PRIORITY BASED MULTI-CONSTRAINED QUALITY OF SERVICE ROUTING IN MILITARY APPLICATIONS

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ABSTRACT

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QUALITY OF SERVICE ROUTING IN
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This thesis proposes a new algorithm for multi-constrained Quality of Service Optimal Path Routing in the context of military applications. The objective of our routing algorithm is to manage network traffic according to quality of service requirements of connection requests using military metrics. The algorithm is mainly based on communication priority. The QoS metrics such as bandwidth, delay and packet loss ratio are considered as basic metrics on path finding. If there is no suitable path for the request, some existing connections with lower priorities may be broken to make space for a higher priority level connection request. In this case, priority and bandwidth are used as decisive metrics in cost computation.

Keywords: QoS routing, priority based routing, multi-constrained routing.

ÖZ

ASKERİ UYGULAMALARDA
ÇAĞRI ÖNCELİĞİNE DAYALI ÇOKLU KISITLAMALI
SERVİS KALİTESİ YÖNLENDİRMESİ

Araz, Bora

Yüksek Lisans, Bilişim Sistemleri Bölümü

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Bu tez ağ askeri uygulamalar bağlamında çoklu kısıtlamalı ağlarda uygun yol bulma için yeni bir yönlendirme algoritması önermektedir. Algoritmanın asıl amacı ağ trafiğini servis kalitesi gereksinimlerine göre askeri parametreler kullanarak yönetmektir. Algoritma esas olarak çağrı önceliğine dayanmaktadır. Yol seçmede servis kalitesi parametreleri olarak bant genişliği, gecikme ve hata oranı esas alınmıştır. Gelen istek için uygun bir yol bulunamadığı takdirde, mevcut bağlantılardan daha düşük önceliklere sahip olanlar, daha yüksek öncelikli isteklere yer açmak maksadıyla kırılabilir. Bu durumda öncelik ve bant genişliği masraf hesaplamada karar verici parametreler olarak kullanılmıştır.

Anahtar Kelimeler: Servis kalitesine göre yönlendirme, önceliğe göre yönlendirme, çoklu kısıtlamalı yönlendirme.

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ATM	:	Asynchronous Transfer Mode
BFS	:	Breadth-First Search
CBF	:	Constrained Bellman-Ford
DCR	:	Dynamically Controlled Routing
DiffServ	:	Differentiated Services
DNHR	:	Dynamic Nonhierarchical Routing
IntServ	:	Integrated Services
LCP	:	Least Cost Path
LDP	:	Least Delay Path
LG	:	Limited Granularity
LPH	:	Limited Path Heuristic
MCOP	:	Multi-Constrained Optimal Path
MCP	:	Multi-Constrained Path
MPLS	:	Multi Protocol Label Switching
QoS	:	Quality of Service
PLR	:	Packet Loss Ratio
RSP	:	Restricted Shortest Path
RSVP	:	Resource Reservation Protocol
SAMCRA	:	Self-Adaptive Multiple Constraints Routing Algorithm
SMM	:	Single Mixed Metric
SP	:	Shortest Path
TAMCRA	:	Tunable Accuracy Multiple Constraints Routing Algorithm
TCP	:	Transmission Control Protocol

CHAPTER 1

INTRODUCTION

The main purpose of a military communication system is providing secure, fast and survivable communication whenever required. In battlefield, because of huge number of communicating troops, there are always some problems such as capacity, performance and cost, which limit the communication. Although security, performance, cost, priority and characteristics of the battlefield affect choosing communication system, ultimate purpose is the efficient usage of resources.

For the efficient usage of resources, routing has a very high importance. The routing algorithms, which will be used in battlefield, should enable voice, data and video communications according to military preferences and an efficient utilization of the network resources. Classical routing generally considers a single metric in route computations, such as delay or hop count. Since routing decisions need to be based on more than one metric to support military applications, routing is more complex in military communications. Finding optimal solution to the routing problem in battlefield with different metrics is the subject of this thesis.

1.1. Objective and Scope

In this thesis, a priority based multi-constrained quality of service routing algorithm is proposed for military applications. In the proposed routing algorithm both QoS routing metrics and military metrics are used. We consider QoS routing using bandwidth, delay and packet loss ratio. Another QoS routing metric, jitter, is not currently considered in algorithm implementation. Military applications also impose requirements as priority, security and communication owner but only priority is used in this study as a military metric. The usage of other two military metrics is considered as future work.

Our routing algorithm consists of two parts. In the first part, if resources are available to support the requested service then the connection is established. In the second part, if there are not enough resources to support requested service, military metric priority based cost is calculated among existing lower priority level connections in order to determine the connections which will be broken to make space for the connection request. Freeing up some space by breaking existing connections according to three different levels of priority, makes the difference between military communication systems and commercial communication systems.

In this thesis, we focus primarily on the routing algorithm itself and implementation aspects are out of scope of this thesis. A possible implementation of this algorithm may need a central controller which keeps the current state of the network and finds the routes for requests accordingly. We also consider that all packets belonging to the same connection travel through the same route. Obviously, this cannot be guaranteed in an ordinary datagram network. However, the approaches like MPLS may help to satisfy this constraint.

1.2. Routing Approach

Three QoS metrics such as bandwidth, delay and packet loss ratio are used to select a path that meets the QoS requirements in the new routing algorithm. Another QoS metric, jitter, is not considered in our routing algorithm implementation. If there is no suitable path for a connection request, then priority as a military metric is used to compute cost in order to determine connections which will be broken to make space for the connection request. It is possible to free up some space by breaking connections in military communication, although it may not be possible in commercial communication. The communication for higher priority level connection requests are always considered as vital and lower priority level connections may be broken to find a path for a higher priority level connection request in military perspective.

In the cost computation, the lower priority level connections are thought as candidate connections to be broken and bandwidth occupied by these lower priority level connections are used in computation for each link on every possible path. Therefore, a list of candidate connections to free up some space for higher priority level connection requests is obtained. The connections in the list are broken and a path for higher priority level connection request is emptied. In cost computation, at most three connections are allowed to be broken for one higher priority level connection request.

The performance is evaluated on MESH, ARPA and NSF networks. A special-purpose event driven simulation tool to measure the performance of the proposed routing algorithm is implemented and tool is verified with M/M/m/m queue simulations. On each mentioned network, the blocking probability with and without preemption and breaking probability values are measured by this simulation tool and compared for three different traffic profiles according to connection priorities.

1.3. Thesis Organization

The rest of the thesis is organized as follows. In Chapter II, a literature survey on the QoS routing algorithms and different approaches to QoS routing are presented. In Chapter III, a new priority based multi-constrained path routing algorithm is proposed. The performance of this algorithm is evaluated by computer simulations on different networks and the results are compared in Chapter IV. In Chapter V, a summary of the work done, results and what can be done in the future are given. In Appendices, screenshots of applied networks and performance graphics for the algorithm on well known ARPA and NSF networks are presented.

CHAPTER 2

LITERATURE SURVEY

The efficient usage of network resources is an important issue and some proposals consisting of Integrated Services (IntServ), Differentiated Services (DiffServ) and Multi-Protocol Label Switching (MPLS) are gaining ground. As an example, MPLS is often used to build virtual private networks that can span different Internet domains. Since application necessities and availability of network resources must be considered simultaneously, the optimal path finding in Quality of Service (QoS) routing is much harder than the conventional routing. The metrics, which can be thought as additive (sum of the corresponding costs of the links along the path) and non-additive (minimum or maximum cost of the links along the path) makes the QoS routing algorithms more complex. Routing algorithms can be broadly categorized as Restricted Shortest Path Routing Algorithms (RSP) and Multi-Constrained Path Routing Algorithms (MCP). For RSP, it is possible to say that the main objective is to find a minimum cost path among the paths that satisfy only delay constraint. But in MCP, there is more than one constraint that must be satisfied. In the rest of the literature survey, architectures that provide QoS guarantees, some RSP and MCP algorithms with other approaches to QoS routing are mentioned.

2.1. Quality of Service

The IP protocol provides best effort service in the Internet but it does not guarantee the bandwidth, delay and delivery for the datagrams that are transmitted. Because of the nature of some applications which need bandwidth and maximum delay guarantees new mechanisms are needed. Since timely delivery is much more important than the reliable delivery for some applications, most of the protocols use UDP as a transport mechanism instead of TCP to circumvent large delay and low throughput especially in the case of congestion. Even though UDP is advantageous over TCP, it is not enough for some multimedia applications.

The most important issue in QoS capable communication networks is to specify what the requirements are and to quantify them accurately. In [1], transmitted traffic through communication networks is characterized by four primary parameters: loss, delay, jitter, and bandwidth. According to these parameters, different kinds of traffic can be classified. Most of the real time applications can be classified as delay-sensitive traffic sources and applications such as file transfer and e-mail can be classified as loss-sensitive traffic sources. For some applications, security might also be thought as a decision parameter. A confidential video conferencing can be classified as multi-sensitive traffic with security and delay parameters. Most of the time, multiple metrics model both networks and applications more accurately. But the problem of finding a path subject to multiple metrics is difficult and in many cases is considered as NP-complete. It cannot be solved in a real time scale, which is very crucial for the many of applications in general and for delay-sensitive applications in particular [2].

The cost metric used in route computations can be one of the following or compositions of them [3] [4]:

- Additive metrics:

It can be represented mathematically as follows

$$m(p) = \sum_{i=1}^{LK} m(lk_i)$$

Where $m(p)$ is the total of metric m of path p, lk_i is a link in the path (p) and LK is the number of links in path (p). Delay and jitter can be thought as examples of this class.

- Concave metrics:

$$m(p) = min/max(m(lk_i))$$

Bandwidth can be thought as an example of this class.

- Multiplicative metrics

$$m(p) = \prod_{i=1}^{LK} m(lk_i)$$

Reliability (error free transmission probability) can be thought as an example of this class.

Routing in the Internet is composed of two terms, routing protocol and routing algorithm. The routing protocol mainly gets the information about the current state of the network and informs all routers in the network. The routing algorithm computes the path that the packets must follow to reach their destinations.

In order to enable a routing algorithm to make an optimal routing decision, it is important to make this decision based on correct and the most recent information about the topology and states of the links of the network. This routing information (state) can be collected in local, global or aggregated global levels [2].

For the local state, each router is assumed to keep its local information up-to-date including queuing and propagation delay, bandwidth of the outgoing links, security, loss probability, and the availability of other resources.

In link state protocols, every router needs global state which is collected by exchanging local states among all routers. In distance vector protocols, local state information and information collected by exchanging the local states among the neighboring routers are used. Link-state protocols broadcast the states of links between routers so that each router knows the topology of the network and the state of every link. Distance-vector protocols periodically exchange distance vectors among adjacent routers.

For the aggregated global state, a common approach to achieve scalability is to reduce the size of the global state by aggregating information according to the hierarchical structure of large networks.

