Clustered Architecture for Adaptive Multimedia Streaming in WiMAX-based Cellular Networks

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***Abstract*—In the recent years, there has been an increasing demand for high quality multimedia services over wireless networks. Triple play services (voice, data and video) require data-rates of the order of several megabits per second (Mbps). However, the large transmission distance and the limited battery power of the hand-held wireless device serves as a major bottleneck. There has been no successful mechanism developed till date that would provide live video streaming over wireless networks. In this paper, a novel cluster-based double dumbbell topology is proposed for adaptive multimedia streaming in WiMAX-based multihop cellular networks. The performance of the network is evaluated for a two-hop model and compared with a traditional single-hop cellular design. Extensive simulations have been carried out in terms of different kinds of network traffic and over different protocols. It is observed that the performance of the proposed cluster-based design for WiMAX networks is significantly superior to the one-hop design, not only in terms of the perceived quality, but also in terms of the loss rate and the average bit rate.**

***Keywords* - bit rate, double dumbbell, loss rate, multimedia streaming, perceived quality, quality oriented adaptive scheme.**

I. INTRODUCTION

With the advent of third generation (3G) mobile systems, video conferencing and downloading of movies/documentaries that requires huge file transfers of the order of several hundreds of megabytes per second (Mbps) have been in great demand. Many service providers are willing to invest huge amount of money in order to provide video-on-demand (VoD) to the end users. However, there are several technological challenges that needs to be addressed before the actual development of such a system [1]. Multimedia transmission and VoD streaming requires high data rates which can be achieved either by increasing the bandwidth or by increasing the signal power at the receiver. However, the total bandwidth of the network being controlled by the Government and cannot be increased arbitrarily. Similarly, the wireless devices are energy-constrained units. Hence, the transmission power of these devices cannot be increased indiscriminately. In this scenario, an efficient mechanism to achieve high-data rate communication is to use multihop transmission between the source and destination node [2]. A hierarchical multihop design with a single central entity and several smaller devices that would serve as intermediate relays is shown in Fig. 1. The relays reduce the transmission distance between a Tx-Rx pair which in turn reduces the power requirement and at the same time, increases the achievable maximum data rate of a communicating link [3].

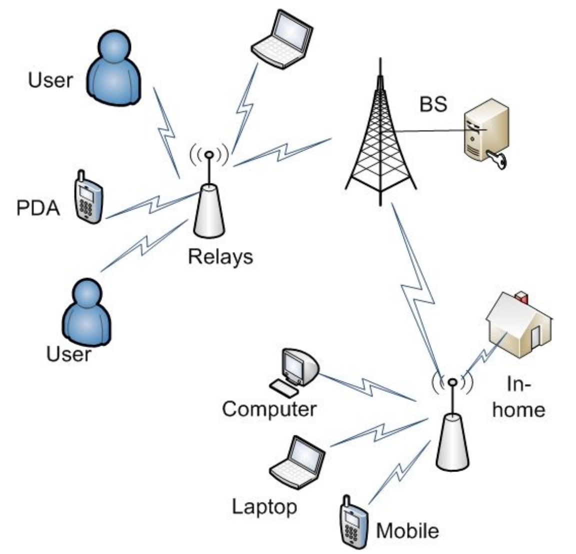

Fig. 1. Next generation two-hop hierarchical wireless architecture

In their landmark paper, Gupta and Kumar [4] proved that the data rate, and hence, the system capacity increases as $O(n^2)$, with an increase in the number of nodes n in the network. In a significant result, it is shown that the data rate can be increased significantly along with a significant reduction in the outage when the traffic is diverted from *highly loaded* to *lightly loaded* regions [5]. However, resource allocation in multihop networks is a challenging task. In fact, optimum resource allocation in a hierarchical multihop network is an NP-hard problem [6]. Hence, researchers across the world have focused mainly on two-hop hierarchical networks. In this context, a novel cluster-based design for two-hop hierarchical networks has been recently proposed in [7], wherein, it has been shown that the cluster-based two-hop design shows a significantly superior performance as compared with the state-of-the-art resource algorithms.

