UNIVERSITI PUTRA MALAYSIA

MULTI AGENT QUALITY OF SERVICE ROUTING BASED ON SCHEME ANT COLONY OPTIMIZATION ALGORITHM

MAASSUMEH JAVADI BAYGI

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By

MAASSUMEH JAVADI BAYGI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

Agust 2014

DEDICATION

**I dedicate this dissertation to my parents,
my husband, my daughter and above all almighty and merciful god**

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

A MULTI-AGENT ROUTING SCHEME BASED ON ANT COLONY OPTIMISATION ALGORTIHM FOR QUALITY OF SERVICE IN IP NETWORKS

By

MAASSOUMEH JAVADI BAYGI

January 2014

Chairman : Abd Rahman Ramli, PhD

Faculty : Institute of Advanced Technology

The current Internet needs to support a wide variety of applications with different demands in terms of Quality of Service (QoS) requirements including constraints on throughput, delay, jitter, loss rate. Differentiated Service (DiffServ) has been proposed by the Internet Engineering Task Force (IETF), motivated by the desire to serve different types of traffic in IP networks. While much of the existing work on DiffServ focus on scheduling policies, in order to provide QoS for high-quality Internet applications, QoS-aware path selection is important. Known as QoS Routing (QoSR), this multiple constraints path selection is considered NP-Complete. Some algorithms provide QoS in term of routing, but they usually focus on improving the performance of the highest priority traffic, at the expense of the lower priority classes. In order to fully exploit the network resources, and to meet QoS requirements of various classes concurrently, it is important to establish class dependent paths. Therefore, an algorithm which can adaptively assign network resources to meet the QoS requirements of different classes simultaneously is still needed.

This research presents a per class QoS routing approach based on Ant Colony Optimization (ACO) called ACR-QoS to provide QoS for different Class of Services (CoSs). Traffic of different classes can be distributed in accordance with network states and QoS requirements. The important new aspect of ACR-QoS is the combination of constraint-based routing and DiffServ architecture, in Swarm Intelligence (SI) structure where a set of artificial ants is used to determine the optimal path for each class to construct class-based routing tables. This approach allows easy and efficient design of service classes, while no changes are needed at lower layers. This study also introduces a new probe-based procedure for discovery and setup QoS path for real-time traffic. The proposed scheme has been simulated by OMNET++ and compared with standard AntNet and two well-known standard QoS routings; Widest Shortest Path (WSP) algorithm and

Shortest Widest Path (SWP) algorithm. Experiment results show that the desired service class differentiation is obtained and ACR-QoS satisfies the QoS requirements of each CoS without discriminating against the best-effort traffic. In comparison with standard AntNet, results confirm that the modifications and extensions applied to AntNet can significantly reduce the average packet delay and jitter by about 11.8% and 46% respectively in transient regime. It can also improve the throughput in link failure state by about 25% and decrease the packet loss rate by 27% and 39% before and during link failure respectively. Moreover, the proposed approach outperforms the WSP and SWP algorithms, where network efficiency in saturated load gains an 8.39% improvement while the satisfaction of delay and jitter constraints for time critical applications are also achieved. In saturated load, efficiency is a very important parameter and a few changes in it can result in high performance of network to delivery of data.

Abstrak tesis dikemukakan untuk Senat Universiti Putra Malaysia bagi Memenuhi Keperluan Ijazah Doktor Falsafah

SKEMA PENGHALAAN MULTI-AGEN BERASASKAN PENGOPTIMUMAN KOLONI SEMUT UNTUK KUALITI PERKHIDMATAN DALAM RANGKAIAN IP

Oleh

MAASSOUMEH JAVADI BAYGI

Januari 2014

Pengerusi : Abd Rahman Ramli, PhD

Fakulti : Institut Teknologi Maju

Untuk menyediakan Kualiti Perkhidmatan (QoS) bagi aplikasi Internet semasa berkualiti tinggi dengan keperluan yang pelbagai ke atas kekangan seperti kadar celus, kelambatan, dan ketaran, Pemilihan laluan berkesedaran QoS adalah penting. Dikenali sebagai Penghalaan QoS (QoSR), pelbagai kekangan dalam pemilihan laluan ini dianggap sebagai NP-keras. Kajian ini membentangkan suatu skema penghalaan QoS inovatif berasaskan Pengoptimuman Koloni Semut (ACO) yang dikenali sebagai ACR-QoS bagi menyediakan QoS kepada pelbagai Klas Perkhidmatan (CoS) dalam internet. Aspek baru yang paling penting dalam ACR-QoS adalah kombinasi penghalaan berdasarkan kekangan dan seni bina perkhidmatan terbeza (DiffServ). Struktur Kumpulan Cerdas (SI) di mana satu set semut tiruan telah digunakan untuk mengenalpasti laluan optimum bagi setiap kelas dan untuk membina jadual penghalaan berdasarkan kelas. Kaedah ini membenarkan rekaan yang mudah dan cekap bagi kelas perkhidmatan dengan tiada perubahan diperlukan pada lapisan bawah. Kajian ini juga memperkenalkan suatu prosedur siasatan untuk penemuan dan membentuk laluan QoS untuk trafik masa nyata.