Obviously, routing information has to be updated frequently. The more frequent updating, the more accurate the routing decision. However, there has to be a trade-off between accuracy and overhead.

The routing algorithms can be classified according to many criteria [2]. From the perspective of this thesis, number of QoS metrics can be thought as a classification criteria and routing algorithms can be classified as follows:

- Single metric routing

It includes routing algorithms that consider only one metric like delay, bandwidth or hop count. Dijkstra or Bellman-Ford shortest path algorithms [5] can be used to find optimal routes.

- Multiple metric routing.

SMM (Single Mixed Metric) can be considered in this category. The main idea is to eliminate the links or paths that do not have enough bandwidth and then work the routing algorithm based on SMM. The algorithm combines delay and loss probability by using propagation delay and the value of "logarithmic transmission success probability function (slog)" which will be explained in section 2.4.6

2.2. Architectures that provide QoS guarantees

One of the architectures that extend the original TCP/IP architecture to cater for QoS requirements is the Integrated Services (IntServ). IntServ needs keeping state information at each router for the connections passing through that router and needs a separate reservation protocol [6]. This protocol uses the information about the ongoing connections and available resources at the routers from source to destination whether they have sufficient resources to satisfy the requested QoS guarantees or not for a connection request. The Resource Reservation Protocol (RSVP) is currently the protocol that can be used for reservations. In RSVP, the source sends a path message to receiver. The path message includes the data packet formats and the traffic characteristics of the data connections. The path message stores the IP addresses of the routers. After receiving the message, the receiver replies with a descriptor used to request resource reservations. Every router along the path may reject or accept the message. If any router rejects the message, it sends an error message back to the receiver and reservation signaling terminates. If any router accepts the message, it allocates the reserved bandwidth and buffer space for connection state information is placed on the database and a reservation request is passed to the next router on the path.

The problems with IntServ model such as large operating cost of keeping connection state information on the routers, the extra time to extract necessary information to classify a datagram and looking up the database to identify connection and the need for a separate signaling protocol for reservation have motivated the development of Differentiated Services (DiffServ).

The basic idea of DiffServ model is the simplification of the packet classification. Packets are classified at the network boundaries into several classes, which are treated differently according to different packet scheduling and policing rules with in the network [6].

Another architecture that may enable QoS provisioning, Multi Protocol Label Switching (MPLS), uses labels to forward the packets [7]. A label distribution protocol is used to inform the MPLS-capable routers on how to forward packets with a specific label. Since the labels are shorter than IP addresses, the packets can be forwarded at a faster rate. The use of labels also brings other advantages, like the support for explicit routing. This gives network/service providers a great deal of flexibility to divert and route traffic around link failures, congestion and bottlenecks, and to provide QoS routing. Therefore, in MPLS networks, quality of service routing may be supported and it is allowed packets, belonging to the same connection, following the same route whereas it is not guaranteed in datagram networks.

2.3. Restricted Shortest Path Algorithms (RSP)

2.3.1. Exact Algorithms

The optimal path for RSP problem can be found by searching over every path between source and destination. The brute-force depth search algorithm can find an optimal path for any route request if the network is not large and no time constraint exists. As the size of the network increases, the number of paths increases exponentially and it is not feasible to find a solution in practical time period.

Another algorithm, known as Constrained Bellman-Ford (CBF) [8] is also not useful in practice. The CBF concept consists of discovering the lowest cost paths while increasing their delays in total. CBF keeps a list of paths from source to every other node with increasing cost, delay and performs a breadth-first search until it finds a node whose list contains a path that satisfies delay request and has a minimum cost. Although CBF solves the RSP problem, the execution time of this algorithm grows exponentially with the size of the network.

2.3.2. Backward-Forward Heuristic

In backward-forward algorithms [9], the network is searched based on the combination of the two parts. The first part is the path from source *s* to any intermediate route *u* where the path is so far explored. The second part is the least delay or least cost path from intermediate node *u* to destination *d*. The backward-forward algorithms can be implemented in a centralized or distributed manner. In the distributed case the algorithm sends a probe packet over the preferred links one at a time. If the receiving node accepts the packet, it sends it to the next node. If the receiving node rejects the packet, the algorithm tries to send the probe packet over another preferred link. In the centralized manner the algorithm calculates the least delay path (LDP) and the least cost path (LCP) from every intermediate node *u* to destination *d*. After calculation, the algorithm starts to search the network from source as in Dijkstra's algorithm.

2.3.3. LARAC

As it is mentioned earlier, a routing problem is NP-complete if the number of additive QoS routing parameters is more than one. Most of the routing methods do not intend to solve this complex problem. Instead of solving the problem, they define simpler problems. The problem to find a path that is minimal for a cost and delay of it remains under the bound can be defined as *Delay Constrained Least Cost Problem (DCLC).* The Lagrange Relaxation-Based Aggregated Cost Algorithm (LARAC) [10] provides a heuristic solution to DCLC problem.

In LARAC algorithm, the shortest path is calculated on cost function with Dijkstra algorithm. It means the shortest path is calculated by the algorithm with whatever the original cost is (Delay, hop count, bandwidth…). If the found path meets the delay requirement then the algorithm stops. Otherwise the algorithm store the path as the best path and it checks whether an appropriate solution is exists or not. In checking process, algorithm calculates the shortest path on delay *d.* If the shortest path meets the delay requirement then algorithm stores the path as the best path. Otherwise there is no suitable path from source to destination and algorithm stops.

2.3.4. ε - Optimal Approximation

One of the general approaches to deal with an NP-complete problem is to use a polynomial time algorithm which finds an approximation of the optimal one. A ε-optimal algorithm must return a path whose cost is at most (1+ ε) times the cost of the optimal cost for ε > 0. In [11], Hassin proposed an algorithm where he initially determines an upper bound (**UB**) and a lower bound (**LB**). The algorithm starts with LB=1 and UB are equal to the sum of the (N-1) largest link costs and then control these bounds using a testing procedure. After LB and UB is computed, the algorithm finds the cost of every link by rounding and scaling it by εLB. At the end, a polynomial time algorithm is applied with new link weights.

2.3.5. Rerouting

The main idea of dynamic rerouting especially in circuit-switched networks is to increase the performance by routing the existing connections to alternate paths when the direct path is blocked. In addition, the use of alternate paths usually consumes more network resources as cost and path length usually is longer. The alternate path search decreases the throughput of network. Therefore, many different dynamic rerouting strategies such as Dynamic Nonhierarchical Routing (DNHR) and Dynamically Controlled Routing (DCR) are developed. [12]

In dynamic routing, when a connection request arrives, the routing decision must be made with available information on the network at that time. One method to increase the throughput of the dynamic routing is to redistribute network load to eliminate bottlenecks. Rerouting is the practice whereby connections on alternate paths can be rerouted back to direct paths or to other less congested alternate paths.

2.4. Multi-Constrained Path Algorithms (MCP)

2.4.1. Chen's Algorithm

Chen proposes an algorithm [13] for MCP problem with a polynomial time complexity. With this algorithm, first the NP-complete problem is reduced to a basic one, which can be solved in polynomial time, and then it is solved by using extended Dijkstra's or Bellman-Ford algorithm. For a directed graph $G = \{V, E\}$, from source vertex s, to destination vertex t, two weight functions which are additive $w_1: E \rightarrow R^+$ and $w_2: E \rightarrow R^+$, two constants $c_1 \in R^+$ and $c_2 \in R^+$ are defined. The problem is described as for $MCP\ (G, s, t, w_1, w_2, c_1, c_2)$ finding a path p from s to t where $w_1\ (p) \leq c_1$ and $w_2\ (p) \leq c_2$.

In multi-constrained routing, for example, two constraints delay and bandwidth can be taken into account as two weight functions. Given a source node s and a destination node t, delay and bandwidth constrained routing problem is to find a path p from s to t such that delay $(p) \leq D$ and bandwidth $(p) \leq B$ where D and B are required to have end to end delay and bandwidth bounds respectively.

2.4.2. Jaffe's Algorithm

Jaffe's approximation algorithm first determines two positive multipliers as d_1 and d_2 [14]. The algorithm uses these multipliers to calculate a composite weight value for every link *w (u, v)* by linearly combining the original weights. After calculation, algorithm finds the shortest path with respect to these weights. The shortest path search process is illustrated in Fig. 1. All possible paths between source *s* and destination *d* are indicated by black circles. The paths, whose path lengths are equal with respect to weights, are indicated by a line. The search for the minimum length path is equivalent to sliding this indication line outward from the origin until a path is hit. This path is the solution to routing problem. The figure also shows that the returned path does not necessarily reside within the feasibility area defined by the constraints. In fact, Jaffe proposed using a nonlinear function whose minimization guarantees finding a feasible path. But there is no shortest path algorithm to minimize such a nonlinear function. Instead, Jaffe provided this algorithm and showed how to determine d_1 and d_2 based on this nonlinear function.

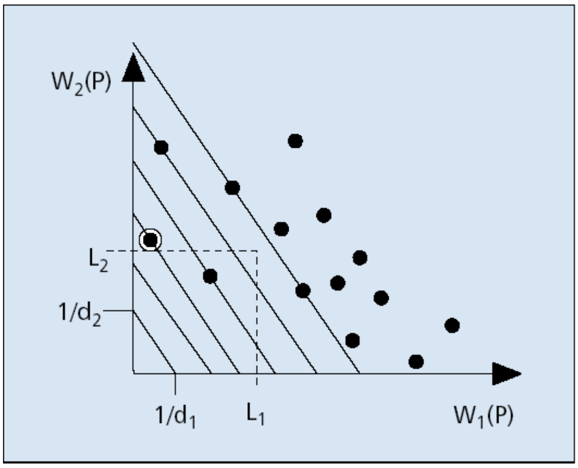

Figure 1 Search process in Jaffe's algorithm.

2.4.3. TAMCRA and SAMCRA

TAMCRA finds a path between a given source and destination subject to the constraints L_j on each QoS measure. Mainly TAMCRA is based on three fundamental concepts [15] :

- A non-linear measure for the path length
- *k*-shortest path approach
- Non-dominated path principle

In the path length calculation, all additive QoS measures are considered having equal importance and each link associated with an m-dimensional weight vector as *(w1, w2, w3… wm)*. The path vector $w_j(P) = \{w_1(P), w_2(P), w_3(P) \ldots w_m(P)\}$ is the vector sum of the weights of links along that path. An important point in non-linear length function is "the subparts of shortest paths in multiple dimensions are not necessarily shortest paths". It suggests considering more paths than only the shortest one. The k-shortest path concept is applied to intermediate nodes between source and destination. A *k*-shortest path algorithm does not stop when the destination has been reached for the first time, but continues until it has been reached through *k* different paths succeeding each other in length.