In this paper, a novel cluster-based double dumbbell topology is proposed for adaptive multimedia streaming in WiMAX-based two-hop cellular networks. Different adaptive

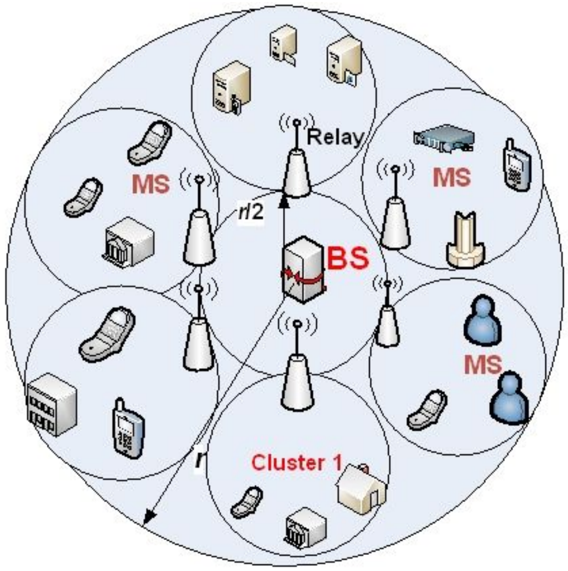

Fig. 2. Cluster-based two-hop wireless networks

multimedia techniques, viz., LDA+ (enhanced loss delay adaptation protocol), TFRCP (TCP friendly rate control protocol), RBAR (receiver based auto-rate protocol) and QOAS (quality oriented adaptive design) are considered in the network design, and their performance is analyzed for both single-hop (dumbbell topology) and cluster-based two-hop design (double dumbbell topology). It is shown that the QOAS-based wireless network with double dumbbell topology performs significantly better than any other adaptive solutions and topology, not only in the perceived quality, but also in terms of the bit rate and the average loss rate.

The paper is organized as follows: Section II describes the cluster-based two-hop wireless network model in detail, along with QOAS and other adaptive solutions. Section III describes the simulation model, the set up, and the simulation scenarios. The simulation results are explained in Section IV, and the conclusions are written in Section V.

II. Architectural Design

A. Cluster-based Two-Hop Design for WiMAX Networks

A cluster-based hierarchical two-hop cellular design based on IEEE 9802.16j (multihop relay networks) is established between the server/base station (BS) and the end-user mobile stations (MSs), as shown in Fig. 2. As per this design, there are *six* clusters in a coverage area. The circular coverage area has a radius, r, and is divided into two layers. The wireless nodes in the inner-layer communicate directly with the server whereas the wireless terminals in the outer-layer are grouped into several clusters (six clusters in Fig. 2). In each cluster, a wireless terminal located at the boundary of the inner and outer layer of the network region is selected as a cluster-head node, alternately known as 'relay'. The server always communicates with the users in the outer-layer through the relay. Hence, the maximum transmission distance of a communicating pair in the network is $r/2$ [8].

In order to reduce the additional interference arising from the simultaneous communication of multiple communicating pairs, a *Protocol Model* is considered for interference avoidance in the two-hop design [7]. The reusability of the available spectrum resource (time slot in a time division multiple access system and a frequency band in a frequency division multiple access system) is increased in the cluster-based design by allowing two multihop clusters in the network to utilize the same spectrum resource. It should be noted that the number of clusters in the cluster-based design need not be always six [9]. But it should be an "even" number due to the basic principle of simultaneous transmission of communication pairs located in the diametrically opposite clusters.

B. QOAS - Quality Oriented Adaptive Scheme

The primary aim of integrating QOAS with the cluster-based design in the IEEE 802.16j wireless model is to maintain a high end-user perceived quality even with an increase in the number of wireless devices in the network. QOAS relies on the fact that the impact on the end-user perceived quality is greater in case of random losses than that of controlled reduction in quality [10]. The system architecture of the feedback-based QOAS includes multiple instances of the end-to-end adaptive client and server applications [11]. Following ITU-T R. P.910 standard [12], a five state model is defined for the multimedia streaming process. The QOAS client continuously monitors the transmission parameters and estimates the end-user perceived quality. The Quality of Delivery Grading Scheme (QoDGS) regularly computes Quality of Delivery (QoD) scores that reflect the multimedia streaming quality in current delivery conditions. These grades are then sent as feedback to the server arbitration scheme (SAS). The SAS assesses the values of a number of consecutive QoD scores received as feedback in order to reduce the effect of noise in the adaptive decision taking process [13]. Based on these scores SAS suggests adjustments in the data rate and other parameters.

