. MHA can be used to find the set of paths.

II. Put (*S,D*) pairs in *ascending order* according to the number of possible paths. If two (*S,D*) pairs have equal number of possible paths, give priority to the one with higher number of hops.

III. From the set of path for each (*S,D*) pair, select the one that produce $max\{min\{C_{ij}/T_{ij}\}\}$ for all links within the path and update the traffic load for all links within the selected path with $T_{ij}=T_{ij}+1$.

IV. Repeat III until all (S,D) pairs have been considered.

Note that only the set of path with minimum number of hops between (*S,D*) pairs are used. We start assigning routes to (S,D) pairs with less number of options. For instance, those (*S,D*) pairs with only one possible path of minimum distance must be considered first. However, It may occur the case that several (*S,D*) pairs have the same number of possible paths. In this case, priority is given to the path 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. Note that the increment by 1 in T_{ij} is the result of the assumption of even traffic load among nodes, however it could be modified to include differences in traffic between different (*S,D*) pairs. Note also that the resulting routing table used by each node is a matrix (rather than a vector as in MHA), which 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.

IV. NUMERICAL RESULTS

Two parameters have been used to evaluate performance, the upper bound for stable *end-to-end throughput* λ^* given by (7) 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. The *end-to-end packet delay* allows us to evaluate quality of service (user point of view) under low, moderate, and high traffic[11].

Networks A, B, and C shown in Fig.2 were used for performance evaluation. Each node transmits with constant power that produces a maximum radio range of 40 Km with propagation constant $\alpha=3$. Fig. 4 shows the cumulative distribution function of the maximum end-to-end *throughput* for networks A for RA-MHA and random MHA with 100 independent trials. Furthermore, Fig. 5 shows the *end-to-end packet delay* versus the *external total traffic load* λ for networks A (a single snapshot in random MHA was used in this case). The maximum throughput using RA-MHA (indicated with *) occurs with probability one, therefore the CDF is a unitary step function $u(l-l^*)$. Fig. 6 summarizes the maximum *throughput* improvement obtained by RA-MHA compared with the mean value achieved with random MHA.

Fig. 4 shows that when narrow antenna beamwidth are used the RA-MHA may produce significant higher throughput than random MHA. For instance, the throughput improvement applying RA-MHA with 60 degrees antennas was 31.8%, 6.2% and 18.3% higher throughput for network A, B and C respectively respect to the mean value achieved with random MHA (Fig.6). The lowest improvement in network B is produced because nodes are very close to each other as revealed by its topology (Fig.2). In networks A and B the same throughput is achieved with 60 and 10 degrees antennas

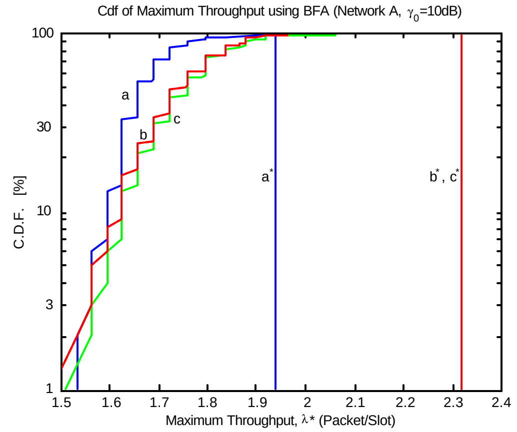

Fig. 4: Cumulative Distribution Function of Maximum Throughput using BFAs (network A). On the graph, letters a, b, and c correspond to MHA with 120, 60 and 10 degrees respectively. The use of RA-MHA is indicated with a*, b*, and c*.

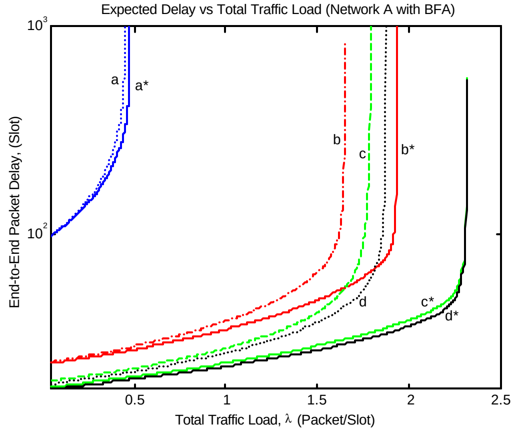

Fig. 5: Packet Delay vs. traffic load (Network A). MHA + TC : a=omni, b=120 deg., c=60 deg., d=10 deg. Beamwidth. RA-MHA: a*=omni, b*=120 deg. c*=60 deg. and d*=10 deg.

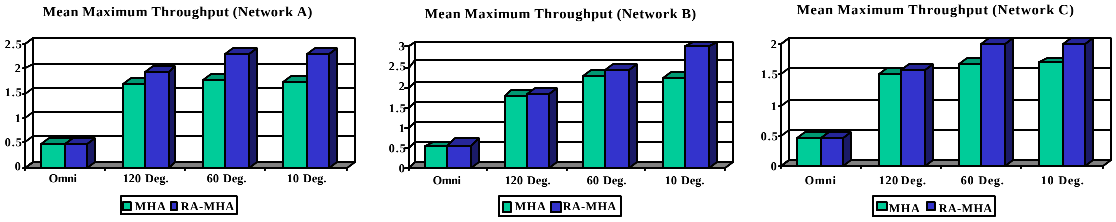

Fig. 6: Maximum throughput for different antenna beamwidth.

with RA-MHA indicating that the MAI is effectively reduced by spatial location, suggesting that the constraint that a node can not receive and transmit at the same time dominates.