The algorithm records the multiple paths from source to any intermediate node but not all paths. The distinction is made based on the non-dominance of a path. For example, for two paths, *X* and *Z*, *X* is said to be dominated by *Z* if $w_i(Z) \leq w_i(X)$ for all $i=1,\ldots m$. TAMCRA only considers non-dominated subpaths that reduce the search space. If a path *P* satisfies $l(P) \leq 1$ then it is a feasible path and it is a solution to MCP problem. But this path may not be optimal in terms of route length.

SAMCRA algorithm is a modified version of TAMCRA. It has an improved version of path finding. It guarantees finding a feasible path if there exists such a path. In addition, it uses buffer and allocates buffer space when really needed and it can adjust the number of stored paths at each node self adaptively. Because stored path number is not predefined in SAMCRA, this adjustment could lead to an exponentially growing stored path at each node and complexity is not polynomial

2.4.4. A Randomized Algorithm

The concept behind the randomization is to avoid unexpected situations by making random decisions during the execution of algorithm [16]. It is obvious that restricting the routes to short paths makes possible efficient resource utilization in QoS based routing. The randomized algorithm tries to select a feasible path with minimum hop count by achieving efficient utilization of resources. The algorithm mainly consists of two steps. (1) Initialization phase and (2) Randomized Search phase.

In the first phase, the algorithm tries to compute the shortest paths from every node to destination with respect to each QoS metric and with respect to linear combination of all QoS metrics. In this phase, algorithm can decide whether there is a chance of finding a feasible path or not. It labels and prunes all links that cannot be on any feasible paths with respect to given constraints. In the randomized search phase, it systematically discovers every node that is reachable from source with randomized and modified version of Breadth-First search (BFS). It randomly discovers those nodes from which there is a high probability of reaching destination. Algorithm can foresee the reaching probability and try other nodes. The simulation results show that the algorithm can find feasible paths with two or three additive constraints on different networks over 99% of all feasible paths.

2.4.5. Limited Path Heuristic

Limited granularity and Limited Path Heuristic (LPH) have a high percentage of finding a feasible path if there exists such a path. Although both methods can solve multi-constrained QoS routing problems in polynomial time, limited granularity requires much more resources than limited path heuristic [17]. Limited granularity is based on the idea of using bounded finite ranges to approximate QoS metrics which reduces the NP complete problem to a simpler form. To achieve good performance limited granularity must maintain large tables in each node which is a time and resource consuming operation. But LHP is based on the extended Bellman-Ford algorithm except that before a path is inserted into PATH database (all optimal QoS paths found so far from source to destination), the size of PATH database is checked. LPH also uses two main concepts used in TAMCRA, k-shortest path approach and non-dominated path principle. But usage of *k*-shortest path approach is different. LPH stores the first *k* paths, not necessarily the shortest path. In addition, LHP check if a subpath obeys the constraints only when destination is reached.

2.4.6. Single Mixed Metric (SMM)

The single mixed metric routing protocols basically have two versions. The first one is based on distance vectors and the second one is based on link states. [18] The metrics, propagation delay, available bandwidth and the link loss probability are taken into account for single mixed metric routing algorithm. According to SMM routing protocol the main idea is to eliminate the links or paths that do not have enough bandwidth and then work the routing algorithm based on SMM. The algorithm combines delay and loss probability by using propagation delay and the value of "logarithmic transmission success probability function (slog)". For a link from node *i* to *j*

$$slog_{ij} = | \log (1-L_{ij}) |$$

where L_{ij} is loss rate of link. In a network, each link (i,j) has the available bandwidth b_{ij} and SMM $u_{ij} = slog_{ij} + d_{ij}$. The integer part of u_{ij} represents delay where as the decimal part represents loss. For a path $p=(i,j,k,....q,r)$, the $w(p)$ is $min[b_{ij}, b_{jk}.. b_{qr}]$ and the $l(p) = u_{ij}+u_{jk}+...+u_{qr}$

The routing problem is to find a path where $w(p) \geq B$ and $l(p) \leq U$ where B is given minimum bandwidth and U is maximum SMM which is equal to $D+P$. D is the maximum delay and P is the maximum logarithmic transmission-success probability. The simulation results show that the average performance gain of Single Mixed Metric Distance Vector Routing Algorithm is 50%.

CHAPTER 3

THE PROPOSED ROUTING ALGORITHM

In this chapter a priority based multi-constrained QoS routing algorithm is proposed for military applications. First, some notation regarding problem definition is given and the cost metrics used in the algorithm are introduced. In the algorithm, QoS metrics delay and packet loss ratio are considered as basic metrics on path selection and a military metric, priority, and bandwidth are used as the decisive metrics in cost computation to determine existing connections to break for a higher priority level connection request for which there is no suitable path to use to provide requested service quality.

3.1. Notation

In the rest of the thesis, a single source and destination pair with various paths through the network is considered for a connection request. For a given connection request, bandwidth, delay and packet loss ratio constraints are represented with $L_{(b)}$, $L_{(d)}$ *and* $L_{(plr)}$.

The network is represented by a graph $G = (V, E)$ consisting of a set of nodes, V, and a set of edges, E. Nodes represent the routers and edges represent the communication links. Fully connected networks with nodes without self-loop links and at most one link between a pair of nodes are considered. A specific link in the set E between nodes u and v is represented as (u, v).

Two classes of QoS measures are used: the additive and min-max QoS measures. For additive QoS measures, the cost of using a path P is the sum of the link's QoS measures along the path P. Additive QoS measures considered are *delay*, *packet loss ratio* (this is actually a multiplicative metric, but it can be converted into an additive metric using logarithm transformation) and *hop count* (this metric is used in algorithm in order to limit the number of possible paths). The military metric *priority* and *bandwidth* are considered as min-max QoS measures.

3.2. Problem Statement

The problem of finding a path that satisfies multiple QoS constraints is known as multi-constrained path search problem which is defined in [19] as follows;

In a given network G = (V, E) where lk_i is a link in the path (p), LK is the number of links in path (p) and L_i given constraints for that metric,
for each additive metric m,
m(p) is the total of metric m of path p,

$$m(p) = \sum_{i=1}^{LK} m(lk_i) \leq L_i$$

for each multiplicative metric m,
m(p) is the product of $m(lk_i)$ along the path p, m(p) is equal to 1 minus multiplication of 1 minus metric m of path p,

$$m(p) = (\ (1-m(lk_i)) * (1-m(lk_j)) * \ldots * (1-m(lk_l))\ )$$

$$m(p) = 1 - \prod_{i=1}^{LK} (1-m(lk_i)) \leq L_i$$

by taking the negative sign of the logarithm of the multiplicative metric on each link, they are transformed to positive, additive metrics.

$$\prod_{i=1}^{LK} (1-m(lk_i)) = -\sum_{i=1}^{LK} \log(1-m(lk_i))$$

For each concave metric m,

m(p) is the min/max of $m(lk_i)$ *along the path p,*

$$m(p) = min/max(m(lk_i))$$

A path that satisfies all constraints is said to be a feasible path. There may be more than one path in the graph that satisfies all the constraints. However, one of these should be chosen according to the desired properties among all feasible paths. In other words, one of the constraints is optimized and the final solution to the path problem is selected according to that constraint.

3.3. Cost Metrics Used

The QoS metrics used in different QoS routing algorithms are very similar to each other. Especially the priority based routing algorithms are based on cost in terms of money. The proposed routing model is different from previous routing algorithms in that military metrics are used.

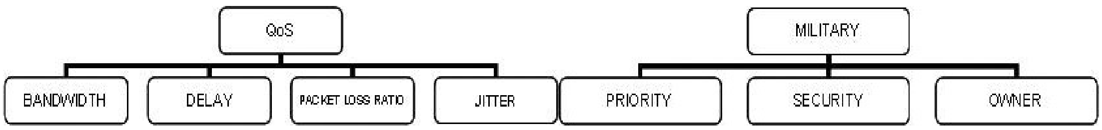

Figure 2 Cost metrics used

In Figure 2, seven different metrics are shown. The first four metrics are accepted as basic QoS metrics. Bandwidth, delay and packet loss ratio are used in our algorithm. The last three metrics are considered as military metrics [20]. But only priority is used in our routing algorithm.

The military priorities and necessities make the development of military applications which are used for decision support systems more complex and time sensitive. The metrics can be broadly categorized into four classes:

- Communication Type

- Communication Priority
- Communication Security
- Communication Owner

The first category involves QoS measures and represents the communication type among the separated troops in an unpredicted size area in battlefield. It can be classified into three types:

- Voice
- Data
- Real Time Applications

The connections can be established for voice or data. In addition, a video conferencing can take place between frontline commanders and command center. As predicted, different types of communication need different bandwidth, delay and packet loss ratio. These three metrics are QoS metrics and they are used in the first part of proposed algorithm.

The other three metrics are defined according to military terminology. In summary, the priority can be explained as level of:

- High
- Middle
- Low

The priority level *high* refers to "very important information that affects the battle capability of troops or cause the troops engage with enemy". *Middle* priority level represents the information that is important. Finally, *low* priority level means the information is about routine activities. The priority level of information is the most important metric among the second group.

The security level of any information can be detailed in three levels:

- Top Secret
- Secret
- Unclassified

The *top secret* security level can be used for foreign and national army intelligence information, personnel intelligence, strategic and tactical war planning.

The top secret information transfer can not be allowed on wireless media, only cable communication is allowed with cryptographic apparatus. The *secret* security level is used for the information which is allowed to be seen by responsible personnel. The *unclassified* security level is referred to the information which is not suitable to be seen by non-military personnel.

The communication owner is also considered as an important metric for military applications. The owner metric can be classified as:

- Command Center
- Special Forces
- Reconnaissance Units
- First Line Troops
- The others

3.4. Routing Algorithm

In a given network, there may be many requests coming from different kinds of applications such as voice, data or real time. After determining the communication type and the destination, the algorithm starts to search a route for the connection request. The bandwidth (b), delay (d) and packet loss ratio (plr) are determined according to the communication type and it is assumed that destination and military metric priority is supplied with the request.