Skema yang dicadangkan telah disimulasikan dengan OMNET++ dan dibandingkan dengan AntNet piawai dan dua penghalaan QoS terkenal iaitu algoritma laluan terluas terpendek (WSP) dan algoritma laluan terpendek terluas (SWP). Hasil eksperimen menunjukkan perbezaan perkhidmatan kelas yang diharapkan dapat diperolehi dan ACR-QoS memenuhi keperluan QoS bagi setiap CoS tanpa membezakan trafik kerja terbaik.

Sebagai perbandingan dengan AntNet piawai, hasil kajian mengesahkan bahawa pengubahsuaian dan sambungan yang diaplikasikan kepada AntNet dapat mengurangkan dengan banyak kelambatan dan ketaran purata paket sebanyak 11.8% dan 46% masing-

masing dalam regim alihan. Juga, ianya dapat mempertingkatkan kadar celur dalam keadaan rangkaian gagal sebanyak 25% dan mengurangkan kadar kehilangan paket sebanyak 27% dan 39% sebelum dan selepas kegagalan pautan masing-masing.

Tambahan pula, prestasi skema yang dicadangkan melangkaui algoritma penghalaan QoS lain yang dikenalpasti dalam kajian ini di mana kecekapan rangkaian dalam beban tepu mendapat peningkatan 8.39% sementara kepuasan bagi kelambatan dan kekangan ketaran bagi aplikasi masa kritikal juga dicapai. Dalam beban tepu, kecekapan adalah parameter penting dan beberapa perubahan kecil dalamnya akan menyebabkan rangkaian berprestasi tinggi dapat menghantar data.

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This thesis is dedicated to my family. I offer my heartfelt gratitude to my husband for his support and sacrifice in taking on most of the family work. Loving thanks to my daughter Asana for her understanding and great patience to endure our separation. I also give my appreciation to my parents who instilled within me a love of creative pursuits and science. It was a great challenge for me to complete my Ph.D. with husband and a daughter. Without the support from all of the above people, I cannot imagine how I could have gone through this long journey and now I am glad that their encouragement and support made this journey a success.

Maassoumeh Javadi Baygi

Approval Sheet

I certify that a Thesis Examination Committee has met on 16 January 2014 to conduct the final examination of Maassoumeh Javadi Baygi on her thesis entitled "Multi-Agent Quality of Service Routing Based on Scheme Ant Colony Optimization Algorithm" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the candidate be awarded the Doctor of Philsophy.

Members of the Thesis Examination Committee were as follows:

Syed Abd Rahman Al-Haddad bin Syed Mohamed, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Mohamed bin Othman, PhD
Professor
Faculty of Computer Sceince and Information Technology
Universiti Putra Malaysia
(Internal Examiner)

Mohd Fadlee bin A Rasid, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Yoshiyasu Takefuji, PhD
Professor
Keio University
Japan
(External Examiner)

NORITAH OMAR, PhD
Associate Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 21 April 2014

Approval Sheet

This thesis submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee are as follows:

Abdul Rahman Ramli, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Borhanuddin bin Mohd. Ali, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Syamsiah Mashohor, PhD
Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

BUJANG BIN KIM HUAT, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 21 April 2014

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Signature: : ________________________

Name of Chairman of Supervisory Committee: :**Syed Abd Rahman Al-Haddad bin Syed Mohamed**

Signature: : ________________________

Name of Member of Supervisory Committee: **Mohd Fadlee bin A Rasid, PhD**

Signature: : ________________________

Name of Member of Supervisory Committee: : **Mohamed bin Othman, PhD**

Signature: : ________________________

Name of Member of Supervisory Committee: : **Yoshiyasu Takefuji, PhD**

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LIST OF ABBREVIATIONS

ABC	Ant-Based Control
ACA	Ant Colony Algorithm
ACO	Ant Colony Optimization
ACR-QoS	Ant Colony Routing with QoS
ACS	Ant Colony System
AF	Assured Forwarding
AI	artificial intelligence
AS	Autonomous System
ATM	Asynchronous Transfer Mode
BA	Behaviour Aggregate
BB	Bandwidth Broker
BE	Best Effort
BGP	Border Gateway Protocol
BRP	Bandwidth Restricted Path
BT	British Telecom
CAC	Connection Admission Control
CAF	Cooperative Asymmetric Forward
CBQ	Class-based Queuing
CBR	Constant Bit Rate
CO	Combinatorial Optimization
CoA	Class of Ant
CoS	Class of Service
CoT	Class of Traffice