The results in Fig. 5 demonstrate that lower delays for almost all traffic conditions were obtained using RA-MHA respect to random MHA. It is interesting to note that the improvements obtained by going from omni to 120 degree beamwidth antennas is substantial while the further improvement in going to 60 or 10 degree antennas is insignificant. Also note that with RA-MHA higher throughput is achieved with 120 degree antennas than 60 or 10 degree antennas with random MHA (network A).

In scenarios where nodes are close to each other like in sample network B higher improvement is obtained with very narrow antenna beamwidth. The gain with omnidirectional antennas is very small suggesting that the *traffic controlled schedule* algorithm effectively manage the unbalance problem created by the routing. Furthermore, the results demonstrate that smart antennas can produce a tremendous capacity improvement respect to omnidirectional antennas with relatively simple antennas array (big improvement with only 120 degrees antenna's beamwidth was achieved).

V. CONCLUSIONS

In this paper a novel combined routing - scheduling strategy that can substantially improve the performance of Spatial - TDMA in multihop Ad hoc packet radio networks was introduced. When interference reduction measures such as narrow antenna beamwidth are used the problem that a node can not receive and transmit at the same time becomes an important limiting factor. In this situation, balancing the traffic through routing, produces a substantial improvement in performance. Both lower end-to-end packet delay and higher throughput were demonstrated through application of the new strategy. The strategy is applicable to static as well as nomadic networks if the rate of topology change is slow enough to allow the measurement of the average radio propagation conditions and the distribution of scheduling updates. In the mobile scenario schedule distribution and synchronization are important issues, which requires some further consideration.

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Appendix A

Routing decision for Reuse Adaptive Minimum Hop Algorithm.

$$C_{ij} = \frac{\text{Time - slots assigne to link (i, j)}}{\text{Period of the schedule}} = \frac{n_{ij}}{N_f}$$

I Collect the set of paths with shortest distance between all (S,D) pairs in the network.

II Put the list of (S, D) pairs in ascending order according to the number of possible paths; i.e. (S, D) pairs with less number of choices are considered first. If two (S, D) pairs have equal number of possible paths, give priority to the one with higher number of hops.

III Set the relative traffic load $T_{ij}=0$ for all links.

IV While there are elements in the list of (S, D) pairs:

- i. Take the first (S, D) pair in the list and take the first path as the best one.
- ii. Store relative traffic load: $BestT_{ij} = T_{ij}$ for all links (i,j)
- iii. Update traffic load: $BestT_{ij} =(T_{ij} + 1)$ for all links (i,j) in the selected path.
- iv. Compute the relative flow vector: $BestFlow=C_{ij}/BestT_{ij}$ for all links in the selected path.
- v. While there are paths not considered for this (S, D) pair:
  - a) Take the next path and store the relative traffic load: $NewT_{ij} = T_{ij}$ for all links (i,j)
  - b) Update traffic load: $NewT_{ij} =(T_{ij} + 1)$ for all links (i,j) in the new path.
  - c) Compute the relative flow vector if we select this path:

    $NewFlow=C_{ij}/NewT_{ij}$ for all links (i,j) in the selected path.
  - d) If Better(NewFlow, BestFlow) /* See fig. A.1 */
    - (1) $BestT_{ij}=NewT_{ij}$
    - (2) BestFlow=NewFlow
- vi. Update Traffic load and routing tables
  - a) $T_{ij}=BestT_{ij}$ for all links (i,j)
  - b) Update table of relaying nodes: put in table of node i, (S,D)=j , for all links (i,j) in the selected path.
  - c) Remove this (S,D) pair from the list.

Boolean Function Better(NewFlow, BestFlow)

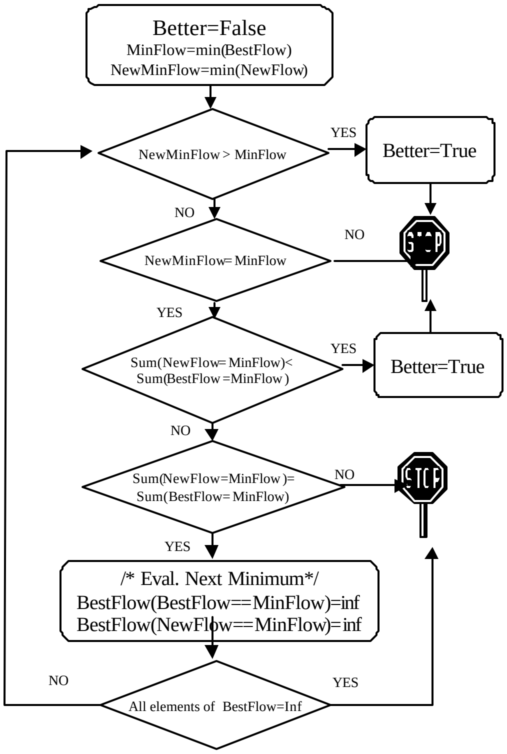

Fig. A.1: Flow diagram of Boolean function Better to decide selection between two paths.