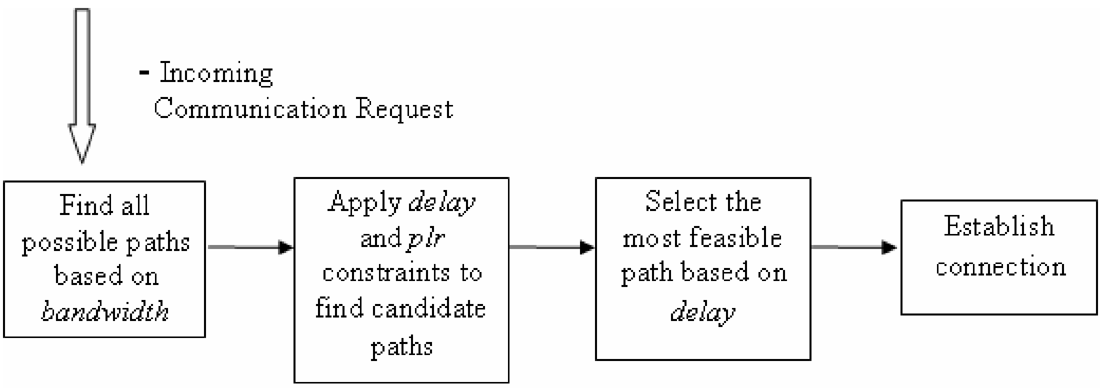

Figure 3 First part flow chart of routing algorithm

In the first part of the algorithm, as shown in figure 3, from source to destination all possible paths are found without examining the delay and packet loss ratio values of the links. While finding all possible paths, only the available bandwidth values of the links which constitutes a path from source *s* to destination *d* is examined. If available bandwidth of link *(u, v)* is smaller than the requested bandwidth, then any path which uses the link between the nodes *u* and *v* is not thought as a feasible path and it is ignored. After finding all possible paths, *delay* and *plr* constraints are applied. The possible paths must satisfy the condition:

$$P = \{s, u, v, \ldots, k, d\}$$

$$P_{(d)} \leq L_{(d)}$$

In other words, the total *delay* value of a possible path must be equal to or smaller than the requested *delay* value and this condition should also be true for *plr* value of the path. The total *plr* value for the path can be found in terms of link *plr* values as:

$$P_{(plr)} = 1 - ((1-plr(s, u)) * (1- plr(u, v)) * \ldots * (1- plr(k, d)))$$

And this value should satisfy

$$P_{(plr)} \leq L_{(plr)}$$

If more than one path satisfies the above constraints, a comparison is done according to the delay metric. The path which has the minimum delay value is selected as the feasible path. The multi-constrained optimal path finding problem can be solved with proposed algorithm and *delay* metric can be used as the decision metric to select the feasible path among all possible paths.

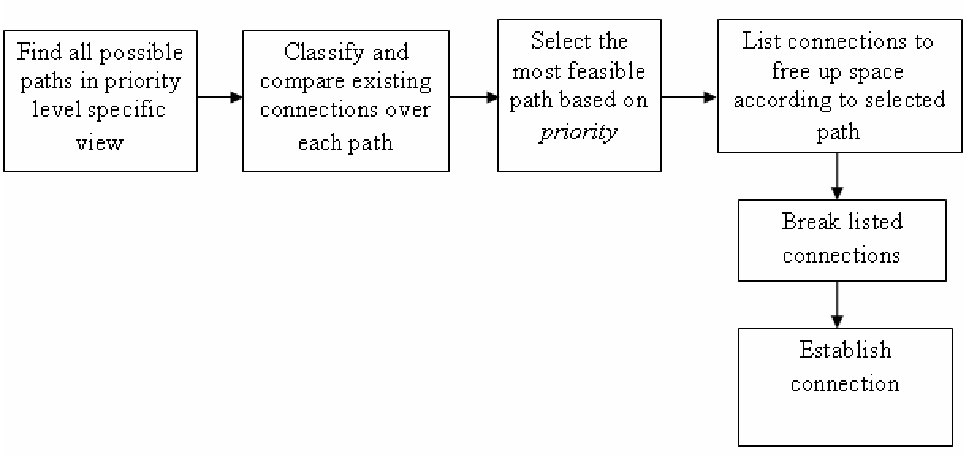

Figure 4 Second part flow chart of routing algorithm

In the second part of the algorithm, as shown in figure 4, if there is no possible path for the connection request, all possible paths are searched in priority level specific view. There are two priority level specific views of the network. The first one is *high priority level view* which is formed with only existing connections with high priority level and second one is *middle priority level view* which is formed with only existing connections with high and middle priority levels. For a high priority level connection request is to be routed, high priority level view is used, and for a middle priority level connection request is to be routed, middle priority level view is used. If there is any path that meets the *bandwidth*, *delay* and *plr* requests at the priority level specific view, it is possible to find a feasible path for connection request by freeing up some space by breaking existing connections. If there is still no path, a *no path message* is sent back and algorithm stops.

After finding all possible paths in related view, the algorithm constitutes a table to keep the information of each possible path. In this table, possible paths, number and priority level of existing connections which should be broken to free up some space for connection request and used bandwidth value of existing connections for each possible path is recorded.

A cost-effective decision making is applied in classification and comparison section of the algorithm. The most feasible path is selected based on the military metric *priority*. If two or more paths which have the same number of the same priority level connections, we choose the one which uses the most bandwidth in the network. In any other case, a combination of *middle* and *low* priority level connections or three *middle* level connections can be found by the algorithm as a solution. Such a case does not change the decisive function of the algorithm.

As an example, suppose that the command center (*S*) wants to make a video conference in *high* priority level with the frontline mission commander (*D*) in the given network in Figure 5 and suppose that the requested bandwidth value for video conference is 8. In this figure, A, B, C represents the routers between source (*S*) and destination (*D*). The values on edges as *B=12* indicates the bandwidth capacity of each edge between any two routers. The connections on each edge are showed as *Call-1=5(M), Call-2=3(H).* The integers, on the right side of the equivalence represent the used bandwidth value of connections and letters (*M: Middle*) and (*H: High*) represent priority levels.

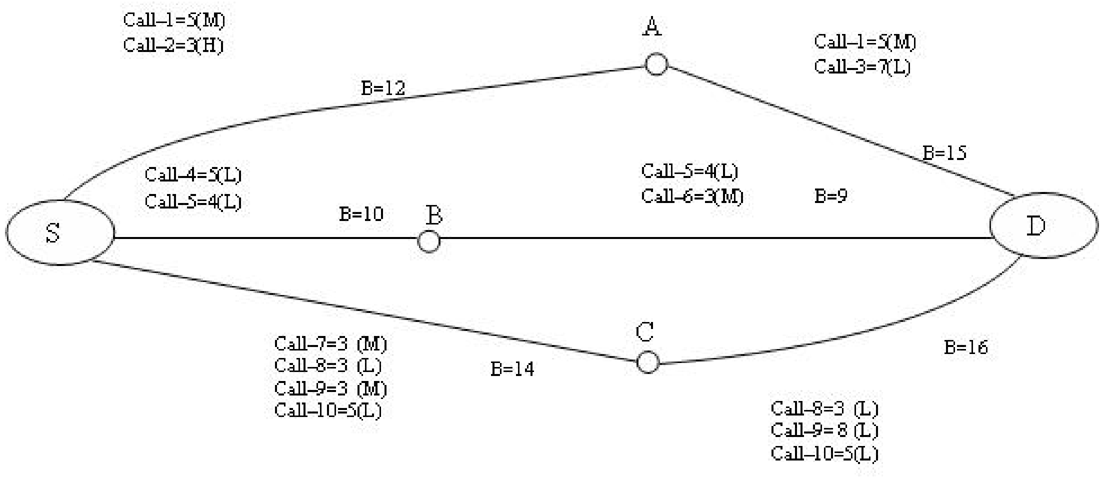

Figure 5 An Example Situation

Since there is not enough bandwidth for video conference request in high priority level, all possible paths are searched in high priority level view as shown in figure 6 (a) and determined possible paths are listed below. Figure 6 (b) is given as an example to middle priority level view.

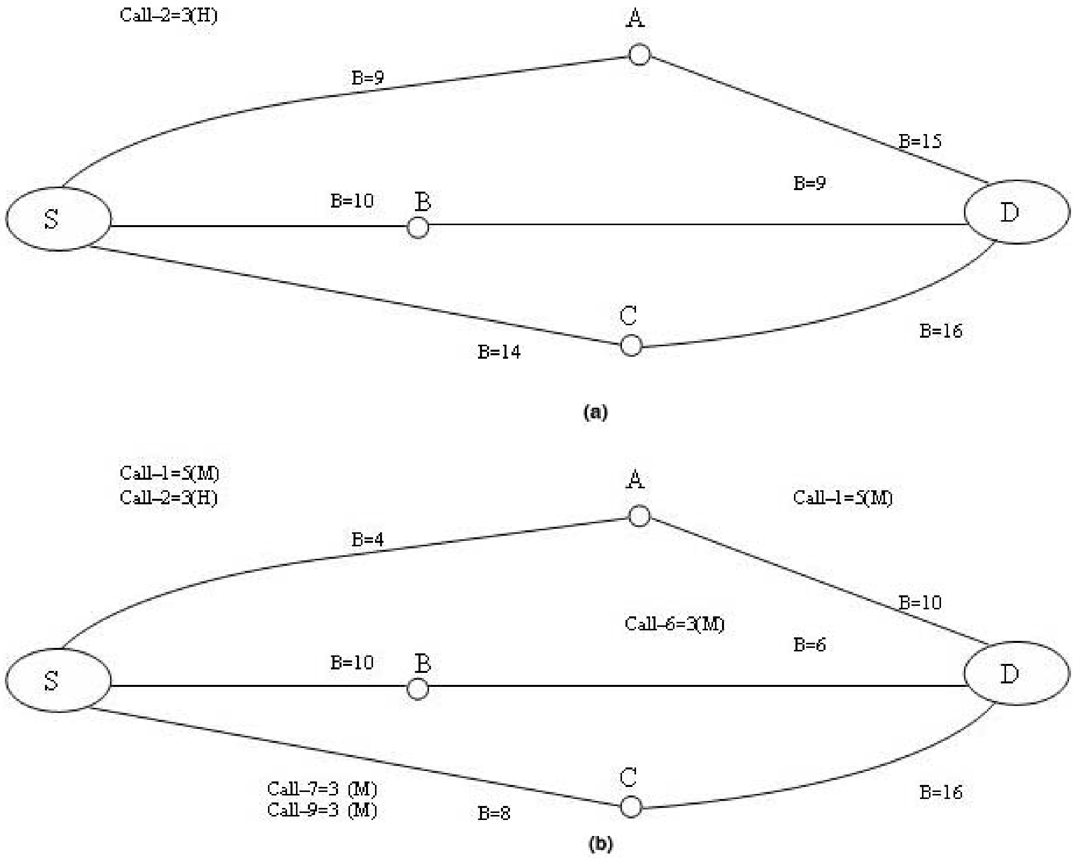

Figure 6 Priority Level Views (a) High Priority Level (b) Middle Priority Level

P_1=*S, A, D,*

P_2=*S, B, D,*

P_3=*S, C, D*

After determining possible paths, we classify the connections to break according to their priority levels and make a comparison for each connection combination with the edges of each path. The connection combinations are derived from the existing connections on each path. For {S, A, D} path, breaking Call-1 is an option where as for {S, C, D} path, breaking both Call – 8 and Call - 10 is an option to free up space. As a result the table given below can be formed:

Table 1 Path Records

Path	Middle	Low	Used Bandwidth
{*S, A, D*}	1 (Call-1)	0	5
{*S, B, D*}	1 (Call-6)	2 (Call-4 & Call-5)	12
{*S, C, D*}	0	2 (Call-8 & Call-10)	8

While deciding on the solution, we select the most feasible path based on the cost priority. As it can be seen from the table, if we choose the first path, we can find a path for video conference by breaking Call-1 with *middle* priority. If we choose the third path we can find a path for video conference by breaking Call-8 and Call-10 with *low* priorities. Because of military priority necessities, we choose the third path as a solution. Instead of breaking a *middle* priority level connection, two *low* level connections can be broken for a higher priority level connection request.

