ROBUST QOS CONTROL
FOR IP-BASED CELLULAR NETWORKS

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Abstract: This paper proposes "Proactive Control and Multipath Control" to realize a robust QoS control system for IP-based cellular networks. In these networks, all kinds of traffic will share the same backbone network. This requires a QoS system that differentiates services according to the required quality. Though DiffServ is thought to be a promising technique for achieving QoS, a technique that is proof against rapid traffic changes and an effective path control scheme are not yet available. Our solution is proactive control using traffic anomaly detection and multipath control using linear optimization. Simulation results show that proactive control and multipath control improve system performance in terms of throughput and packet loss when rapid traffic change takes place.

1 INTRODUCTION

It is expected that the ALL-IP network will become the de-facto platform for the future cellular network, and so all kinds of real time and non-real time traffic will share the same backbone network. In cellular networks, the traffic pattern drastically changes when certain events occur, such as natural disasters or fireworks display. This requires a QoS system that differentiates services according to the required quality. DiffServ has been proposed by IETF, the standardization group for Internet technology. When a packet enters the DiffServ network, the edge router writes DSCP (DiffServ Code Point) in the IP header. DSCP is an identifier of the traffic class. In the router, PHB (Per Hop Behavior), which decides queue assignment and scheduling, is set as per DSCP. DiffServ is a scalable and promising technique because it divides traffic into several classes as units of priority control. The problem with DiffServ is that since it only deals with router internals, it can't guarantee QoS. There are two problems that prevent DiffServ from functioning effectively.

Problem 1 is how to detect rapid traffic change. Conventionally in cellular networks, a traffic anomaly is judged according to a threshold, and congestion control is begun only after the traffic exceeds the threshold. This requires a router metric that mirrors the current traffic situation. After that, router parameters must be appropriately set. If the control procedure is begun after the threshold is exceeded, these procedures might not finish in time leading to a deterioration in communication quality.

Problem 2 involves path control between routers. Routing protocols such as Open Shortest Path First (OSPF) can be used to implement path control. In OSPF, traffic concentrates on a specific path because they forward all traffic across the shortest path (Moy, 1998). The use of label switching like Multi Protocol Label Switching (MPLS) is also available, but the initial Label Switching Path (LSP) of MPLS is the same as that of the other routing protocols (Davie, 1998). Therefore, an effective multipath algorithm is needed to realize QoS control regardless of the forwarding protocol used.

With regard to these two problems, one approach is to prepare in advance router parameters for each type of congestion. For example, by customizing the threshold, or preparing paths groups for each type of congestion, calculations for each traffic situation become unnecessary. However, because in the ubiquitous networks of the future, various kinds of traffic in addition to voice traffic will coexist, it will be impossible to prepare for every possible traffic situation. For this reason we must calculate the router parameters individually for each traffic situation.

This paper tackles Problem 1 by proposing proactive control which can deal with various kinds

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of traffic situations. For proactive control, we first describe the details of a traffic anomaly detection approach that isn't based on thresholding. Next, we introduce a control switching method that makes effective use of traffic anomaly detection. To handle Problem 2, we propose multipath control which enables the path control to be based on traffic classes. As the multipath algorithm, we apply a linear optimization algorithm to guarantee optimality.

From the QoS viewpoint, it is said that distributed control system is not suitable because it fails to offer traffic quality guarantees. Accordingly, we chose the centralized control model. We use a QoS manager that can control the entire network (Figure 1). Proactive control decides whether control is necessary or not. When control is necessary, proactive control sends a message to multipath control which calculates the optimal path setting to realize QoS control.

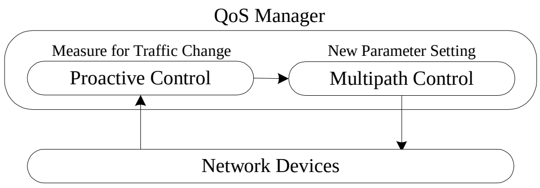


Figure 1: Architecture

The remainder of the paper is organized as follows. Section 2 describes proactive control. First we define the meaning of proactive, and then explain traffic anomaly detection, which is based on the use of attractors. In Section3 we propose a QoS aware multipath algorithm that uses linear optimization. Computer simulations and result are discussed in Section4. Section 5 concludes our paper.