CR-LDP	Constraint Route Based Label Distribution Protocol
DiffServ	Differentiated services
DS	Domain DiffServ Domain
DSCP	Differentiated Services Code Point
DSR	Dynamic Source Routing
DSVC	Distance Vector
EF	Expedited Forwarding
GA	Genetic Algorithm
IETF	Internet Engineering Task Force
IGP	Interior Gateway Protocol
IntServ	Integrated Service
IP	Internet Protocol
ISP	Internet Service Provider
LS	Link State
LSA	Link State Advertisement
LSP	Link State Packet
LSU	Link State Update
LTS	Local Traffic Statistics
MCOP	Multi Constraints Optimal Path
MPLS	Multi-Protocol Label Switching
OR	Operations Research
OSI	Open Systems Interconnections
OSPF	Open Shortest Path First
PHB	Per Hop Bihavior
PQ	Priority Queuing

PSO	Particle Swarm Optimization
QoS	Quality of Service
QOSPF	QoS Open Shortest Path First
QoSR	Quality of Service Routing
RFC	Request for Comments
RIP	Routing Information Protocol
RSP	Restricted Shortest Path
RSVP	Resource reservation protocol
RTT	Round Trip Time
SI	Swarm Intelligence
SLA	Service Level Agreements
SLS	Service Level Specification
SNMP	Simple Network Measurement Protocol
SWP	Shortest Widest Path
TCP	Transmission Control Protocol
TCS	Traffic Conditioning Specification
TE	Traffic Engineering
ToS	Type of Service
TSP	Traveling Salesman Problem
TTL	Time to Live
UDP	User Datagram Protocol
VoIP	Voice of IP
WB	Widest Bandwidth
WFQ	Weighted Fair Queuing
WSP	Widest Shortest Path

LIST OF NOMENCLATOR

Notation	**Description**
$G(V,E)$	A network topology modeled as a graph where V is a set of nodes and E is a set of links in network
$l_{i\rightarrow j} \in E$	Link from node i to node j ; $i, j \in V$
N	Number of nodes in network
N_i	Number of neighbor of node i
$\mathcal{N}_i$	The set of neighbor nodes of node i= { neig□bors (i)}
V	List of visited node by forward ant
dl_i	Delay of the node i
pl_i	Packet loss of the node i
dj_i	Delay jitter of the node i
CoS	Class of service
bw_S	Absolute bandwidth
bw_b	Bottleneck bandwidth
$bw(P)$	The available bandwidth of the path P
$bw_{i\rightarrow j}$	The available bandwidth of link $l_{i\rightarrow j}$
$l_{i\rightarrow j}$	The link connected node i with its neighbor node j
l_b	Bottleneck link
l_t	Tight link
□	Traffic load

$c_{i\to j}$	The cost of link $l_{i\to j}$
$q_{l_{i\to j}}$	Queue length of the link $l_{i\to j}$, connecting node i to node j, $j \in \mathcal{N}_i$
d_{trs}	Transmission delay
$\mathcal{ST}_{dl}^{CoS}, \mathcal{ST}_{bw}^{CoS}, \mathcal{ST}_{dj}^{CoS}, \mathcal{ST}_{pl}^{CoS}$	Statistics tables for delay, bandwidth, delay jitter and packet loss respectively, per each *CoS*
$\mathcal{PT}^{CoS}$	Pheromone table per each *CoS*
$\mathcal{RT}^{CoS}$	Routing table per each *CoS*
$Sdl_j^i, Sdj_j^i, Sbw_j^i, Spl_j^i$	Entries of statistics table for delay, jitter, bandwidth and packet loss respectively for destination *j* (per each node *i* per each class)
P_{ij}	Entry of pheromone table, Probability of selecting node *i* as next hop while destination node is *j* (for mobile agents)
P_{kd}^i	Probability of selecting node *k* as next hop while destination node is *d* and current node is *i*
R_{ij}	Entry of routing table, Probability of selecting node *i* as next hop while destination node is *j* (for data packets)
$P(s,d)$	$= l_{s\to j}, l_{j\to j}, \dots, l_{k\to d}$, The path from node *s* to node *d* included all nodes and links belonged to path
$DL\ CoS$	Delay QoS constraint belong to a specified CoS
$DJ\ CoS$	Jitter QoS constraint belong to a specified CoS
$Bw\ CoS$	Bandwidth QoS constraint belong to a specified CoS
$PL\ CoS$	Packet loss QoS constraint belong to a specified CoS