After path selection, two *low* priority level connections are broken and a path for video conference is established between command center and frontline mission commander.

The proposed routing algorithm guarantees finding a path for a connection request, whether or not necessary resources are used by other connections except the same or higher priority levels. A cost analysis is made based on the military metric priority. It can be thought that the cost of the broken connections may reach a higher value and just for a higher priority request up to three lower priority level connections can be broken is not feasible. But in the military context, it is always accepted that if the priority level increases, the information vitality increases.

CHAPTER 4

PERFORMANCE EVALUATION

In this chapter, performance of the proposed routing algorithm has been evaluated by computer simulations. The performance is evaluated on MESH, ARPA and NSF networks. In the following section, the simulation tool developed for this purpose is presented. On each mentioned network, the *blocking probability* with and without preemption and *breaking probability* values are measured by this simulation tool and compared for three different traffic profiles according to connection priorities.

4.1. Simulation Environment

In this study, a special-purpose simulation tool to measure the performance of the proposed routing algorithm is implemented using Delphi 7. A graphic component [21] is used for drawing figures and simulation is executed on a Pentium 4 with 512 MB RAM to evaluate the performance of proposed routing algorithm. The simulation software executed 9 times for 30 hours on three different networks for three different traffic profiles. The screenshots of the simulation system on applied networks are presented in Appendix A.

The system measures *blocking* and *breaking* probabilities for each priority level. *Blocking probability* is defined as the ratio of number of blocked connection requests to number of all connection requests. *Breaking probability* is defined as the ratio of the number of broken existing connections to make space for new connection requests to the number of all routed connections. Some of the features of the simulation tool are as follows:

- For the sake of simplicity, the networks on which the simulations are to be carried out are hard coded in the simulation tool (a different network may be introduced by changing the simulation software).
- Connection requests and their parameters such as *bandwidth, delay, plr, priority,* are read from an input file in order to repeat the same simulation with different parameters.
- Simulation input files are formed randomly for each different traffic profile on each network.
- Bi-directional links are considered.
- Connection requests arrive according to Poisson process and holding times are distributed exponentially.
- The average holding time is selected as 1000 milliseconds and all the tests are done for 1, 2, 3 and 4 connection requests per second.
- The source and destination for each connection request are chosen randomly.
- Hop limit, *the maximum length of a connection between a source and a destination*, is selected as 10 for the used networks and it can be rearranged for each network by changing the simulation software.
- The confidence interval is selected ± 0.05 with $p>0.95$ probability.
- Three different traffic profiles shown below are used. In the first one, network is loaded heavily with low priority level connection requests, in the second one, network is loaded equivalently with low, middle and high priority level connection requests and in the third one network is loaded heavily with middle and high priority level connection requests.
    - LL: Heavily low priority level connection requests arrive.
        - Low priority level connection request ratio is %60,
        - Middle priority level connection request ratio is %20,
        - High priority level connection request ratio is %20.
    - SL: Connection request's priority level ratio is approximately the same.
        - Low priority level connection request ratio is %33,

        - Middle priority level connection request ratio is %34,
        - High priority level connection request ratio is %33.
    - HL: Heavily high priority level connection requests arrive.
        - Low priority level connection request ratio is %20,
        - Middle priority level connection request ratio is %40,
        - High priority level connection request ratio is %40.

4.2. Performance of the Proposed Routing Algorithm

In the simulations, we consider two performance measures: *Blocking Probability* and *Breaking Probability*. We measure the performance of proposed routing algorithm on three different networks under different loads as explained in section 4.1. We try to find the positive effect of our algorithm on routing by measuring the *blocking probability* with and without preemption. In addition, *breaking probability* is measured to determine the cost of our algorithm while making space for higher priority level connection requests.

4.2.1. Blocking Performance for Middle Priority Level

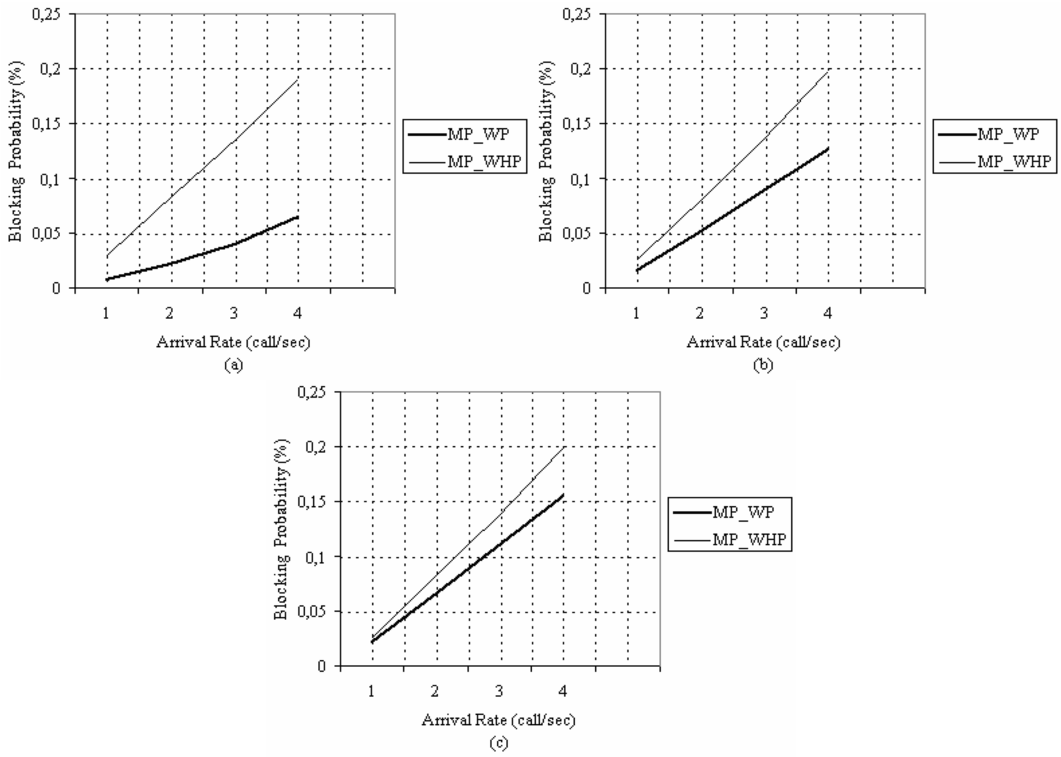

Figure 7 Middle Priority Level Blocking Probability on MESH Network (a) LL (b) SL (c) HL

Blocking probability is measured for middle priority level on LL, SL and HL traffic profiles to show the benefit of the proposed routing algorithm for middle priority level connection requests. When the arrival rate is 1, with preemption (*MP_WP*: *Middle priority with preemption*) and without preemption (*MP_WHP*: *Middle priority without preemption*) blocking probability values are very close to each other in LL, SL and HL traffic profiles on MESH network. As the arrival rate increases, the difference among the blocking probability values *with preemption and without preemption* increases in LL, SL and HL traffic profiles. In LL traffic profile (Figure 7 (a)), middle priority level connection requests have the advantage of finding a path by breaking low priority level connections. Because, low priority level connection request ratio is considerably higher than middle priority level connection request ratio in LL traffic profile. Therefore, the blocking probability value of middle priority level connection request has its minimum value in LL traffic profile. But in

SL traffic profile as shown in Figure 7 (b), and mostly in HL traffic profile as shown in Figure 7 (c), low priority level connection request ratio is lower than LL traffic profile and finding a path by breaking low priority level connection probability decreases and the increase in blocking probability is more than LL traffic profile.

Table 2 Blocking Probability for Middle Priority Level Connection Requests

Network	Without Preemption	With Preemption		
		LL	SL	HL
MESH	0,1912	0,0653	0,1265	0,1547
ARPA	0,1547	0,0473	0,0897	0,1179
NSF	0,2168	0,0665	0,1362	0,1695

In table 2, the blocking probability values are presented under the load of 4 connection requests per second. The blocking probability values of middle priority level in MESH, ARPA and NSF networks are between 0,0473 and 0,1695 with preemption and between 0,1547 and 0,2168 without preemption. According to simulation results, the proposed routing algorithm reduces the blocking probability on average 7,57% in MESH network, 8.1% in ARPA network and 9.27% in NSF network for middle priority level.

Blocking probability performances for middle priority level connection requests on ARPA and NSF networks are presented in Appendix B.

4.2.2. Blocking Performance for High Priority Level

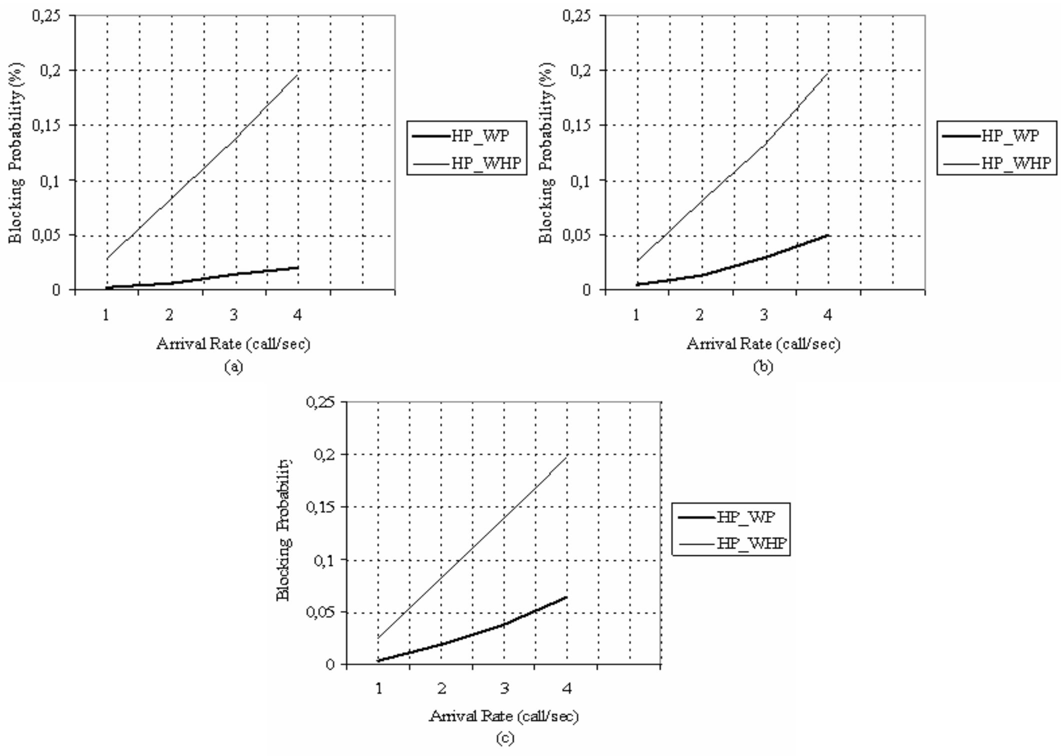

Figure 8 High Priority Level Blocking Probability on MESH Network (a) LL (b) SL (c) HL

Blocking probabilities for high priority level connection requests in LL, SL and HL traffic profiles are measured to evaluate the benefit of the proposed routing algorithm for high priority level connection requests. As shown in figure 8, when the arrival rate is 1, with preemption (*HP_WP*: *High priority with preemption*) and without preemption (*HP_WHP*: *High priority without preemption*) blocking probability values are not close to each other in LL, SL and HL traffic profiles on MESH network as for the middle priority level. In the beginning, the blocking probability value without preemption is about 0.02 whereas it is about 0.002 with preemption when the arrival rate is 1. As the arrival rate increases, the difference among the blocking probability values increases. In spite of the increase in low or middle priority level connection request ratio, in all three traffic profiles, the blocking probability value of high priority level almost has the same increase in percentage. In other words, LL, SL and HL traffic profiles does not affect high priority level blocking probability as they affect middle priority level blocking probability.