C. Other Adaptive Solutions

With an increase in the demand for multimedia streaming in wireless networks, there has been several approaches researched in the recent past. TFRCP is a unicast transport layer protocol, designed for multimedia streaming, and provides nearly the same amount of throughput as that of TCP on wired networks. The TFRCP controls rate based on network conditions expressed in terms of RTT and packet loss probability [14]. Similar to TFRCP, LDA+ (enhanced loss delay adaptation) also aims to regulate the transmission behavior of multimedia transmitters in accordance with the network congestion state [15]. LDA+ uses RTP protocol for calculating loss and delay and uses them for regulating transmission rates of the senders. LDA+ adapts the streams in a manner similar to that of TCP connections. In comparison,

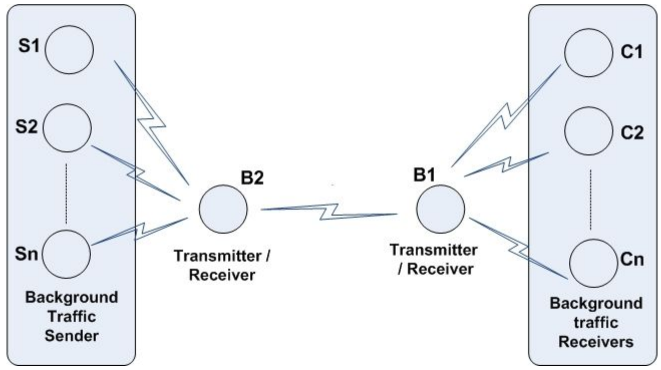

Fig. 3. Dumbbell network topology for single-hop client-server wireless architecture

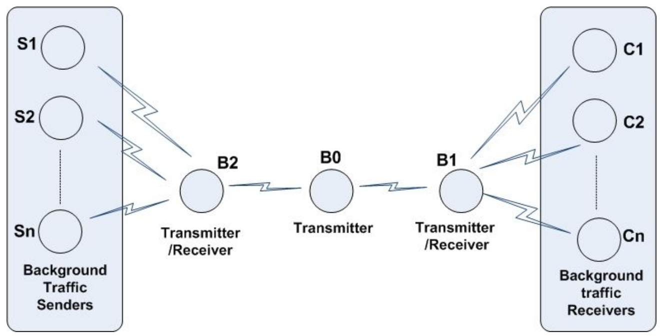

Fig. 4. Double dumbbell network topology for two-hop client-server wireless architecture

RBAR is a receiver based auto-rate mechanism. It is a MAC layer protocol and is based on RTS/CTS mechanism [16]. The main feature of RBAR is that both channel quality estimation and rate selection mechanism are on the receiver side. This allows the channel quality estimation mechanism to directly access all of the information made available to it by the receiver (number of multipath components, symbol error rate, received signal strength, etc) for more accurate rate selection.

III. Simulation Model and Testing

A. Dumbbell and Double Dumbbell Topology

In case of multimedia transmission, the web server acts as the multimedia source, which transmits the multimedia content to all the wireless devices in its coverage area. The end-users are the web-clients which receive the multimedia information. Fig. 3 shows a dumbbell topology for achieving the single-hop communication, wherein, B1-B2 forms the bottleneck link. B1 is the multimedia source and transmits information to the n clients C1, C2, ... Cn. In case of a two-hop communication, there is an intermediate relay between the web source and the end-user client. This can be represented by a double dumbbell topology, as shown in Fig. 4. The multimedia server is represented by B0, whereas the diametrically opposite relays are represented by B1 and B2. The end-users S1, S2, ... Sn on one end and C1, C2 ... Cn on the diametrically opposite cluster are the multimedia clients. B1 and B2 being relay nodes act as both transmitter and receiver, depending on whether it receives information from B0 to the end-users, or sends feedback information from the end-users to B0. The major advantage of the double dumbbell topology (cluster-based two-hop design) over the dumbbell topology (single-hop wireless network) is the hierarchical formation of the network, and the provision for peer-to-peer communication among the wireless nodes.

In the simulation environment, B1-B2 in the dumbbell topology and B0-B1, B0-B2 links in the double dumbbell topology are the bottleneck links, with 2 Mbps bandwidth and 100ms latency. The other communicating links connected to the end-users in the network are over-provisioned. Hence, the congestion in the traffic, packet loss and delays occur mainly because of the bottleneck link. The buffering at the ends of the bottle-neck link uses a drop-tail queue of size proportional to the product of round trip time (RTT) and bottleneck link bandwidth.