2 PROACTIVE CONTROL

2.1 Definition of Proactive Control

In conventional cellular network operation, a certain control procedure is triggered after the threshold is exceeded. This operation can be described as reactive control. The problem of reactivity is the delay in triggering system responses such as congestion control. Using a threshold means that the control procedure is not begun until the traffic exceeds the threshold. If traffic increases rapidly, the control procedure may not be completed in time. To solve this problem, it is natural to lower the threshold to detect traffic anomalies earlier, but this causes control overhead because low thresholds are exceeded far more often.

This problem is caused by the lack of an approach to cope with traffic anomalies. Thus, our solution is to define proactive control as a combination of both local and global traffic anomaly detection. First we describe traffic anomaly detection.

2.2 Traffic Anomaly Detection

There are several approaches to detect traffic anomalies. The methods described are rule-based approaches, finite state machine models, pattern matching, and statistical analysis (Thottan, 2003).

The rule-based approach uses an exhaustive database containing the rules of system behavior to determine if an anomaly has occurred (Ndousse, 1996). Rule approaches are too slow for real-time detection and are dependent on prior knowledge about the anomalous conditions on the network (Lewis, 1993). Moreover, rule approaches rely heavily on the expertise of the network manager, and do not adapt well to an evolving network environment (Franceshi, 1996).

Anomaly detection using finite state machines model alarm sequences that occur during and prior to fault events. A review of such state machine techniques can be found in (Lazar, 1992) and (Jakobson, 1992). The difficulty encountered in using the finite state machine method is that not all faults can be captured by a finite sequence of alarms of reasonable length. This may cause the number of states required to explode as a function of the number and complexity of faults modeled (Thottan 2003).

Statistical analysis uses the standard sequential change point detection approach. The source of such analysis is SNMP MIB data. (Thottan, 1998) proposed duration filter heuristics to obtain real-time alarms using MIB variables.

In pattern matching approach, online learning is used to build a feature map for a given network. These maps are categorized by time of day, day of week, and special days, such as weekends and holidays. The simplest way of making the feature map is to reproduce the traffic pattern. This map, however, has a time-axis which means that the memory capacity increases when the monitoring interval shortens. As for the change in IP traffic volume, changes over periods of 1 second or less are important. In this time scale, it is impractical to make the map mirror the real traffic.

All four approaches are complementary. So we can combine these approaches to realize a better detection system. In this paper, we propose a pattern matching method which utilizes an attractor (Takens, 1981). An Attractor map is constructed from the traffic volume. The traffic volume range is not influenced by the time scale. Moreover, the granularity of the traffic-axis is less significant than that of the time-axis. This means that using only traffic volume makes the map scalable.

2.3 Attractor Map

The attractor is known as a way of extracting a feature map from time series data, which is based on deterministic chaos (Takens, 1981). The attractor can also be used to map certain linear/non-linear time series data. If the traffic has some patterns, such as periodic features, the attractor is created by just coordinate transformation. For example, to extract the attractor of traffic data, all that is necessary is to convert the coordinates of the observation time series system into the delay coordinate system equivalents (Packard, 1980).

Attractor space can be represented as a multiple-dimensional space. We explain attractor transformation for a two-dimensional space. We select two points from traffic data. These data are separated by d. These two points yield one point in the attractor field (Figure 2). The vertical axis of attractor represents the traffic volume at time n, and the horizontal axis is the traffic volume at time n-d. The whole periodic traffic trace is projected to form a closed attractor orbit. We utilize this useful characteristic in proposing the attractor map method.

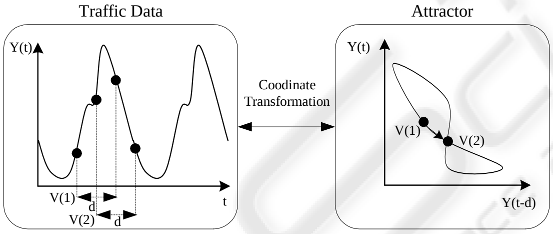


Figure 2: Attractor

First we create an attractor from usual traffic data and prepare an array of bits that has the same dimensions as the attractor space. We set those bits that lie within the attractor orbit as "Normal" and those bits which do not lie within the attractor as "Anomaly". We can detect traffic anomalies by comparing the attractor map for usual traffic with that for the current traffic (Figure 3).

