Impact of Traffic Arrival Distributions on an 802.11 Ad Hoc Network: Modeling and Performance Study

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***Abstract*—This paper investigates the impact of traffic arrival distributions on a typical 802.11 ad hoc network using simulation and modeling. In the investigation, four diverse traffic models (Exponential, Pareto, Poisson, and Constant bit rate) are considered for TCP and UDP. Results show that the network performance for Poisson arrivals is almost independent of traffic load for TCP and UDP but not for Constant bit rate (CBR). However, for both the Pareto and Exponential packet arrivals the network performance is almost independent of load for TCP, but is sensitive to UDP. The network achieves best and worst throughput performance for CBR and Poisson, respectively. The analysis and research findings reported in this paper provide some insight into the impact of the choice of traffic arrival distributions and transport protocols on wireless local area network (WLAN) performance.**

***Index Terms*—Traffic arrival distribution, WLAN, throughput, constant bit rate (CBR)**

I. INTRODUCTION

WIRELESS local area networks (WLANs) become more popular in both business and home networking applications in recent years. People are more interested to use non-data services (e.g. Voice over IP and video-conferencing) in addition to data services such as email and file transfer protocol. Quality of Service (QoS) is an important requirement defined in the network standards through a set of QoS parameters such as packet delay, packet drop ratio, throughput and fairness (i.e. equality in channel access) [1]. For example, a real-time service such as video-conferencing may require a guaranteed minimum end-to-end packet delay [2, 3]. Deciding what traffic arrival distributions and transport protocols are appropriate for these services is an important consideration.

The traffic generated by various applications will have diverse statistical properties. For example, client-server services on the World Wide Web typically generate bursty traffic due to their request (e.g. sending query messages) and response (e.g. down load web pages) type processes. These variable bit rate (VBR) services must be modeled at the packet level so that network can dynamically allocate resources on demand for efficient use of channel bandwidth among the active users. Unfortunately, traffic distribution models that are easier to represent mathematically and that have been used traditionally for network performance analysis (e.g. Poisson) are not well suited to modeling real-life traffic [4]. Real-life data traffic tends to be burstier than that described by traditional traffic models. This has serious implication for system dimensioning.

This paper addresses the following two research questions. ***What impact do the traffic arrival distributions and transport protocols have on the performance of a typical 802.11 network? What is the best traffic arrival distribution model to use in order to meet the requirements of a particular application?***

By considering these issues we can determine how much emphasis should be placed on accurately modeling packet arrival processes at the nodes when developing network dimensioning rules.

To answer the questions posed we examine the impact of four diverse traffic arrival models, namely Exponential, Pareto ON OFF ("Pareto"), Poisson, and CBR on the performance of an 802.11 single-hop ad hoc network for TCP and UDP. The impact of medium access control (MAC) protocol on system performance is not investigated in this paper.

The remainder of this paper is organized as follows. Section II describes the traffic arrival processes used. Section III describes simulation setup for network performance study. The validation of simulation model is also discussed in this section. The simulation results and comparative analysis are presented in Section IV. The practical system implication is discussed in Section V, and Section VI concludes the paper.

Manuscript received May 10, 2012. This work was supported in part by the SCMS research funds, Auckland University of Technology, Auckland, New Zealand

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II. TRAFFIC ARRIVAL PROCESSES

The traffic model describes the number of packet arrivals at nodes on the network. Four commonly used traffic arrival distributions are used which each generate a mean of one packet per slot. These traffic arrival models were chosen because they each have been shown to adequately model a real-life service and are of a relatively generic in nature suggesting that they can be used for a range of services. The packet arrival processes used are:

- **Exponential:** The packets are generated at each station at a fixed rate during the ON periods, and no packets are generated during the OFF periods. Both ON and OFF periods are derived from an exponential distribution. The exponential distribution is very important in queuing theory which is widely used in studying the performance of computer and data communication networks. For example, the service time of a server can often be assumed to be exponential. In ns-2 [5], the length of packets, average ON and OFF times, and packet sending rate were defined for simulation experiments.
- **Pareto:** The Pareto distribution is a power curve with two parameters, namely the shape parameter and the location parameter [6]. The packet arrival processes at the stations is similar to the Exponential arrivals except that both ON and OFF periods are derived from a Pareto distribution. The packet inter-arrival times in various real-life services such as Ethernet LAN [7], TELNET and FTP [4], follow Pareto distribution with shape parameter ranging from 0.9 to 1.5. In ns-2, the shape of the Pareto distribution was set to 1.4 for experimentation.
- **Poisson:** The packets are generated at each station following an independent process with independent increments, with mean λ_i packets per slot. The packet inter-arrival times are exponentially distributed with mean $1/\lambda_i$. Poisson packet arrivals assumptions have been used extensively in the literature to model various telecommunication traffic, however it has limitations for the modeling of self-similar data traffic [4]. In ns-2, Exponential ON-OFF traffic generator is configured to behave as a Poisson process by setting the variable burst time to 0 and the variable rate to a very large value.
- **Constant bit rate (CBR):** In this process, the packets are generated at the stations at a constant rate. This is one of the most simplistic models possible and exactly models CBR services (e.g. voice telephony, video-on-demand). Random noise can be introduced to change the duration of packet intervals. In ns-2, the parameters, such as maximum number of packets that can be sent, packet sending rate, and a flag to specify random noise were set for simulation tasks to 10000, 64 kbps, and 1, respectively.

The models selected have a diverse range of statistical properties and this provides a rapid means of determining how sensitive system performance is on traffic arrival distributions and transport protocols. More details about traffic arrival models including packet arrival processes and their probability density functions can be found in many wireless communications and simulation analysis textbooks [8, 9].

III. MODELING AND SIMULATION

A. Simulation Environment and Parameters

There are several aspects that need to be considered when selecting a network simulator for a simulation study. For example, use of reliable pseudo-random number generators, an appropriate method for analysis of simulation output data, and statistical accuracy of the simulation results (i.e. desired relative precision of errors and confidence interval). These aspects of credible simulation studies are recommended by leading simulation researchers [8, 10-13]. However, the ns-2 [5] simulation package has been used to carry out simulation experiments. Ns-2 was chosen because it is available (including a comprehensive user manual and tutorials) for download at no cost and is extensively used in the academic community. In a recent study on experimental validation of ns-2 wireless models using simulation, emulation, and real networks, Ivanov et al. [14] reported that wireless network topologies are accurately represented in ns-2, once the simulation parameters are accurately tuned. Another motivation for using ns-2 is that one can compare the proposed approach with the other protocols on a single common and pre-validated platform for simulations. Ns-2 version 2.31 was the most recent version of the network simulation package at the time of this work.

TABLE I. SIMULATION PARAMETERS

Parameter	Value
Data rate	11 Mbps
Basic rate	2 Mbps
Wireless card	802.11b
Slot duration	20 µs
SIFS	10 µs
DIFS	50 µs
MAC header	30 bytes
CRC	4 bytes
PHY header	96 µs
Traffic	TCP and UDP
Data packet length	1500 bytes
Channel model	Shadowing
RTS/CTS	Off
PHY modulation	DSSS
CWmin	31
CWmax	1023
Simulation time	10 minutes

Table I lists the parameter values used in the simulation of 802.11b. Each simulation run lasted for 10 minutes simulated time where the first minute was the transient period. The observations collected during the transient period are not included in the final simulation results.

B. Modeling Assumptions

A simulation model was developed using ns-2 to study the effect of traffic arrival distributions and transport protocols on the performance of a typical 802.11b single-hop ad hoc network. We assume that all wireless nodes are stationary and are in direct communication range. Stations communicate using identical half-duplex systems based on distribution coordination function (DCF). The data rate is set at 11 Mbps. Request-to-send (RTS)/Clear-to-send (CTS) are disabled. The shadowing channel model with $\sigma = 7$ dB (a realistic model for indoor radio propagation environments) is used in the simulations. All sources and receivers have an omni-directional antenna of height 1.5 m. Hidden and exposed node problems, noise and signal interference are not considered. Both TCP and UDP streams are used as network traffic content where the source and destination pairs for each TCP/UDP flow are randomly chosen from the set of 10 nodes. Total nine concurrent TCP/UDP streams are competing for the MAC access. The four different traffic arrivals processes described in Section II are used to control traffic loads of TCP and UDP. In the simulation experiments, network traffic load varies from 10 to 100% in order to observe the impact of traffic models and transport protocols on system performance. Data packet lengths of 1500 bytes are used.