$\vec{L}$	The QoS constraints vector: $< DL\ Cos\ , Bw\ Cos\ , DJ\ Cos\ , PL\ Cos\ >$
$\vec{L}_{best}$	The best QoS value vector $< dl_{best}, dj_{best}, bw_{best}\ , pl_{best} >$
$\vec{L}_{mes}$	The measured QoS value vector $< dl_{mes}, dj_{mes}, bw_{mes}\ , pl_{mes} >$
$\square_k$	The list of queue lengths of all of the node k neighbor links
$PRAnt$	path request ant
$BAnt_{CoS}^{d \to s}$	Backward Ant from node *d* to node *s,* belong to *CoS*
$BPRAnt$	Backward path request ant
Brel	Release ant (release all allocated resources)
$FAnt_{CoS}^{s \to d}$	Forward Ant launched from node *s* to destination *d*, belong to *CoS*
$D_{s \to d}$	The structure transported by $FAnt_{CoS}^{s \to d}$ contains visited node info
$S_{s \to d}$	The memory stack transported by forward ants
$\mu_{dl}, \mu_{dj}, \mu_{bw}, \mu_{pl}$	Mean of delay, jitter, bandwidth and packet loss respectively
$\sigma_{dl}^2, \sigma_{dj}^2, \sigma_{bw}^2, \sigma_{pl}^2$	Variance of delay, jitter, bandwidth and packet loss respectively

r_{dl}, r_{dj}, r_{bw}, r_{pl}	Reinforcement signal value for delay, jitter, bandwidth and packet loss respectively
φ_{dl}, φ_{dj}, φ_{bw}, φ_{pl}	Relative importance of delay, delay jitter, bandwidth and packet loss rate respectively
S_p	Size of packet *p*
w	The number of samples in sliding window method
W	The sliding window used to compute the $\vec{L}_{best}$
M	The maximum size of sliding window
τ_{min}	The minimum probability admitted at pheromone table entries
dl_{mes}, dj_{mes}, bw_{mes}, pl_{mes}	Trip time, jitter, available bandwidth and packet loss respectively measured in the new trip by arrived ant

CHAPTER 1

INTRODUCTION

1.1 Background

In today's globalized and borderless world, the Internet is an important aspect in business and in people's daily lives. Current Internet needs to support a wide variety of applications which have different requirements with respect to the service provided to them by the network. These requirements are expressed in terms of QoS requirements, and include constraints on throughput, delay, jitter, loss rate, etc. Internet services like e-mail can tolerate delay and jitter, but not packet loss. In contrast, real-time services such as Voice over IP (VoIP) have strict requirements with respect to delay and jitter, but can handle some packet loss. Services like audio and video streaming can tolerate certain levels of jitter and packet loss, but not delay (Courcoubetis et al., 2011; Shetty et al., 2010) .

The need to deal with this large variety of requirements has led to the development of a number of QoS frameworks. One of the first QoS architectures for the Internet, introduced by IETF, was the Integrated Services (IntServ) architecture (Braden et al., 1994; Zhang et al., 1993). The main drawback of IntServ is that it requires per-flow processing, which is not scalable in large networks such as the Internet (Mieghem and Kuipers, 2004). This scalability problem resulted in the proposal of the Differentiated Services (DiffServ) architecture (Carlsonet al, 1998).

The principle of DiffServ is simply to classify packets into several classes, which are treated differently according to different packet scheduling and policing rules. The advantage of this approach is that the application need not be involved in the QoS negotiations, and application behavior is unaltered. Although DiffServ has proven to be quite scalable, its major drawback is its lack of accuracy in service delivery, so the network may provide a QoS level that is superior or inferior to the specific application needs, which is quite inefficient for delay- and jitter-sensitive real-time applications (Meddeb, 2010; Mohammed et al., 2002).

Obviously, current IETF standards for QoS provision in IP networks are inadequate. All current IETF standards are based on traditional routing algorithms (such as OSPF) that are unaware of QoS. Accordingly, QoS Routing (QoSR) is the missing piece in a full-fledged QoS architecture for the Internet (Mieghem and Kuipers, 2004). Neither IntServ nor DiffServ supports any path discovery feature and relies on the best-effort IP routing tables, such that best-effort paths will be used for both best-effort traffic and distinguished traffic. In this way, the paths assigned cannot guarantee the constraints, which will result in blocking. To ensure QoS and fully utilize the potential of these QoS architectures, the routing tables and the method of path selection should also be QoS-aware. Thus, constraint-based routing, which computes paths based on multiple constraints, is needed. The QoSR algorithm therefore becomes a Multi-Constrained (Optimal) Path [MC(O)P] routing problem (Wang and Crowcroft, 1996).