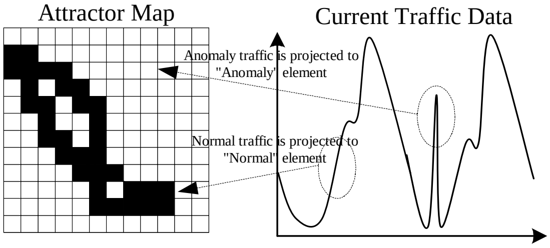


Figure 3: Usage of Attractor

2.4 Soft Standby

Conventional cellular network control is based on thresholding. A threshold represents to two things: anomaly detection and response triggering. The traffic is recognized as anomalous if it exceeds the threshold. When the traffic exceeds this threshold, certain control actions such as congestion control are initiated. If the threshold is set too low, unnecessary control actions are triggered. If the threshold is set too high, the network has insufficient time to react properly if the traffic increase is rapid. Though the attractor map enables the detection of anomalous traffic at an early stage, if congestion control is triggered at each detection point, the overheads would be excessive. In this paper, we propose the control switching method; Soft Standby, which combines the attractor map with threshold-based triggering; this is shown inFigure 4. The QoS manager collects the traffic information and verifies it using the attractor map. Figure 4 (A) indicates the state in which the network is normal and each router is using its default setting. If traffic begins to increase abnormally and the attractor map detects an anomaly, the system enters the proactive state Figure 4 (B). In this state, the QoS manager forecasts the future traffic using linear prediction and calculates new multipath parameters for each router. Details of multipath setting are given later. Routers store the settings but continue to use the default setting. If the network returns to normal, the system returns to state Figure 4 (A) and default settings continue to be used. On the other hand, if the traffic continues to increase and exceeds the threshold, the system enters the anomalous state Figure 4 (C). The routers then activate the new settings; this prevents any quality deterioration such as packet loss or delay increase.

The conventional method delays the determination of new parameter settings until the threshold is exceeded. In our proposal, the new settings are calculated and loaded when the anomaly is detected. When the traffic reaches the network limit, the only control function needed is to activate the new router parameters and this change can be done in a short time. It follows that our proposal yields faster control response than the conventional method.

3 MULTIPATH CONTROL

Using proactive control, the QoS manager can deal with rapid traffic change. The next problem is calculating the parameter settings. As mentioned before, current path control is based on singlepath routing. This causes the traffic to concentrate on the shortest path. To solve this problem, this chapter details the multipath control approach.

In conventional networks, the traffic concentrates on a specific path because existing routing protocols forward the traffic using shortest path information. Label switching techniques such as MPLS do offer a form of multipath control, but the initial path of MPLS is the same as that of routing protocols. In an MPLS network, when a node sends priority traffic, the sender should collect network information such as topology/path utilization and calculate the best path using a constraint-based routing protocol such as CSPF (Jamoussi, 2002). This calculation is independent in each node, so optimality is not guaranteed. For instance, when the low priority traffic dominates the shortest path, high priority traffic has to make a detour because the sender of high priority traffic can't make the sender of low priority traffic accept a detour route. This sender-based approach can't realize complete QoS control. Moreover, network information such as topology and path utilization can not be sent to end terminals, so sender-based approaches are not practical. Another approach to realize QoS label switching is to set up LSPs beforehand. High priority traffic is allocated to the shortest paths, and low priority traffic is allocated to round-about routes. This approach makes the lower priority traffic take a detour route even if the shortest path is empty. This degrades communication and consumes network resources. Therefore, a truly effective multipath algorithm is needed.

In this paper, we propose a centralize method which utilizes a linear programming to find optimal QoS paths group.