C. Performance Metrics

The four important network performance metrics, namely network mean throughput, packet delay, fairness, and packet drop ratio are used in this study. The throughput (measured in Mbps) is the mean rate of successful message delivery over a communication channel. The mean packet delay at node i ($i = 1, 2,\dots, N$) is defined as the average time (measured in seconds) from the moment the packet is generated until the packet is fully despatched from that node. A packet arriving at station i experiences several components of delay including queuing delay, access delay and packet transmission time.

The MDT fairness is defined as follows.

$$MDT = \frac{\sum \left|(T_i - \overline{T})\right|}{N} \quad (1)$$

Where T_i is the throughput at station i; $\overline{T}$ is the network mean throughput; and N is the number of active nodes.

As shown in (1), MDT is defined as the spread or variation of an individual node's throughput from the network wide mean throughput. The value of MDT indicates the level of unfairness of a network protocol. A network is said to be 100% fair if MDT is zero (i.e., $T_i = \overline{T} \ \forall i$). The MDT fairness defined in (1) is used to measure the fairness of 802.11b.The packet drop ratio is directly related to packet collision rates, and high packet collisions at the destination nodes result in high packet drop ratios.

D. Simulation Model Validation

A credible network simulator may produce invalid results if the simulation parameters are not correctly configured. Therefore, simulation model verification becomes an important part of any simulation study. The ns-2 simulation model was verified in several ways. First, the simulation model was validated through radio propagation measurements from wireless laptops and access points for 802.11b WLANs [15, 16]. A good match between simulation and real measurement results for N = 2 to 4 nodes validates the simulation model. Second, the detailed status information was traced throughout the simulation to verify the model. Third, ns-2 results were compared with the results obtained from OPNET Modeler [17] and a good match between two sets of results validated our models [16]. The simulation results presented in this paper were also compared with the work of other network researchers to ensure the correctness [18-21].

IV. Results and Comparative Analysis

All simulation results report the steady state behaviour of network and were obtained with a relative statistical error ≤ 1%, at 99% confidence level.

A. Effect of packet arrival processes on system performance

The summary of empirical results for the effect of Pareto, Poisson, Exponential, and CBR on network performance is presented in Tables II to V, respectively.

Table II shows that network mean throughput is slightly higher for 1500–byte packets than for 512–byte packets, for both TCP and UDP. This throughput behavior is expected because proportionally longer payloads are achieved using longer packets compared to shorter packets. By comparing TCP and UDP, one can observe that the network mean throughput for UDP is better than for TCP. This throughput improvement results from UDP having fewer transmission overheads than TCP (i.e. no ACK). By looking at the network throughput, packet delay, MDT fairness and packet drop ratio, one can observe that they are independent of traffic load for TCP, but not for UDP. In fact for UDP network throughput increases while packet delay, MDT fairness and packet drop ratio deteriorate with increasing traffic load.

The impact of Poisson packet arrivals on system performance is illustrated in Table III. Network performance is independent of traffic load for TCP. For UDP, however, the network throughput increases slightly with traffic load. Another observation is that the network experiences slightly longer packet delays for UDP than for TCP. This longer delay is expected because the network packet delay increases with throughput due to traffic congestion on the network.

The empirical results for the effect of Exponential arrivals on system performance are summarized in Table IV. As with Pareto and Poisson, the network performance for Exponential is independent of traffic load for TCP. For UDP, however, the throughput improves, while packet delay, MDT fairness and packet drop ratio deteriorate with increasing traffic load.