B. Simulation Setup

The simulation setup consists of a number of mobile nodes distributed in the given coverage area. There is a server located at the center of the coverage area. In case of a one-hop network, the server communicates directly with all the wireless terminals in the network. However, in case of the cluster-based two-hop design, there are six gateways/relays at equidistant locations, mid-way across the coverage area, as shown in Fig. 2. Hence, a hierarchical structure exists between the server, the relays and the MSs, as shown in Fig. 2. The system is simulated using the server and client instances inbuilt in network simulator, NS-2. The length of all NS-2 simulations is 250s. The video streams are modeled using Transform Expand Sample (TES) and then encoded using MPEG4. The primary reason for using MPEG4 is that it supports media streaming and is suitable for home networking applications with its low bit rate as well as its interoperability of audio and video signals [17].

A binary phase shift keying (BPSK) modulation technique is used at the physical layer. A slow varying flat fading channel is assumed throughout the simulations. In addition, a two-ray model with a lognormal shadowing of 4 dB standard deviation is considered [18]. At the MAC layer, an IEEE 802.11g based distributed coordination function (DCF) is used. The simulation is done at the packet level and the performance is evaluated in terms of average bit rate, loss rate and estimated user perceived quality. The end-user perceived quality is measured by developing a relationship between coding bitrate, packet loss ratio and user-level quality. Traffic with different sizes and shapes are considered as in [10], so as to emulate the real life scenario of varieties of traffic sources with different average bit rates. The network performance is analyzed in terms of the perceived quality, the loss rate and the average bit rate, not only for QOAS technique, but also compared with other protocols, i.e., LDA+, TFRCP and RBAR.

IV. Results

Fig. 5 presents the performance results for UDP-CBR periodic traffic case, using ‘dumbbell’ and ‘double dumbbell’ topology respectively. The traffic patterns are kept identical for both single-hop and clustered two-hop scenario. It can be observed from Fig. 5 that for all three kinds of periodic traffic considered, the perceived quality obtained for the cluster-based two-hop design (double dumbbell topology) is significantly superior to that obtained using the single-hop design (dumbbell topology). For exampe, Fig. 5-a shows the results, wherein, in case of 1 x 0.6 Mbps traffic with 20s on - 40s off, the perceived quality obtained with QOAS in the single-hop model is 3.9082, whereas that obtained using the two-hop model is 4.2098, an increase of 7.71%. In addition, for the same traffic model, the perceived quality of QOAS in the single-hop design is better than any other scheme (LDA+) by 5.25% (QOAS has a Q of 3.9082 whereas LDA+ has a Q of 3.7025). However, in case of a cluster-based two-hop design, the improvement in the perceived quality between QOAS and LDA+ is atleast 9.97%, almost twice the benefit obtained from using the ‘dumbbell’ topology. The performance of different adaptive schemes in terms of the perceived quality, loss rate and the average bit rate is shown in Table I and II for the single-hop dumbbell topology and clustered two-hop design using double dumbbell topology. It can be observed from the results that double dumbbell topology is superior to the plain dumbbell topology, for all kinds of UDP-CBR periodic traffic considered in the simulations.

In a similar result, in case of UDP-CBR staircase traffic, the perceived quality obtained from the ‘double dumbbell’ topology scores significantly over the ‘dumbbell’ scheme, as can be seen from Fig. 6. For example, in case of 4 x 0.4 Mbps (Up 40s steps), the perceived quality of QOAS using ‘dumbbell’ scheme is 3.8082, whereas the same using ’double dumbbell’ scheme is 4.2986, an increase of 12.87%. Not only with QOAS, but also with other methods like LDA+, TFRCP and RBAR, the perceived quality, loss rate and the average bit rate is notably superior when the double dumbbell topology is used. Table III and IV shows the detailed results of the UDP-CBR staircase traffic. It can be seen from Table III and IV that the improvement in the average bit rate and the loss rate is also notably high in case of the double dumbbell topology, as compared to the dumbbell scheme. Similarly, the improvement in the loss rate for QOAS under the same traffic model is over *six* times (0.04 using ‘double dumbbell’ scheme and 0.24 using ‘dumbbell’ technique). Also, it should be noted that the performance improvement obtained from the two-hop design remains consistent over many different traffic scenarios of staircase traffic, as shown in Table III and IV.