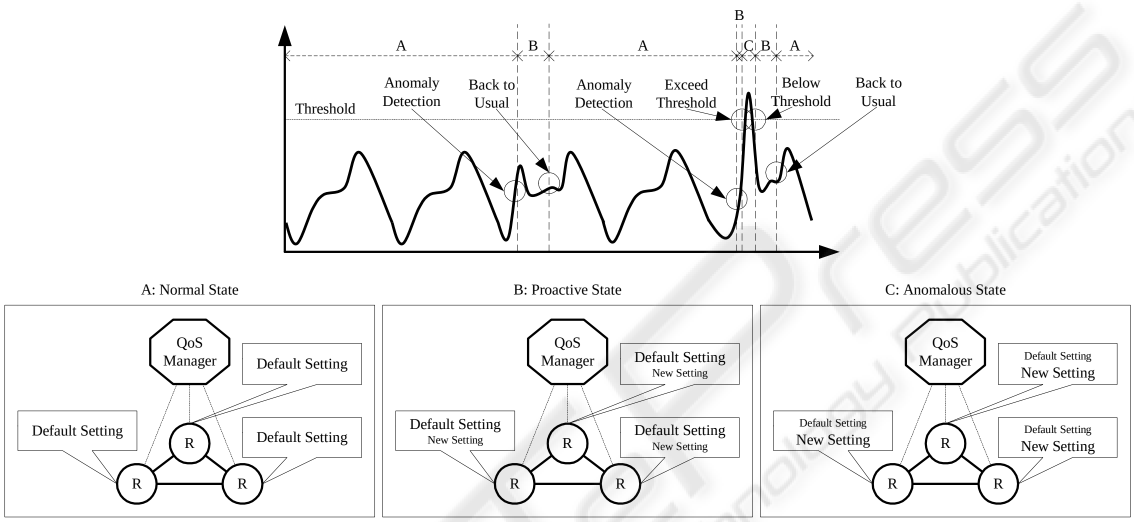


Figure 4: Outline of Soft Standby

3.1 Linear Optimization

The problems that QoS Manager should solve are, a) can the current path can satisfy the demands of the current traffic? b) if the current path is sufficient, how to make the best correspondence between the paths and traffic classes?, c) if the current path is not sufficient, how to find the additional path? Problem a) is equal to a linear problem that verifies whether the answer that satisfies constraints exists or not. Problem b) is equal to a linear optimizing problem which minimizes a certain objective function. In short, linear programming can be applied to problem a) and b). Refer to (Press, 2002) for details of linear programming. In linear programming, the objective function that should be minimized or maximized is represented by a linear expression. The constraints are also composed of linear expressions. The objective of linear programming is 1) to verify whether the answer that meets the all constraints exist, 2) when the answer exists, to find the optimal variable that minimizes/maximizes the objective function.

For N independent variables, minimize the function

$$f = a_{01}x_1 + a_{02}x_2 + \cdots + a_{0N}x_N \quad (1)$$

subject to the primary constraints

$$x_1 \geq 0, x_2 \geq 0, \cdots, x_N \geq 0 \quad (2)$$

$$a_{i1}x_1 + a_{i2}x_2 + \cdots + a_{iN}x_N \leq b_i(b_i \geq 0) \quad (3)$$

$$a_{j1}x_1 + a_{j2}x_2 + \cdots + a_{jN}x_N \geq b_j \geq 0 \quad (4)$$

$$a_{k1}x_1 + a_{k2}x_2 + \cdots + a_{kN}x_N = b_k \geq 0 \quad (5)$$

a_{xx} can have either sign or be zero. A set of values that satisfies the constraints is called a feasible vector. The function that we are trying to minimize is called the objective function. The feasible vector that minimizes the objective function is called the optimal feasible vector.

Characteristic 1) is applicable to problem a), while characteristic 2) is applicable to problem b). The unsolved problem is problem c). In order to find the necessity additional path, an understanding of graph theory is essential.

3.2 Bottleneck Link Detection

We set the traffic amount of each path as the variable of linear programming. Constraints are composed of equalities/inequalities concerning the link bandwidth, traffic amount, delay etc. When a present path group doesn't offer enough bandwidth, there exists a bottleneck link. In this case, at least one path around the bottleneck is necessary. By repeating the addition of these necessary paths, we can get the new path group that satisfies all constraints. This addition is composed of only necessary paths, so we can define this as optimal path addition.

To realize optimal path addition, we first have to find the bottleneck link first. We take advantage of the Simplex method, commonly used on linear programming, to do this.