Table 3 Blocking Probability for High Priority Level Connection Requests

Network	Without Preemption	LL	SL	HL
MESH	0,1968	0,0202	0,0496	0,0643
ARPA	0,1578	0,0146	0,0306	0,0476
NSF	0,1685	0,0176	0,0498	0,063

In table 3, the blocking probability values are presented when the arrival rate is 4 requests per second. The blocking probability values of high priority level in MESH, ARPA and NSF networks are between 0,0146 and 0,0643 with preemption and between 0,1578 and 0,1968 without preemption. According to simulation results, the proposed routing algorithm reduces the blocking probability on average 15,21 % in MESH network, 12,68 % in ARPA network and 12,5 % in NSF network for high priority level.

Blocking probability performances for High priority level connection requests on ARPA and NSF networks are presented in Appendix C.

4.2.3. Breaking Probability Performance

The proposed routing algorithm may find paths for higher priority connection requests by breaking lower priority level connections when necessary. Breaking probability of lower priority level connections is also measured in three different networks for different traffic profiles.

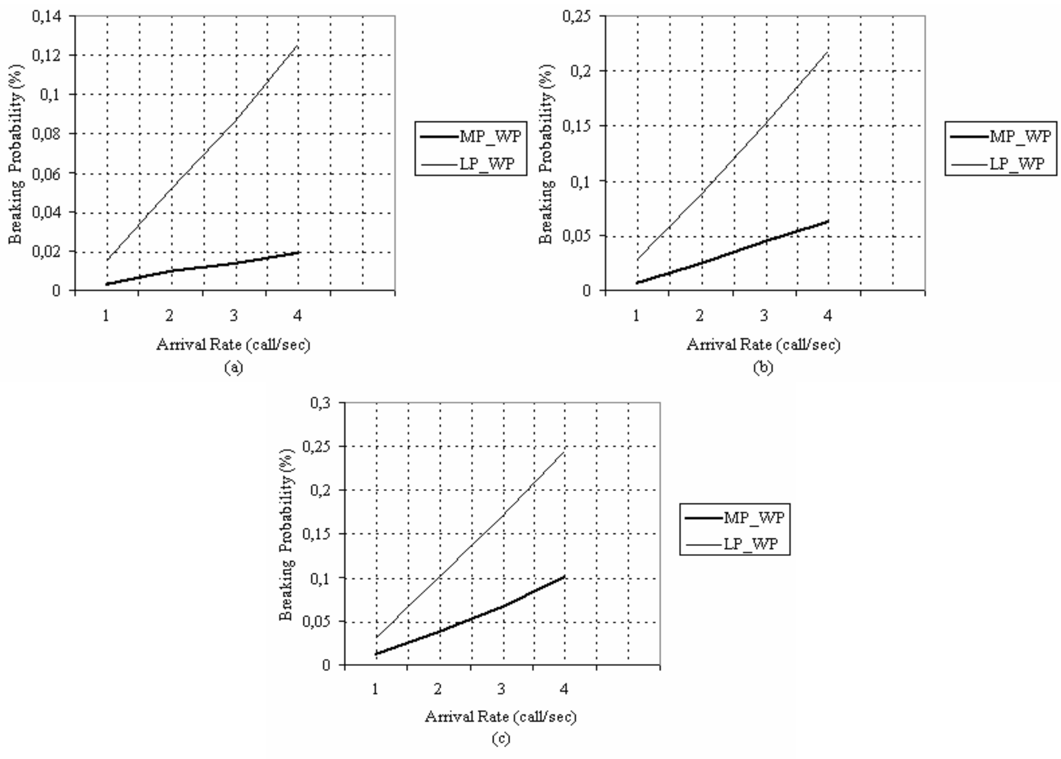

Figure 9 Breaking Probabilities on MESH Network (a) LL (b) SL (c) HL

In Figure 9, low and middle priority level connection breaking probabilities are shown (*LP_WP: Low priority with preemption, MP_WL: Middle priority with preemption)* in different traffic profiles. Low priority level connection breaking probability increases as middle and high priority level connection request ratio increases in the network. In SL traffic profile, middle and high priority level connection request ratio increases approximately 50% percent with respect to LL traffic profile and in HL traffic profile middle and high priority level connection request ratio increases 25% percent with respect to SL traffic profile. The change in middle and high priority level connection request ratio increases the breaking probability of low priority level connections. However, the same comment cannot be done for the breaking probability of middle priority level connections. Because lower priority level connections are broken first and there is no need to break middle priority level connections if there are enough low priority level connections in the network. Moreover, in the algorithm, we allowed breaking of up to three low priority level connections instead of a single middle priority level connection.

Connection breaking probabilities for low and middle priority level connections on ARPA and NSF networks are presented in Appendix D.

CHAPTER 5

CONCLUSION

In this thesis, a new multi-constrained Quality of Service Optimal Path Routing Algorithm is proposed to meet the future needs of armed forces in the battlefield. In our algorithm, a military metric is used as well as a basic quality of service metric in cost computations. We used quality of service metrics such as bandwidth, delay and packet loss ratio to find a path for connection requests. If there is no suitable path for a connection request, existing connections are checked to see if the connection request can be routed by breaking some of the existing connections. For this purpose, a military metric, priority, is used in cost calculation to determine the connections to break to free up space for a higher priority level connection request.

The proposed routing algorithm consists of two parts. In the first part, if resources are available to provide the requested service quality then the connection is established. In the second part, if there are not enough resources to provide the requested service quality then priority and bandwidth based cost is calculated among existing lower priority level connections. After cost computation, if there are some existing connections that can be used to free up space for a higher priority level connection request, those connections are broken and requested connection is established.

It is expected that the proposed routing algorithm should decrease the blocking probability of middle and high priority level connection requests and the cost of breaking connections is at a reasonable level. The performance evaluation by simulations has revealed that proposed routing algorithm decreases blocking probability on average between 7% and 15% in different networks with different priority levels and average breaking probability is on average 3% for middle priority level connections and 10% for low priority level connections. It is also noticed that breaking the most bandwidth consuming connections in the case of equivalence in priority level value of cost table has provided lower blocking probability.

In the proposed routing algorithm, we used only priority as the decisive military metric while determining the connections to break and the connections having the same priority level are not considered. However, having the same priority level, two connections may be compared to each other according to other metrics such as security and communication owner which can also be used along with priority as a weighted military metric. Security is related to infrastructure most of the times and it should be handled separately. If the infrastructure is wireless, then the security metric value should be high. If infrastructure is wired, then security metric value should be low. The security metric can also be measured as a kind of min/max metric. The usage of more than one military metric needs combination of other metrics with priority. By the help of this approach, the same priority level connection requests can also be considered in the cost calculation and this is considered as a future work.

When compared to some of the other routing algorithms, there exist some differences between proposed routing algorithm and the algorithms mentioned in chapter II as Multi-Constrained Path Algorithms. Chen's Algorithm and Jaffe's algorithm use two weight functions for two constraints. TAMCRA and SAMCRA apply non-dominated path principle and along with Single Mixed Metric use m-dimensional weight vector. In our algorithm, we use three metrics and all metrics are considered separately. There is no any weighted value for metrics. In addition, none of them use forth metric as decisive metric in case of equivalence.

Although the implementation aspects are not addressed, it is thought that a central controller based implementation is possible for this algorithm. Maintaining the last updated traffic information, finding paths for each request and deciding which existing connections to break for a high priority request if required can be done on this central controller. Distributed version of this algorithm is considered as a future work issue.

It is further assumed that all packets belonging to the same connection travel the same route. Although this cannot be guaranteed for a datagram network, special architectures like MPLS can help to satisfy this assumption..