In the Internet environment, traffic is generally bursty, as in case of FTP traffic. Table V and VI shows the performance for different FTP and WWW traffic models. Also, with regard to the perceived quality, Fig. 7 show the obtained results for tests carried out on both FTP and WWW traffic for the duration of 250s. Similar to the results obtained in case of UDP transmission, the performance of the ‘double dumbbell’ topology is superior to that obtained from the ‘dumbbell’ topology for both FTP and WWW traffic.

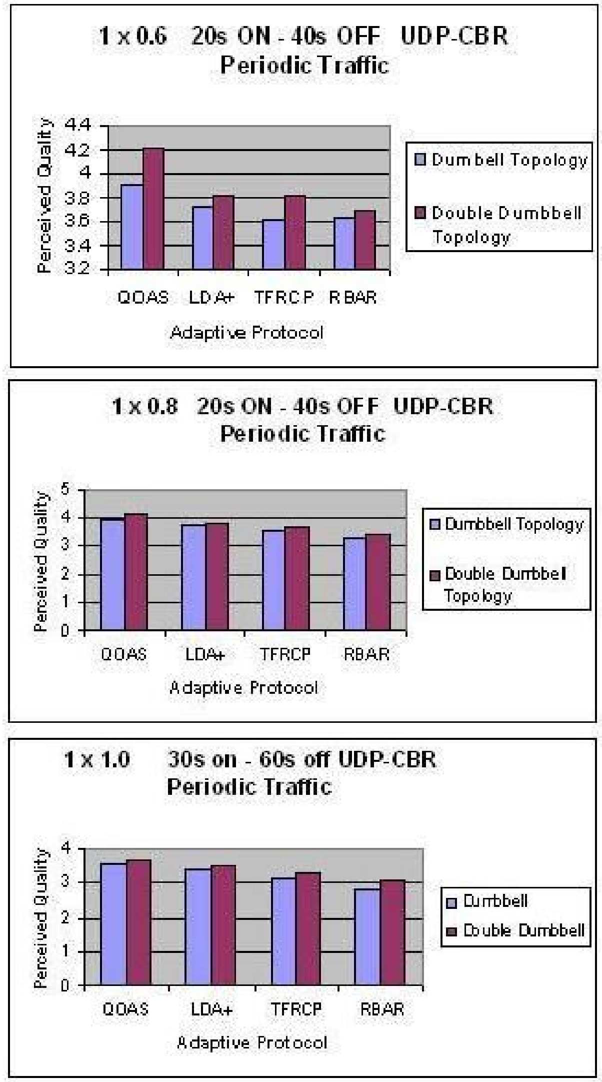

Fig. 5. Perceived quality of users for UDP-CBR periodic traffic in single-hop and cluster-based two-hop network design

V. Conclusions

This paper proposes a resource-efficient cluster-based design for adaptive multimedia streaming in IEEE 801.16j enabled two-hop cellular network. A ‘double dumbbell’ topology is considered in the cluster-based two-hop design so that the clients that are located diametrically opposite to the web server could communicate simultaneously. The ‘state-of-the-art’ adaptive solution - QOAS, when combined with the cluster-based design not only results in superior multimedia transmission as compared to single-hop network, but also outperforms other protocols like LDA+, TFRCP and RBAR. In addition, the loss rate of the video frames is reduced, *even up to a factor of 10*, when the two-hop cluster-based design is used. This is a very significant result. It demonstrates the feasibility of