Imagine that we start with a full N-dimensional space of candidate vectors. We then eliminate the regions that are indicated by each constraint. The area that remains after the elimination is called the feasible region. If the feasible region doesn't exist, there is no feasible vector that satisfies all constraints. If the feasible vector exists, the optimal feasible vector should be on the boundary because the objective function is linear. The simplex method takes advantage of this characteristic and searches for the optimal feasible vector along the boundary.

The simplex method is composed of two steps. First step is the judgment of whether a feasible vector exists; the second step is to find the optimal feasible vector. In step 1 we replace our objective function by a so-called auxiliary objective function which becomes 0 if the feasible vector exists.

To solve the linear programming problem, we need to get rid of the inequalities that have form (3) or (4). We do this by adding to the problem so-called slack variables; x_{N+i} which, when their nonnegativity is required, convert the inequalities to equalities. There is another trick to the auxiliary objective function. That is the introduction of artificial variables; we denote them by z_i .

The introduction of slack variables and artificial variables turns (3) (4) (5) into

$$z_i = b_i - a_{i1}x_1 - \cdots - a_{iN}x_N - c_{iN+i}x_{N+i} \quad (6)$$

Form (6) is not the same as (3) (4) (5). Only when all z_i are zero do these forms become the same. Thus we set (7) as the auxiliary objective function.

$$f' = -\sum_{i=1}^{M} Z_i \quad (7)$$

M is the number of constraints.

In step 1, we try to maximize the auxiliary objective function. If the auxiliary objective function becomes 0, the feasible vector exists and the next step begins. If the auxiliary objective function doesn't become 0, the simplex method stops and returns the result that there is no feasible vector.

As previously mentioned, this maximization process advances along the wall of the constraints. When the process reaches the vertex, and the auxiliary objective function has not become 0, there is no feasible vector that satisfies all constraints. The coordinate of the vertex represents the answer of the simultaneous equations used by the process. In other words, this coordinate means the feasible vector that satisfies the constraints followed by the simplex procedure, so this coordinate is the current maximum traffic volume of each path within the network limitation. This allows us to find the bottleneck link by comparing the vector at which the simplex method stopped with the link bandwidth. After detecting the bottleneck link, we use Dijkstra's algorithm, well known as the shortest path algorithm, to find an additional roundabout path. We recursively repeat this procedure until we get the sufficient paths to satisfy the constraints.

3.3 Minimization of Network Resource Consumption

If the paths are sufficient and the feasible vector exists, step 2 begins to find the optimal feasible vector. In our proposal, the objective function realizes optimality in terms of network resource consumption.

c_l is the cost of each link l per traffic unit. The cost of path p_i is set as follows

$$C_{P_i} = \sum_{l \in P_i} C_l \qquad (8)$$

where variable x_i represents the traffic load of path p_i ,

$$f = \sum_{i \le n}^{i=1} C_{P_i} x_i \qquad (9)$$

If we can find a feasible vector that satisfies the constraints and minimizes form (9), it can be said that the feasible vector is the optimal answer that minimizes the network resource consumption.

3.4 Scalability Consideration

The practicality of the linear programming method is not clear. In fact, an attempt to solve for an entire network may yield a large amount of variables and constraints. However, the linear programming formulation can be applied to a uniform topology, such as a cellular network. Furthermore, the linear programming method can generate optimal solutions for small areas of a network, and these local solutions can be combined to create a global approximation. And with suitable simplification, some variables and constraints can be removed. These considerations above show the applicability of linear programming to the cellular networks.

4 SIMULATION

We combined our proposals, Proactive Control and Multipath Control, and evaluated its performance by computer simulation. To this end we modified Network Simulator2 (NS2). Figure 5 shows the simulated topology, which is tree-based structure typical of cellular and ISP (Internet Service Provider) networks.