Multi-Constrained path routing[1] is computing and selecting routes based on multiple constraints given by the application. The goals of constraint-based routing are to select routes that can meet certain QoS requirements and to increase utilization of the network (Kuipers et al., 2004; Kuipers et al., 2002). Consequently, while determining a route, constraint-based routing considers not only network topology, but also the requirements of the flow and resource availability of the links. Therefore, it may find a longer but lightly-loaded path better than the heavily-loaded shortest path; network traffic is thus distributed more evenly. In order to have constraint-based routing, routers need to distribute new link states information and compute routes based on such information. Considering that the traditional routing algorithms use flooding mechanism to distribute link states over the network, large overhead of this mechanism is an important restriction to deployment of constraint-based routing. In addition, constraint-based routing algorithms have high route computation complexity and their complexity depends on the metrics chosen for the routes (Masip-Bruin et al., 2006; Mieghem and Kuipers, 2004). It is stated in (Mieghem and Kuipers, 2004) that the provisioning of QoS based network services is in general terms, a complex problem. A significant part of this complexity lies in the routing layer and the complexity of the path computation algorithm. As mentioned, the complexity and processing overhead caused by QoSR is mainly due to two factors, namely, path computation algorithm complexity and the frequency of path computation. As the number of constraints that need to be satisfied by the routing algorithm increases, the complexity of the path computation algorithm becomes higher. Thus the problem of finding multi-constrained path has high computational complexity (Xiao and Ni, 1999; Mieghem and Kuipers, 2004) and the problem is known to be an NP-complete problem (Gary and Johnson, 1979). Accordingly, a difficulty with the MC(O)P problem is that only heuristic methods are considered feasible for solving (Masip-Bruin et al., 2006; Min, 2005; Mieghem and Kuipers, 2004; Wang and Crowcroft, 1996).

This point of view has resulted in the publication of a wealth of heuristics, most of them based on Swarm Intelligence (SI) (Farooq and Di Caro, 2008). The advantages of Swarm Intelligence mainly stem from Stigmergy (Bieszczad et al., 1998; Webb, 2002), and the use of mobile agents that yield the best global solution. The heuristic nature of Swarm Intelligence can give an optimal solution (optimal path) to a constraint-based problem. In comparison with other heuristic methods like Genetic Algorithm (GA), Tabo Search and Scatter Search, SI algorithms have several unique features to help in designing a distributed adaptive routing. These features can be summarized as follows: scalability, adaptation, fault tolerance, speed, autonomy, modularity, and parallelism. In addition in (Di Caro and Dorgio, 1998) the routing performance of a swarm-based algorithm and several state-of-the-art routing algorithms were compared, in which SI algorithm outperformed others.

[1] Multi-Constrained path routing and constraint-based routing are used interchangeably.

The vast majority of SI algorithms in routing area, are inspired by ant colony societies and in particular, by their ability to discover and follow shortest paths between their nest and sources of food (Dorigoa et al., 2000). This group of SI algorithms is called Ant Colony Algorithms (ACAs). In ACA, nodes obtain routing information using ant-like agents which repeatedly sample and reinforce good paths. These ants are in fact small control packets.

Considering that the future of the Internet will depend on effective QoS methods, the main objective of this research is to design an adaptive QoS-Routing scheme with a DiffServ architecture that provides different classes of traffic in packet-switched networks and satisfies the QoS requirements of each class while effectively utilizing network resources. A routing scheme (either QoS-based or not) generally involves two entities: routing protocols and routing algorithms. Thus, the proposed scheme includes a routing algorithm and a routing protocol. The routing algorithm is a multi-constraint-based algorithm that simultaneously satisfies four QoS requirements: bandwidth, delay, jitter, and packet loss. This algorithm computes routes based on these metrics using the pheromone routing table belonging to each class to enable the packets of different services to follow appropriate paths to reach their destinations. Following the ACO method and inspired by MACO (Sim and Sun, 2003), a separate ant colony is considered for each class to determine the optimal path based on class requirements. The proposed method is also capable of meeting the strict QoS requirements of real-time traffic through a proposed reactive procedure while providing QoS for other classes in a proactive manner. The routing protocol, as another entity of routing that manages the dynamics of the routing process, is also designed. This routing protocol acquires quality information on the current state of the network and distributes this information to network nodes while avoiding the flooding mechanism by using ant-like mobile agents. To achieve this goal and to develop an adaptive QoSR scheme, the AntNet (Di Caro et al., 1997), a well-known and successful ACO algorithm for adaptive routing in best-effort IP networks, has been adopted as a basis for the scheme and is extended based on the principle of per class QoS processing. To improve network performance and achieve higher robustness and faster convergence, some modifications to the standard AntNet are considered.