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APPENDICES

A. SCREEN SNAPSHOTS OF APPLIED NETWORKS

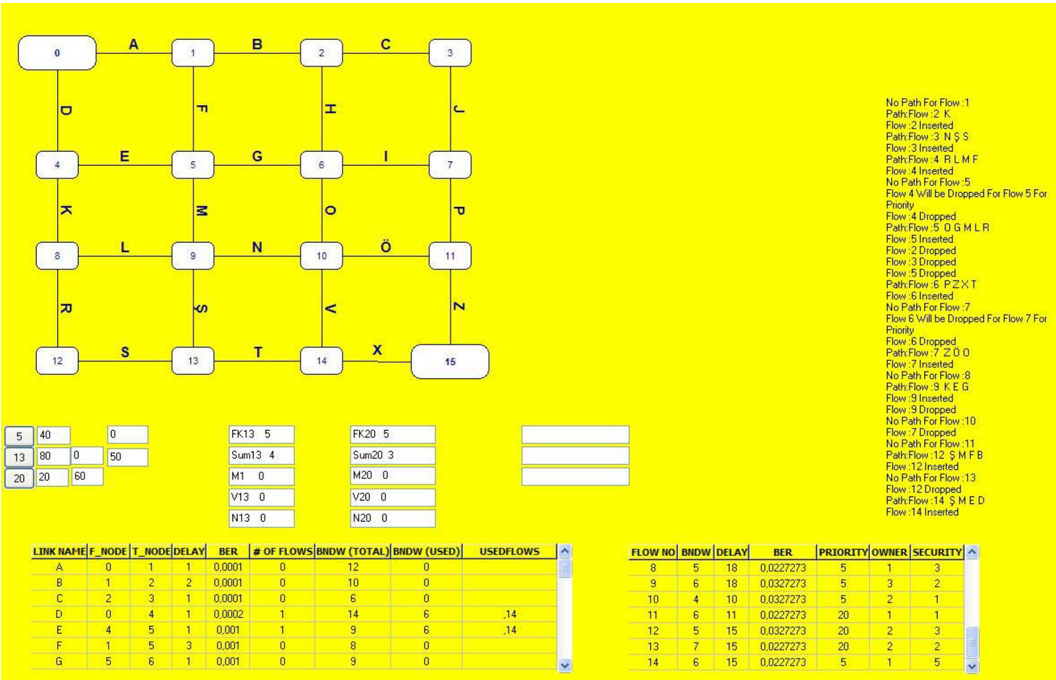

Figure 10 MESH Network

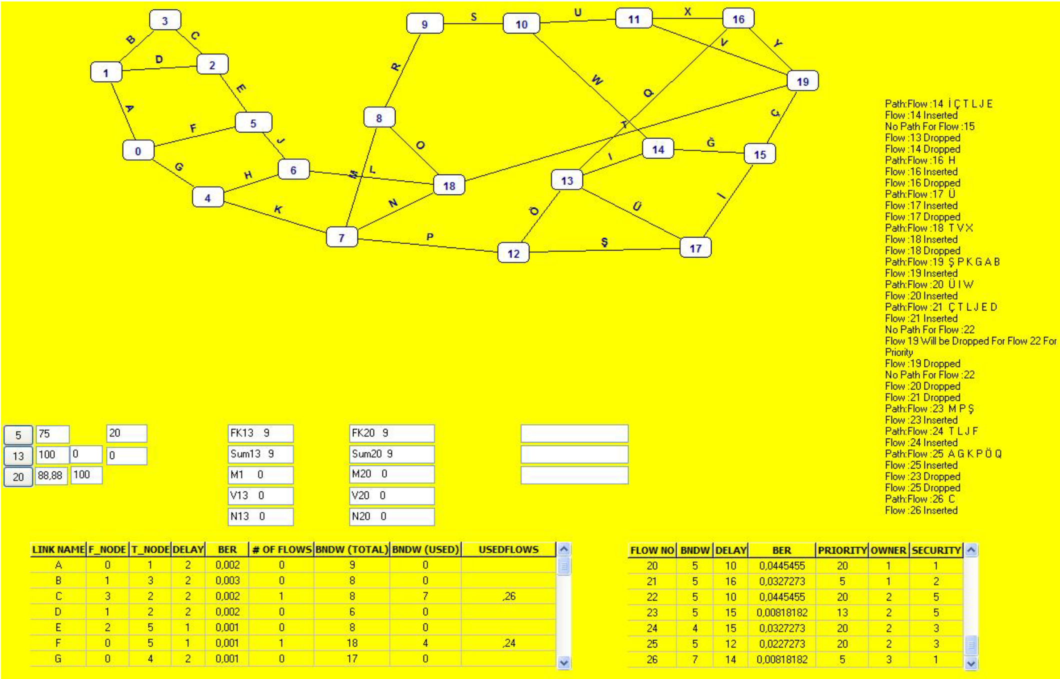

Figure 11 ARPA Network

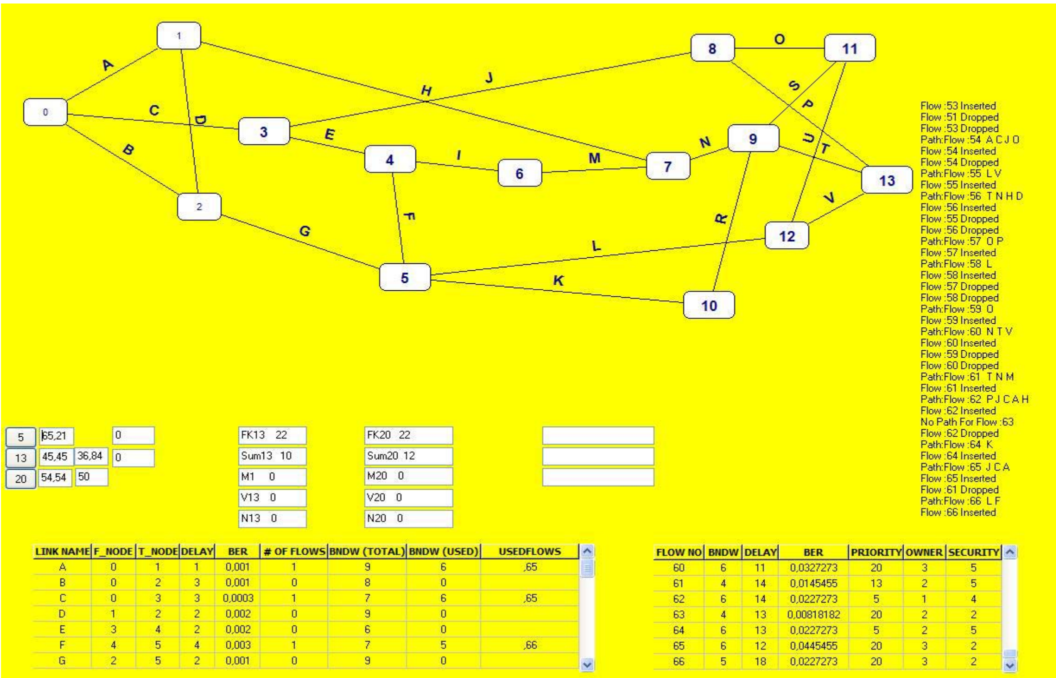

Figure 12 NSF Network

B. MIDDLE PRIORITY LEVEL BLOCKING PROBABILITY

ARPA Network

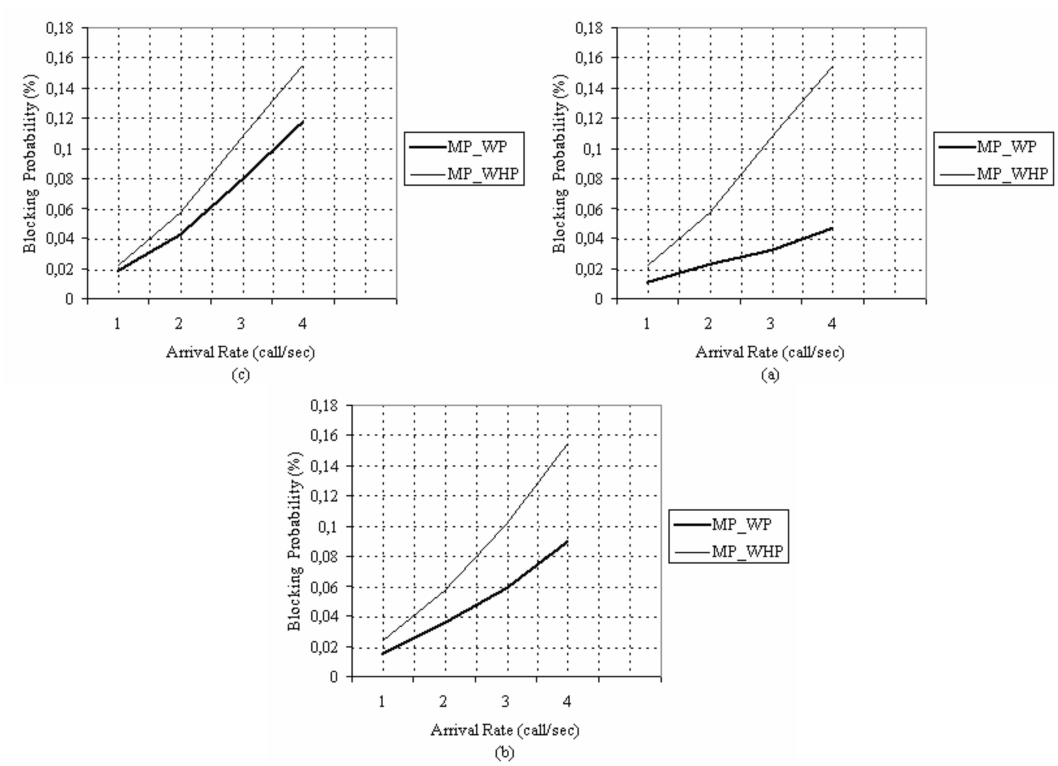

Figure 13 Middle Priority Level Blocking Probability on ARPA Network (a) LL (b) SL (c) HL

NSF Network

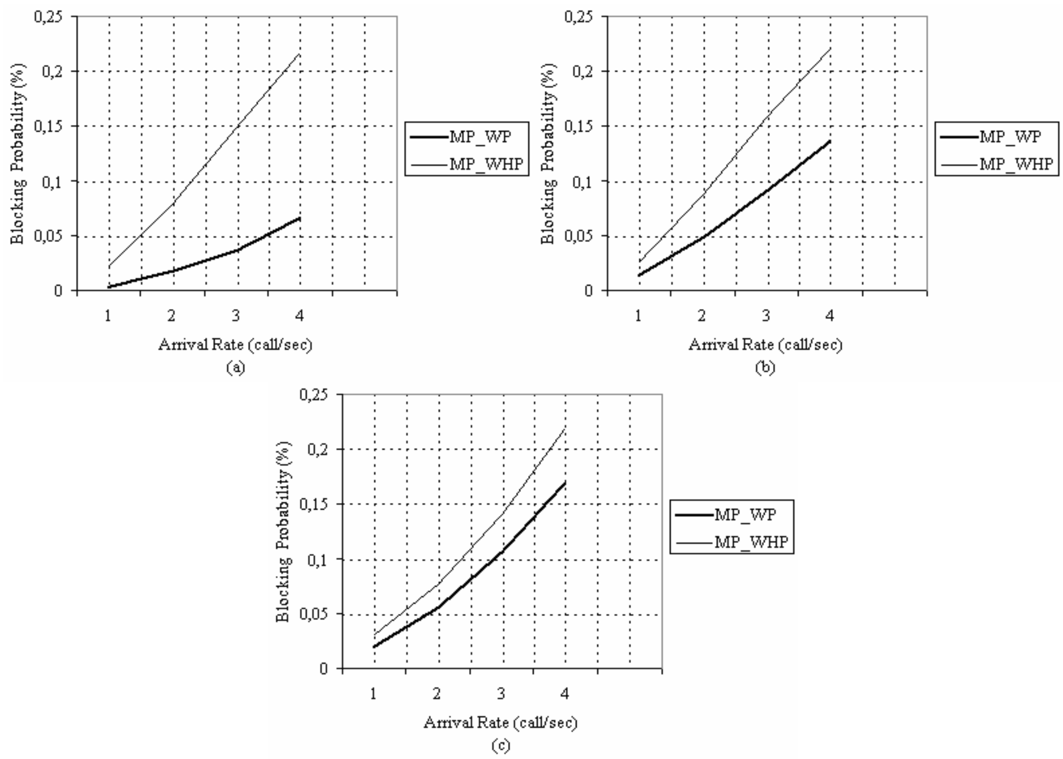

Figure 14 Middle Priority Level Blocking Probability on NSF Network (a) LL (b) SL (c) HL