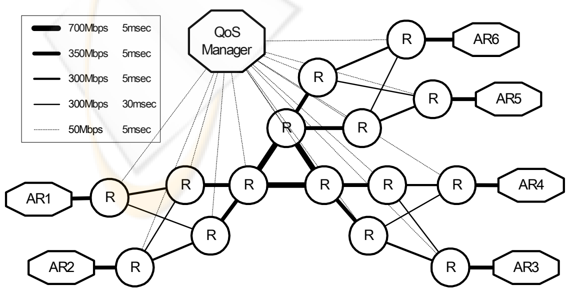


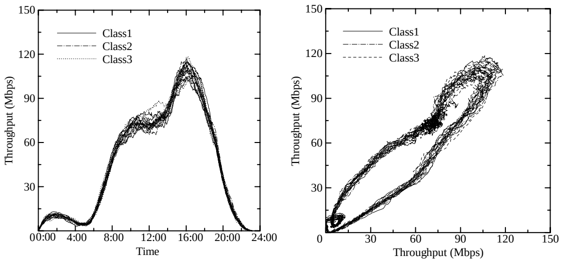
Figure 5: Simulation Topology

The simulation parameters are shown in Table 1. The communication time was assumed to follow an exponential distribution; Destination AR was randomly set. Figure 6 (a) is a graph of usual traffic for one day. This traffic data was collected from the statistics database of Ministry of Public Management, Home Affairs, Posts and Telecommunications in Japan (Soumu). Figure 6 (b) image is a sample of the resulting attractor. These attractors constructed from normal traffic data are projected to two-dimensional attractor maps (50x50 elements).

We evaluated our proposal in 2 scenarios. For each scenario, additional traffic is added to usual traffic. The additional traffic followed a normal distribution. The parameters were variance V[minutes] and terminal number N[terminals].

Table 1: Simulation Parameter

Attractor Map		
Time Delay [d]	15 minutes	
Soft Standby		
Threshold	150M	
Multipath		
Link Cost of all Paths	1	
Traffic		
Traffic Class	*Bandwidth*	*Delay*
Class1	150Kbps	50msec
Class2	150Kbps	-
Class3	Best Effort	
Number of Terminals per AR	3000 (1000 per Class)	
Traffic of All Classes	150Kbps UDP	
QoS Manager		
Preparation time of New Param.	30sec	
DiffServ Router		
Number of Queues	3	
Queuing Method	Weighted Fair Queuing Q1:Q2:Q3=10:5:1	
Queue Assignment	Class1/Signaling:Q1 Class2:Q2 Class3:Q3	

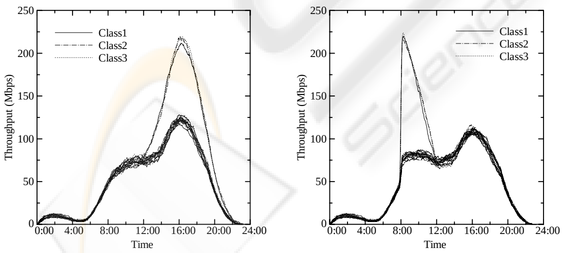


(a) Usual Traffic (b) Attractor

Figure 6: Usual Traffic and Attractor

Scenario 1 is the fireworks congestion model. The feature of the fireworks congestion model is that the additional traffic follows a wide distribution; V=135, N=9000. The fireworks event takes place at 17:00. In Scenario 2, the earthquake congestion model, the additional traffic follows a narrow disrtibution; V=6, N=6000. The earthquake takes place at 8:00. Figure 7 plots the ideal throughput of each scenario.

The events in both scenarios were generated using AR1. The especially high traces in Figure 7, which represent the theoretical throughput of AR1, indicate the traffic concentration. We compared 3 methods. Method 1 is a conventional singlepath control that doesn’t change the path even when traffic becomes congested. Method 2 is a combination of our multipath routing and conventional reactive control; threshold based control triggering was used. The threshold is set to trigger multipath control when link utilization arises to 80%. Method 3 is our proposal, multipath and proactive control; anomalous traffic detection was used. In this method, QoS manager detects a traffic anomaly using attractor maps and trigger multipath control when link utilization exceeds 80%.