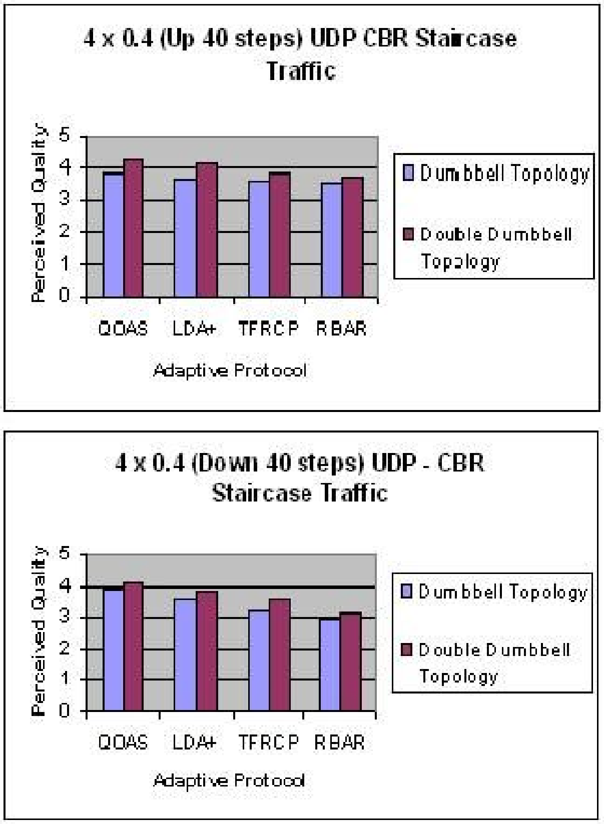

Fig. 6. Perceived quality of users for UDP-CBR staircase traffic in single-hop and cluster-based two-hop network design

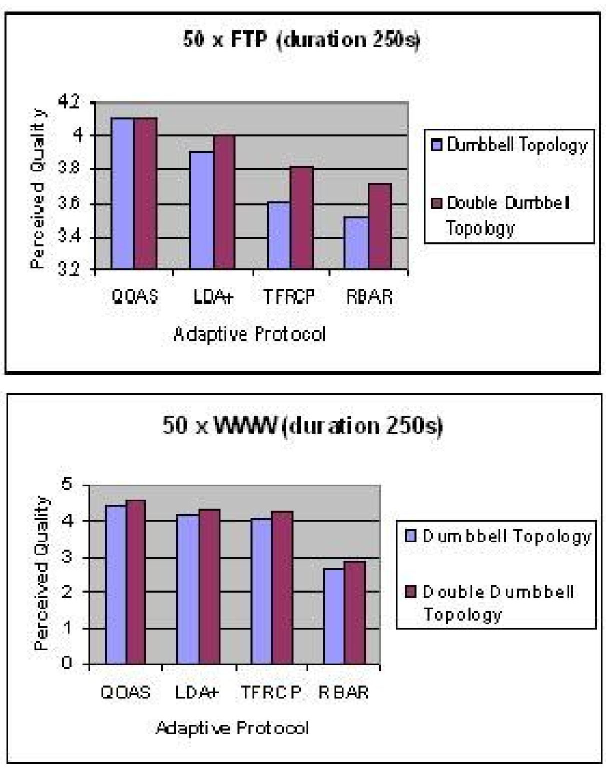

Fig. 7. Perceived quality of users for FTP and WWW traffic in single-hop and cluster-based two-hop network design

multimedia streaming for the wireless network users. This would boost the network operator to incorporate the QOAS scheme and implement the cluster-based design in the design of next generation hierarchical multihop wireless networks, in order to provide high quality video and multimedia streaming to the wireless end-users.

VI. Acknowledgement

The authors would like to thank Irish Research Council for Science Engineering and Technology (IRCSET) for supporting this research work.

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Characteristics	**Perceived Quality (1-5)**				**Loss Rate (%)**				Average Bit Rate (Mbps)			
Size of traffic (Mb/s)	**QOAS**	**LDA+**	**TFRCP**	**RBAR**	**QOAS**	**LDA+**	**TFRCP**	**RBAR**	**QOAS**	**LDA+**	**TFRCP**	**RBAR**
1 x 0.6 20s on - 40s off	3.9082	3.7225	3.6082	3.6215	0.18	0.42	0.20	0.22	0.7261	0.7136	0.7086	0.7028
1 x 0.6 30s on - 60s off	3.8098	3.6243	3.4934	3.4674	0.18	0.42	0.18	0.20	0.7343	0.7263	0.7184	0.7206
1 x 0.8 20s on - 40s off	3.9421	3.7546	3.5715	3.2793	0.14	0.40	0.16	0.18	0.7763	0.7364	0.7409	0.7319
1 x 0.8 30s on - 60s off	3.6086	3.5863	3.2163	3.0106	0.14	0.38	0.16	0.16	0.7634	0.7343	0.7404	0.7451
1 x 1.0 20s on - 40s off	3.8098	3.6098	3.2823	2.9453	0.10	0.24	0.14	0.14	0.8022	0.7727	0.7621	0.7588
1 x 1.0 30s on - 60s off	3.5650	3.4050	3.1653	2.8295	0.10	0.24	0.14	0.14	0.8025	0.7721	0.7727	0.7624