1.2 Problem Statement

This study deals with the following research problems:

1. Despite that, DiffServ has proven to be quite scalable, and can provide different classes in network but it is not able to satisfy the QoS requirements of different traffic types accurately and simultaneously. It does not take into account QoS requirements of each traffic class separately in the path selection process (the way of path selection is not class-based). Consequently it provides a QoS level that is superior or inferior to specific application needs. In particular, it is inefficient for delay- and jitter-sensitive real-time applications (Meddeb, 2010). Some researchers have studied end-to-end QoS in DiffServ networks, but they usually focus on improving the performance of the highest priority class (Lea and Chu, 2004; Moghim et al., 2010; Shan

and Yang, 2007; Striegel and Manimaran, 2003; Zarifzadeh et al, 2004), at the expense of the lower priority classes.

2. Diffserv has no traffic engineering provision and uses only the classical shortest path protocols. As a result, some links in the domain might be subjected to congestion while other links go unutilized; consequently it fails to prevent congestion (Toguyeni and Korbaa, 2009; Hsu et al., 2010)

3. DiffServ does not use any QoS provisioning and route optimization method, which can adaptively modify existing resources to be shared dynamically among traffic classes in respect of their priorities and distribute the traffic over the network. This results that DiffServ fails to manage and fully utilize the network resources (Curado and Monteiro, 2004; Bos, 2007).

4. The flooding process of link states causes a large overhead which is a critical limitation to deployment of constraint-based routing specially in today's distributed networks. Mechanisms used to overcome this problem, such as the ones that limit the frequency of the emission of updates, introduce new problems, namely routing information inaccuracy. Thus, considering that it is necessary to implement state-dependent QoS-aware network protocols, the conception of new QoSR schemes that do not rely on flooding or that overcome its flaws is an issue that needs to be addressed (Masip-Bruin et al., 2006; Acer et al., 2010).

Here it is worth to mention that the nature of the ACAs is based on the need for controlling dynamic environments involving the challenge of uncertainty. AntNet faces the dynamism by its exploring ants which consecutively explore the network to keep routing tables fresh and update. In a steady traffic pattern after a transient regime feasible routes are found and the whole network converges to these paths while the following occurrences can cause problems that should be well handled:

- **Unpredicted link/node failures:** If a link or node fails, the failure affects the whole network traffic particularly the paths containing the failure by increasing packet/ant delivery delays or packet/ant delivery loss. This situation triggers routing tables to update their information by the new exploring ants to select other feasible paths. In fact, after one more transient regime, routing tables cope with the current situation. Convergence speed in this situation depends on the number of exploring ants each node forwards through the network.

- **Traffic fluctuations:** This situation makes the challenge more considerable since there will not be a transient regime for the network to cope with the problem. Whenever a feasible situation is found, a new pattern shows up forcing the routing tables to update their data again. So packets in this situation encounter with changing source-destination paths which can decrease QoS factors of the algorithm.

- **Intensive traffic:** In normal condition congestion traffic is not a big deal for the algorithm; it only increases the delay and packet loss because of the congested queues throughout the network. By increasing the traffic routing tables tends to multiple paths from each source-destination pair so a kind of distribution occurs. This is because of the increased delay in the popular paths which decreases its popularity and increases the popularity of other alternatives. It should be considered that fluctuating huge traffic would be a challenge as discussed in the previous paragraph.

- **Real-time traffic versus non-real-time:** evidently in real-time communication, a virtual tour is first granted and the transmission starts from the first packet to the last. To deal with this situation the algorithm should be customized to support multi-priority transmissions for such communication requirements.

Some of the mentioned challenges relating AntNet have been addressed in this research.

1.3 Motivation

In spite of the popularity and important role of QoS to access many attractive services in the Internet, the provision of end-to-end QoS, still remains as one of the most challenging problems in the research area of communication networks. This is the main motivation for this research. Other enthusiasms for this research are listed as follow:

1. The numbers of applications that need QoS requirements, are significantly increasing. Some of these applications are very attractive, facing with a high demand from the people. This has encouraged researcher to pay special attention to QoS provision in Internet and design a QoSR scheme to meet the QoS requirements of end users.

2. A full-scale deployment of QoS is still missing in the IETF QoS architecture. All current Internet standards rely on traditional QoS-unaware routing and QoSR can be considered as a missed piece in a full-fledged QoS architecture for the Internet.

3. Since distinct applications require different level of QoS requirement it is needed to satisfy the wide range of requirements. There is no any QoS algorithm in research level which can provide QoS for a variety class of services in the Internet according the class requirements.

4. Apart from the desirability of QoS from users' point of view, another powerful motivation which is important from network engineering's perspective is its capability to optimize the network resource utilization. QoSR is supposed to enhance the performance of networks and direct network traffic in an efficient way to maximize the total network throughput. Every service provider wants to maximize the utilization of its current network facilities.