(a) Fireworks Traffic (b) Earthquake Traffic

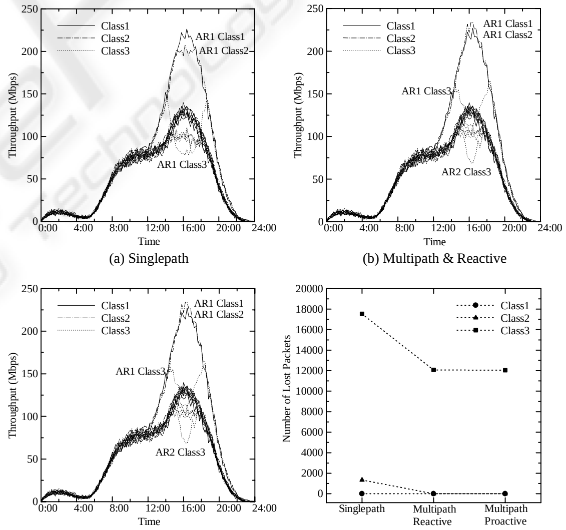
Figure 7: Theoretical Throughput

4.1 Fireworks Scenario

The resulting throughput and packet loss in the fireworks scenario are shown in Figure 8. The difference between singlepath and multipath is seen in the throughput at the traffic peak. The throughput of Class2 in AR1 is lower than that of Class1. On the other hand, with multipath control, both Class1 and Class2 keep their guaranteed throughputs and Class3 throughput is also improved. Moreover Class3 throughput at AR2 is decreased. This is because Class2 traffic was detoured and influenced Class3 traffic in multipath control. In short, multipath control improved the whole network throughput and realized QoS control. On the contrary, there is little difference between reactive control and proactive control. This is because the preparation procedure can be finished in time since the traffic increase is not rapid, unlike earthquake congestion. In short, in the fireworks scenario, multipath is better than singlepath but there is little difference between proactive and reactive.

4.2 Earthquake Scenario

The resulting throughput and packet loss in the earthquake congestion model are shown in Figure 9. As in the fireworks scenario, multipath control offers improved throughput with AR1. In this scenario, there is a slight difference between reactive and proactive control when the earthquake occurs.



(a) Singlepath (b) Multipath & Reactive

(c) Multipath & Proactive (d) Packet Loss

Figure 8: Results of Fireworks Scenario

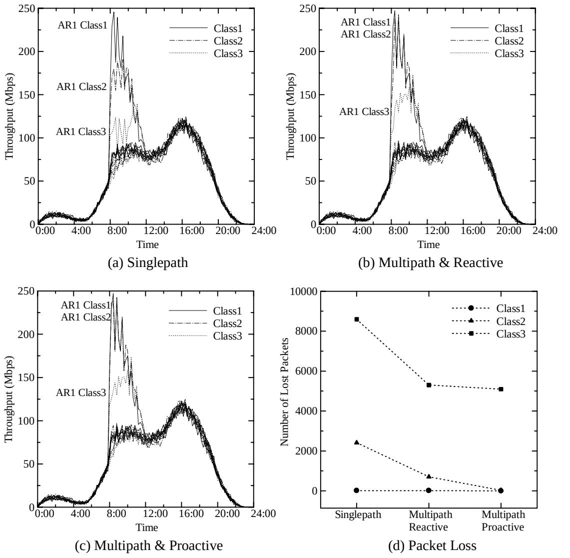


Figure 9: Results of Earthquake Scenario

The difference is seen in the number of Class2 packets lost. The reason for the difference is the difference in preparation time. In the proactive method, the procedure began when the QoS manager detected the traffic anomaly using agent-initiated traffic reporting and the attractor map so the calculation and preparations could be finished before the traffic exceeded the network limit. On the other hand, in the reactive method, the QoS manager didn't detect the rapid traffic change until the next monitoring period. Since the procedure began after the traffic exceeded the threshold, it could not be completed in time, so Class2 packets were lost until the new settings were established. In short, in the earthquake scenario, both proactive and multipath control improved communication quality.

5 CONCLUSION

In this paper, we proposed proactive control and multipath control to cope with the rapid traffic change in IP-based cellular networks. Proactive control is based on traffic anomaly detection via attractor maps. Proactive control includes a control triggering method that efficiently switches the network states. Linear programming is applied to determine the multipath setting and guarantee optimality in terms of network resource consumption.

NS2simulations showed that our multipath control approach achieved better performance in terms of throughput and packet loss than conventional singlepath control. The simulations also showed that proactive control is especially effective when the traffic increase is rapid. Proactive control prevented packet loss in priority traffic class unlike the conventional reactive control.

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