TABLE I
PERFORMANCE ANALYSIS FOR UDP-CBR PERIODIC TRAFFIC USING DUMBBELL TOPOLOGY

Characteristics	**Perceived Quality (1-5)**				**Loss Rate (%)**				Average Bit Rate (Mbps)			
Size of traffic (Mb/s)	**QOAS**	**LDA+**	**TFRCP**	**RBAR**	**QOAS**	**LDA+**	**TFRCP**	**RBAR**	**QOAS**	**LDA+**	**TFRCP**	**RBAR**
1 x 0.6 20s on - 40s off	4.2098	3.8142	3.8098	3.6928	0.08	0.38	0.12	0.18	0.7316	0.7564	0.7261	0.7036
1 x 0.6 30s on - 60s off	4.0323	3.7243	3.6923	3.4231	0.08	0.38	0.12	0.18	0.7316	0.7564	0.7384	0.7181
1 x 0.8 20s on - 40s off	4.1124	3.8549	3.6741	3.4040	0.04	0.34	0.16	0.16	0.7564	0.7876	0.7574	0.7354
1 x 0.8 30s on - 60s off	3.8786	3.5860	3.3146	3.0165	0.04	0.34	0.16	0.16	0.7564	0.7876	0.7661	0.7578
1 x 1.0 20s on - 40s off	3.9887	3.8098	3.3083	3.1245	0.01	0.21	0.10	0.12	0.8125	0.7926	0.7826	0.7789
1 x 1.0 30s on - 60s off	3.6905	3.5050	3.2605	3.0829	0.01	0.21	0.10	0.12	0.8125	0.7926	0.7926	0.7862

TABLE II
PERFORMANCE ANALYSIS FOR UDP-CBR PERIODIC TRAFFIC USING DOUBLE DUMBBELL TOPOLOGY

Characteristics	**Perceived Quality (1-5)**				**Loss Rate (%)**				Average Bit Rate (Mbps)			
Size of traffic (Mb/s)	**QOAS**	**LDA+**	**TFRCP**	**RBAR**	**QOAS**	**LDA+**	**TFRCP**	**RBAR**	**QOAS**	**LDA+**	**TFRCP**	**RBAR**
4 x 0.4 (Up 40s steps)	3.8082	3.6825	3.5852	3.4815	0.24	0.46	0.26	0.24	0.7165	0.7060	0.6866	0.6702
4 x 0.8 (Up 40s steps)	3.8621	3.6767	3.4815	3.1793	0.18	0.42	0.18	0.20	0.7630	0.7466	0.7209	0.7112
4 x 1.0 (Up 40s steps)	3.7263	3.4963	3.1763	3.0065	0.18	0.40	0.18	0.18	0.7534	0.7483	0.7344	0.7251
4 x 0.4 (Down 40s steps)	3.8875	3.5798	3.2025	2.9543	0.16	0.28	0.18	0.18	0.8002	0.7527	0.7420	0.7388
4 x 0.8 ((Down 40s steps)	3.7273	3.5606	2.8709	2.7845	0.14	0.24	0.14	0.16	0.8461	0.8145	0.8001	0.7624
4 x 1.0 (Down 40s steps)	3.5805	3.3208	2.6870	2.6770	0.14	0.24	0.13	0.16	0.8585	0.8005	0.8087	0.8009