The motivation that AntNet framework is chosen as the basis of proposed QoS scheme could be listed below:

1. AntNet was compared with 6 state-of-the art routing algorithms. Result showed superior performance in terms of delay, and robustness to load changes and to its internal parameters.

2. AntNet performs well in periods of congestion, one of the fails inside a DiffServ domain when provisioning is not carefully performed.

3. Solving QoS is a dynamic problem. AntNet is a dynamic (adaptive) algorithm that performs well in dynamic scenarios.

4. AntNet does an inherent load balancing of the network.

5. AntNet is a scalable algorithm that works well in large networks.

1.4 Research Objectives

The main aim of this research was to design an adaptive class-based QoS Routing scheme in a DiffServ architecture using ACO to satisfy the QoS requirements of different Class of Services (CoS) in terms of delay, jitter, bandwidth and loss rate. It should be able to meet the strict requirements of real-time traffic without decreasing the performance of best-effort traffic.

This approach will allow dynamic scheduling and class-based forwarding in a DiffServ network using both stochastic routing and probe-base routing. Specific objectives are as follows:

1. To develop a DiffServ architecture based routing algorithm which can consider four QoS metrics including delay, jitter, bandwidth and loss rate simultaneously and to satisfy the requirements of each class in terms of these metrics concurrently.

2. To develop a QoS provision mechanism in the DiffServ network. This objective needs to develop an adaptive multipath algorithm which can dynamically distribute the traffic of different classes over the network and assign network resources to them while in this process take into account not only the class priorities but also the importance of each QoS metric for each traffic class.

3. To develop a QoS Routing protocol that does not rely on flooding.

4. To develop an algorithm that satisfies the stringent requirements of real-time traffic while does not decrease the performance of lower priority traffic.

1.5 Research Scope

In this research work, a QoS scheme based on the idea of the ACO method and in particular from the AntNet is presented. This scheme is called ACR-QoS (Ant Colony Routing with QoS). ACR-QoS has been designed to provide QoS for various classes of traffic in a packet switched network and take all mentioned needs into account.

At first the ACR-QoS is a constraint-based routing algorithm which should consider four important QoS metrics including: delay, packet loss rate, bandwidth and jitter to calculate paths for different types of traffic. Thus it uses Ant colony optimization heuristic method to solve this NP-Complete problem.

Secondly, due to serve different classes of traffic in network, ACR-QoS is designed to work inside DiffServ architecture. ACR-QoS provides different classes of traffic including Expedite class (EF class), Assured class (AF class) and Best-Effort class (BE class).

Thirdly, since most of the existing DiffServ frameworks focus only on scheduling policies not forwarding and use the paths and routing tables that belong to best effort traffic without any QoS awareness, ACR-QoS extends the AntNet (Di Caro and Dorgio, 1998) algorithm in order to establish QoS aware and class-based routing tables. Consequently this can fully exploit the network resources.

And finally to provide a strict QoS guarantee which is needed for real-time traffic (EF class), ACR-QoS uses a reactive phase and probe-base routing to find and establish a feasible path and reserve resources across it for delivery a real-time flow. Performance assessment of the proposed scheme in a typical Internet backbone infrastructure by a set of simulation studies and experiments shows its superior performance over classical routing algorithms. Figure 1.1 shows the scope of research.