C. HIGH PRIORITY LEVEL BLOCKING PROBABILITY

ARPA Network

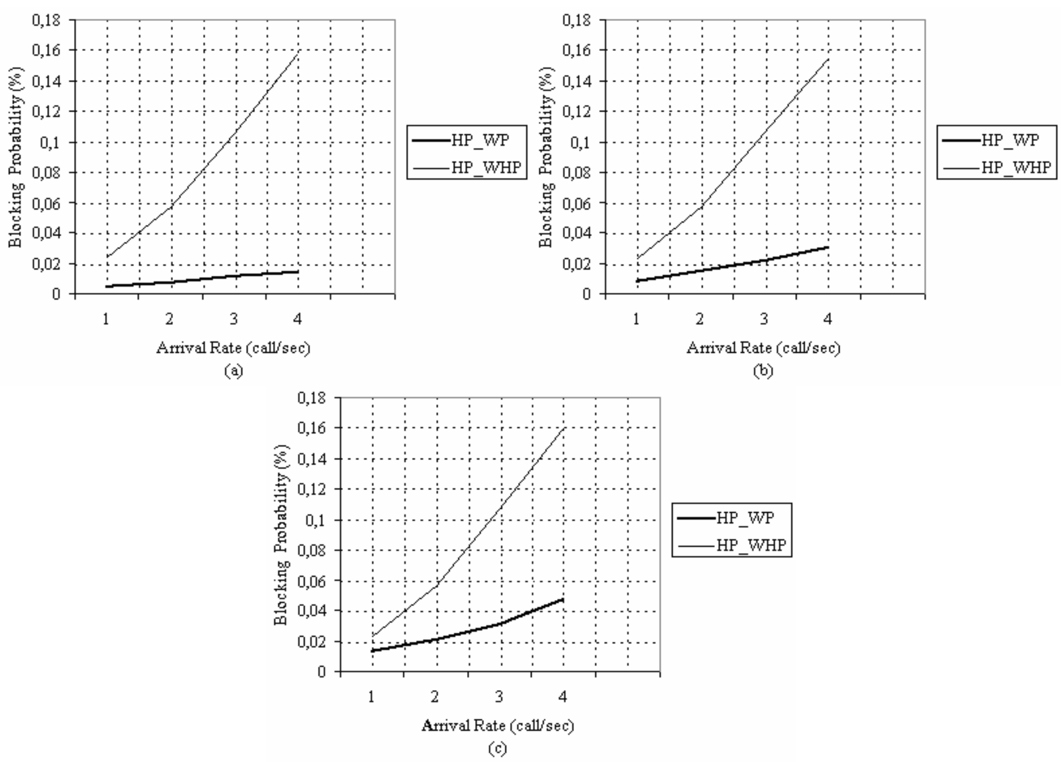

Figure 15 High Priority Level Blocking Probability on ARPA Network (a) LL (b) SL (c) HL

NSF Network

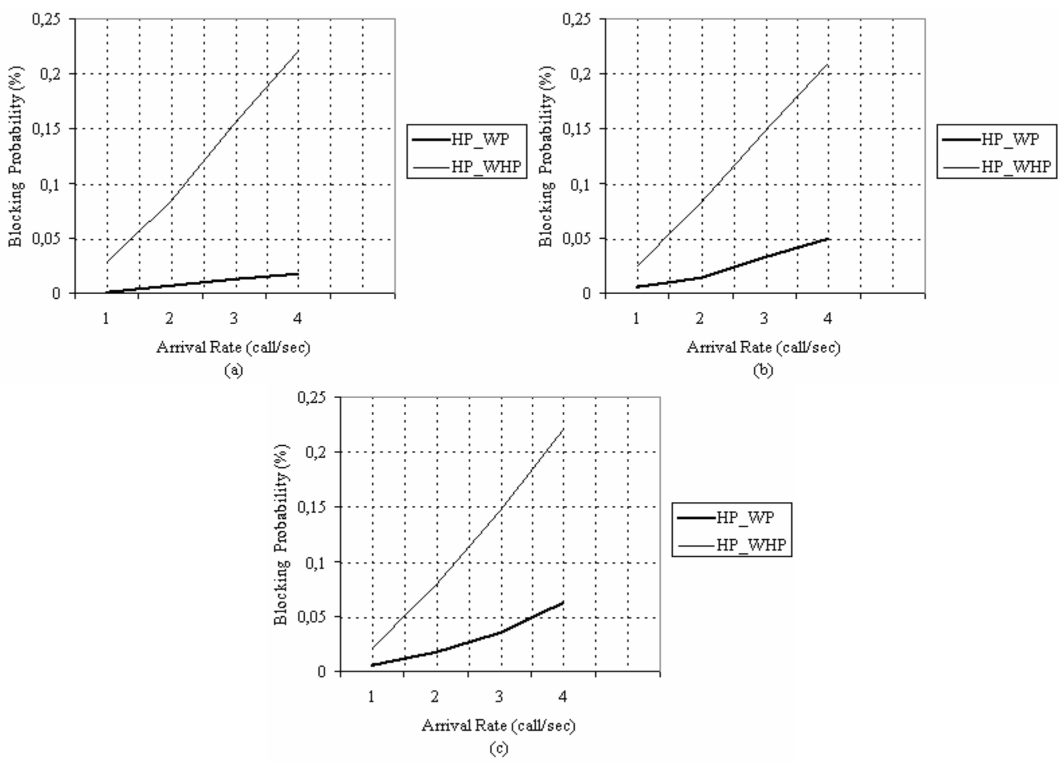

Figure 16 High Priority Level Blocking Probability on NSF Network (a) LL (b) SL (c) HL

D. LOW AND MIDDLE PRIORITY LEVEL BREAKING PROBABILITY

ARPA Network

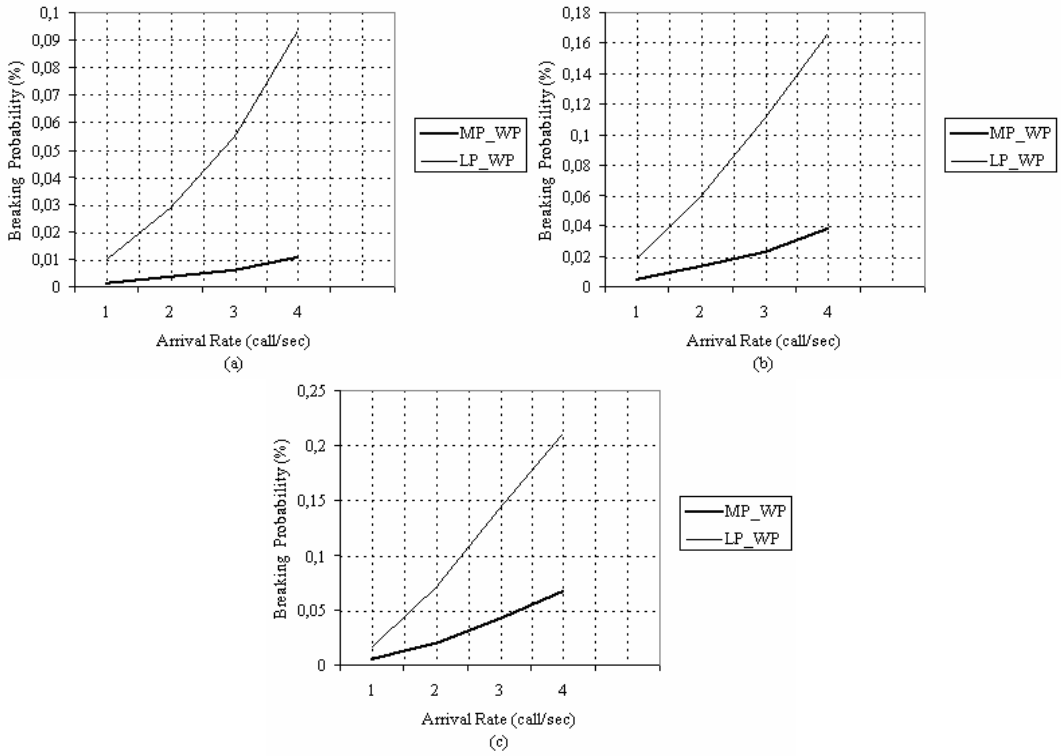

Figure 17 Breaking Probabilities on ARPA Network (a) LL (b) SL (c) HL

NSF Network

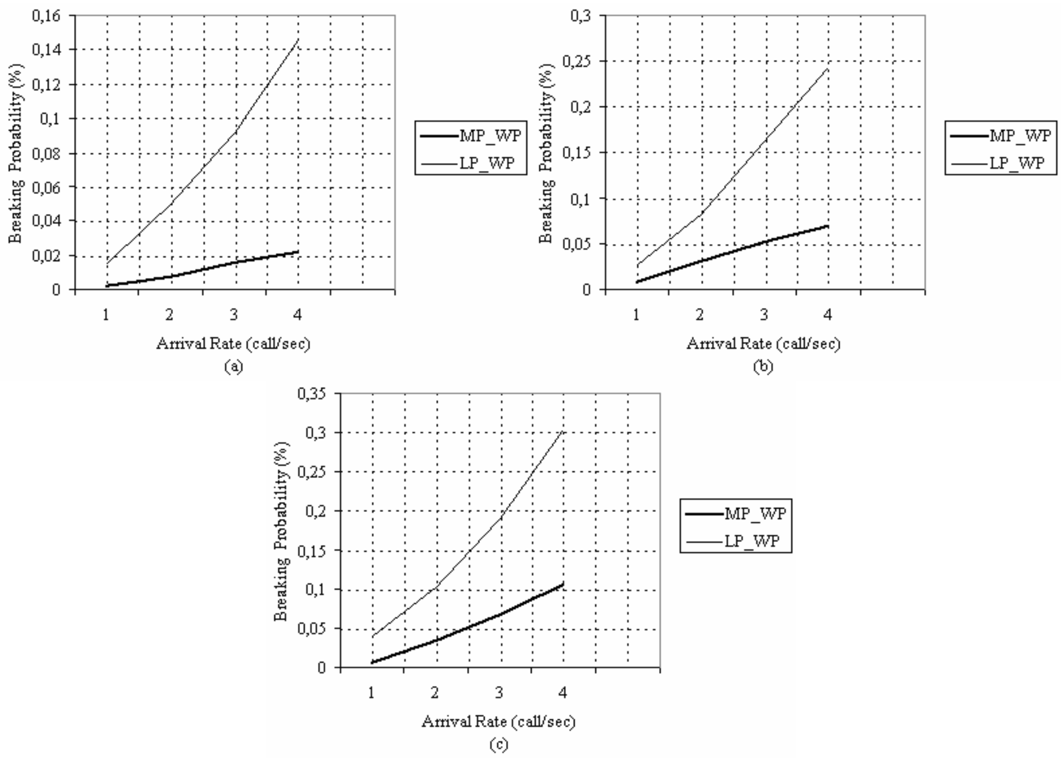

Figure 18 Breaking Probabilities on NSF Network (a) LL (b) SL (c) HL