TABLE III
PERFORMANCE ANALYSIS FOR UDP-CBR STAIRCASE TRAFFIC USING DUMBBELL TOPOLOGY

Characteristics	**Perceived Quality (1-5)**				**Loss Rate (%)**				Average Bit Rate (Mbps)			
Size of traffic (Mb/s)	**QOAS**	**LDA+**	**TFRCP**	**RBAR**	**QOAS**	**LDA+**	**TFRCP**	**RBAR**	**QOAS**	**LDA+**	**TFRCP**	**RBAR**
4 x 0.4 (Up 40s steps)	4.2986	4.0965	3.8340	3.7214	0.04	0.24	0.08	0.08	0.7356	0.7256	0.7056	0.7025
4 x 0.8 (Up 40s steps)	4.1249	3.9290	3.6756	3.4847	0.00	0.18	0.03	0.14	0.8087	0.7886	0.7876	0.7678
4 x 1.0 (Up 40s steps)	4.0608	3.8608	3.6363	3.2410	0.0	0.18	0.04	0.10	0.8184	0.7686	0.7984	0.7561
4 x 0.4 (Down 40s steps)	4.0983	3.8030	3.5972	3.1446	0.06	0.16	0.1	0.12	0.7125	0.6826	0.6825	0.6789
4 x 0.8 ((Down 40s steps)	3.9601	3.6615	3.4401	3.0045	0.01	0.11	0.04	0.12	0.7978	0.7678	0.7678	0.7024
4 x 1.0 (Down 40s steps)	3.8347	3.6347	3.3347	2.9555	0.0	0.09	0.03	0.12	0.8178	0.8076	0.7878	0.7254

TABLE IV
PERFORMANCE ANALYSIS FOR UDP-CBR STAIRCASE TRAFFIC USING DOUBLE DUMBBELL TOPOLOGY

Characteristics	**Perceived Quality (1-5)**				**Loss Rate (%)**				Average Bit Rate (Mbps)			
Size of traffic (Mb/s)	**QOAS**	**LDA+**	**TFRCP**	**RBAR**	**QOAS**	**LDA+**	**TFRCP**	**RBAR**	**QOAS**	**LDA+**	**TFRCP**	**RBAR**
50 x FTP Duration(250s)	4.0928	3.9003	3.6095	3.5121	0.10	0.20	0.14	0.18	0.7434	0.7140	0.7136	0.6928
54 x FTP Duration(250s)	3.7223	3.7250	3.4734	3.3067	0.08	0.20	0.14	0.22	0.7736	0.7236	0.7374	0.7161
58 x FTP Duration(250s)	3.7012	3.6125	3.3052	3.2879	0.08	0.18	0.14	0.22	0.7755	0.7390	0.7517	0.7392
40 x WWW (Duration 250s)	4.7943	4.3933	4.2035	2.7545	0.10	0.14	0.14	0.24	0.7002	0.6845	0.6902	0.7518
50 x WWW (Duration 250s)	4.4504	4.1601	4.0650	2.6598	0.08	0.14	0.14	0.24	0.7119	0.7009	0.7010	0.7421
60 x WWW (Duration 250s)	4.0020	3.9220	3.6820	2.8045	0.15	0.18	0.19	0.18	0.7584	0.7484	0.7161	0.7805

TABLE V
PERFORMANCE ANALYSIS FOR TCP-FTP TRAFFIC USING DUMBBELL TOPOLOGY

Characteristics	**Perceived Quality (1-5)**				**Loss Rate (%)**				Average Bit Rate (Mbps)			
Size of traffic (Mb/s)	**QOAS**	**LDA+**	**TFRCP**	**RBAR**	**QOAS**	**LDA+**	**TFRCP**	**RBAR**	**QOAS**	**LDA+**	**TFRCP**	**RBAR**
50 x FTP Duration(250s)	4.1098	4.0003	3.8098	3.7121	0.00	0.10	0.1	0.1	0.7564	0.7240	0.7364	0.7025
54 x FTP Duration(250s)	3.9723	3.9020	3.6723	3.5067	0.01	0.10	0.1	0.12	0.7876	0.7406	0.7576	0.7226
58 x FTP Duration(250s)	3.8012	3.7122	3.5012	3.3879	0.04	0.14	0.12	0.12	0.7975	0.7595	0.7675	0.7549
40 x WWW (Duration 250s)	4.8093	4.5993	4.4093	2.9245	0.01	0.11	0.04	0.14	0.7125	0.7005	0.7025	0.7689
50 x WWW (Duration 250s)	4.5650	4.3601	4.2650	2.8298	0.01	0.12	0.04	0.14	0.7209	0.7190	0.7109	0.7692
60 x WWW (Duration 250s)	4.1620	4.0620	3.8620	2.9045	0.05	0.15	0.09	0.12	0.7768	0.7528	0.7368	0.7904

TABLE VI
PERFORMANCE ANALYSIS FOR TCP-FTP TRAFFIC USING DOUBLE DUMBBELL TOPOLOGY