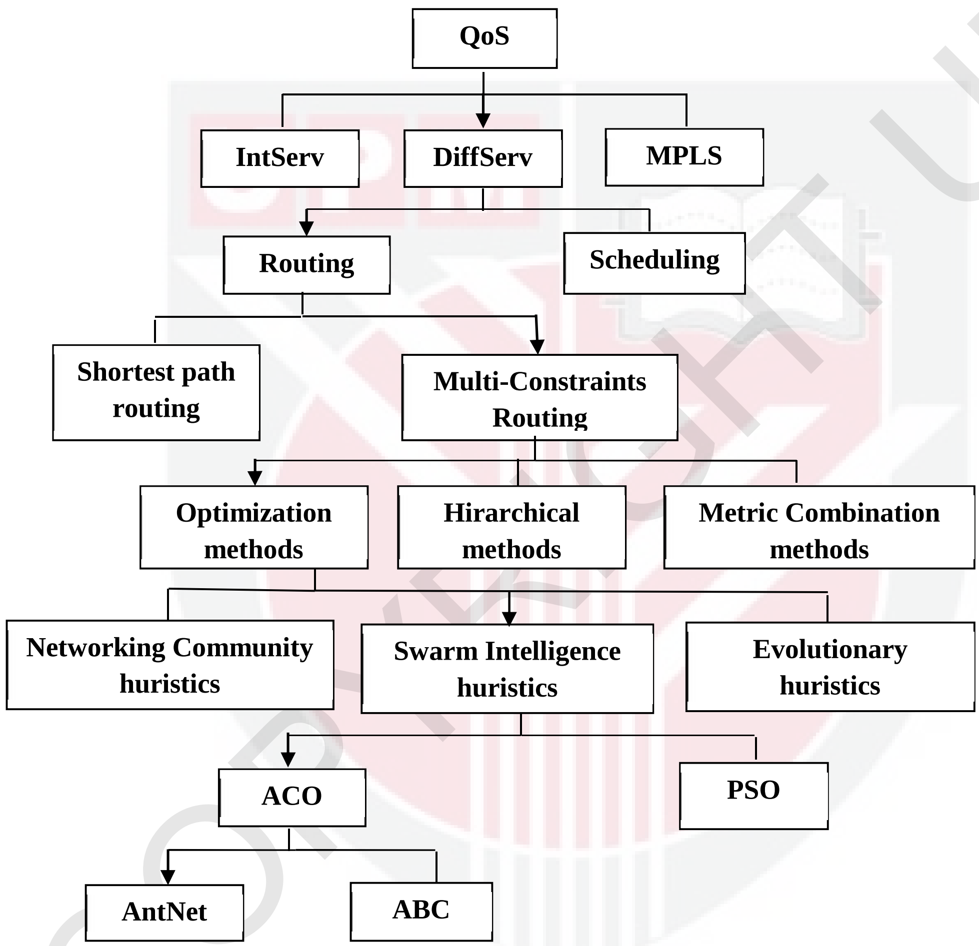

Figure 1.1. The scope of research

1.6 Research Contributions

The main contribution of this research work is designing a Diffserv architecture with class-based routing tables, where the differentiation is achieved in terms of both routing and scheduling, whereas exiting works use best effort tables for all types of traffics and much of them focus only on scheduling policies.

1. The proposed algorithm is able to optimize the routes for each class while taking these parameters into account: delay, jitter, bandwidth and loss rate, and can satisfy their QoS needs concurrently.

2. Regarding QoS provision in DiffServ and adaptive distribution of traffic in proper paths, the algorithm can fully exploit the network resources while increase the network efficiency in saturated load about 8.39% in comparison with shortest-widest- path algorithm.
3. This algorithm is able to avoid flooding for providing the required network states information in nodes.

4. This algorithm is able to meet the strict requirements of real-time traffic according to its QoS constraints and also improves the best-effort traffic performance. In other words it respects the class priorities in the allocation of the best paths, while still giving an acceptable performance to lower priority traffic. Regarding to best effort traffic and in comparison by standard AntNet under link failure and topology changes, the proposed algorithm is able to improve the throughput and decrease packet loss even in an unbalanced network like NTTNET.

1.7 Organization of Thesis

This thesis consists of five chapters. Chapter 2 provides a general overview of routing in the Internet, and QoS routing problems in wired IP networks. The conclusion is that there is still much space for improvements when adaptivity to traffic is considered. This chapter describes ACO algorithm. Several important ACO algorithms and their ramifications for adaptive routing tasks in telecommunication networks are introduced and their general characteristics are discussed. In particular, the chapter introduces AntNet, ABC and their variants. Most important section, the chapter includes a comprehensive survey of current AntNet-inspired and, more generally, ant based implementations and proposal for routing and QoS routing tasks. The pros and cons of each approach have been briefly mentioned.

Chapter 3 describes the methodology adapted for the presented work. Required modification and extensions to adopt AntNet as a foundation framework for the proposed QoS routing scheme are applied. In order to satisfy several QoS parameters a multi constraints-base routing algorithm is designed base on ant colony heuristic method in this chapter. A new set of mathematical formula has been driven and used in the algorithm. Other thoughts on the choice of data structures in nodes, scheduling policies, behaviour of proactive and reactive mobile agents (artificial ants), link states gathering in the form of repeated sampling of paths, statistically spreading of data packets, and other implementation details are provided in this chapter.

Chapter 4 presents and discusses the experimental results for ACR-QoS routing scheme. In this chapter, experimental results obtained by simulation are reported. Experiments are divided in 3 parts. The first part is assigned to the evaluation of the scheme. In this section ability of ACR-QoS as a constraint-based algorithm to find optimal paths, and also its ability to distribute traffic over multiple paths as a multi-path algorithm are investigated. After that, a lot of experiments have been done to analysis the performance of scheme for various classes that network provides. Also the effect of ant launching rate on the performance of the scheme and routing overhead are investigated. In second part ACR-QoS is compared to standard AntNet as an adaptive multipath routing algorithm and in the third part the throughput and efficiency of ACR-QoS are compared to well-known QoS algorithms. In all sections, the results and the rationale behind them are thoroughly discussed.

Chapter 5 concludes the thesis with a summary of the main contributions. It also describes possible future research work and directions.

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