TABLE II. IMPACT OF PARETO ON 802.11B (N= 10 STATIONS; SHADOWING MODEL WITH Σ = 7 DB)

Load (%)	Transport protocol	Packet size (bytes)	Throughput (Mbps)	Packet delay (ms)	MDT fairness	Packet drop ratio
20	UDP	512	1.161	2.512	0.033	0.012
		1500	1.234	4.153	0.022	0.011
50	UDP	512	2.310	179.364	0.046	0.178
		1500	2.630	31.358	0.038	0.016
60	UDP	512	2.348	208.484	0.061	0.274
		1500	3.060	177.764	0.037	0.180
80	UDP	512	2.374	363.829	0.086	0.522
		1500	3.202	259.308	0.093	0.317
90	UDP	512	2.363	301.965	0.101	0.514
		1500	3.290	338.616	0.081	0.383
All loads	TCP	512	0.529	4.780	0.027	0.006
		1500	1.561	8.662	0.078	0.012

TABLE III. IMPACT OF POISSON ON 802.11B (N= 10 STATIONS; SHADOWING MODEL WITH Σ = 7 DB)

Load (%)	Transport protocol	Packet size (bytes)	Throughput (Mbps)	Packet delay (ms)	MDT Fairness	Packet drop ratio
20	UDP	512	0.651	4.707	0.001	0.011
		1500	0.701	4.101	0.010	0.012
50	UDP	512	1.801	4.808	0.001	0.009
		1500	1.901	29	0.022	0.012
60	UDP	512	2.010	4.836	0.001	0.009
		1500	2.202	125	0.029	0.102
80	UDP	512	2.302	4.915	0.001	0.009
		1500	2.580	200	0.061	0.299
90	UDP	512	2.750	4.938	0.001	0.009
		1500	2.803	250	0.059	0.340
All loads	TCP	512	0.053	3.101	0.002	0
		1500	0.149	3.932	0.007	0

TABLE IV. IMPACT OF EXPONENTIAL ON 802.11B (N= 10 STATIONS; SHADOWING MODEL WITH Σ = 7 DB)

Load (%)	Transport protocol	Packet size (bytes)	Throughput (Mbps)	Packet delay (ms)	MDT Fairness	Packet drop ratio
20	UDP	512	1.098	2.453	0.009	0.009
		1500	1.140	3.887	0.011	0.011
50	UDP	512	2.129	173.012	0.036	0.183
		1500	2.634	36.561	0.026	0.020
60	UDP	512	2.357	255.826	0.044	0.321
		1500	2.942	143.697	0.047	0.102
80	UDP	512	2.196	327.391	0.065	0.507
		1500	3.228	297.036	0.072	0.311
90	UDP	512	2.379	325.073	0.055	0.512
		1500	3.244	325.840	0.066	0.398
All loads	TCP	512	0.455	4.322	0.021	0
		1500	1.336	7.023	0.064	0.018

TABLE V. IMPACT OF CBR ON 802.11B (N= 10 STATIONS; SHADOWING MODEL WITH Σ = 7 DB)

Load (%)	Transport protocol	Packet size (bytes)	Throughput (Mbps)	Packet delay (ms)	MDT fairness	Packet drop ratio
20	TCP	512	1.165	25.040	0.082	0.073
		1500	1.528	5.087	0.066	0
	UDP	512	2.174	33.958	0.009	0.028
		1500	2.218	17.472	0.003	0.018
50	TCP	512	1.294	383.976	0.078	0.080
		1500	2.720	349.797	0.173	0.065
	UDP	512	2.251	482.124	0.126	0.601
		1500	3.234	483.517	0.166	0.452
60	TCP	512	1.285	358.420	0.082	0.084
		1500	2.791	420.107	0.169	0.074
	UDP	512	2.356	491.381	0.132	0.655
		1500	3.289	531.633	0.174	0.546
80	TCP	512	1.310	381.888	0.088	0.073
		1500	2.868	404.120	0.190	0.083
	UDP	512	2.380	494.578	0.146	0.740
		1500	3.336	553.773	0.220	0.669
90	TCP	512	1.311	366.104	0.086	0.077
		1500	2.848	411.086	0.191	0.098
	UDP	512	2.339	492.120	0.128	0.771
		1500	3.433	560.931	0.233	0.704

The empirical results for the effect of CBR on 802.11b are summarized in Table V. The network throughput increases slightly whereas the packet delay increases dramatically for both TCP and UDP. This dramatic increase in packet delay is due to the characteristic of CBR sources whose constant stream of packets causes traffic congestion. Another observation is that both MDT fairness and packet drop ratio deteriorate slightly for both TCP and UDP.

A. Effect of arrival distributions on network throughput

In Fig. 1, the network mean throughput is plotted against traffic loads for Exponential, Pareto, Poisson, and CBR packet arrivals for TCP. The network mean throughput for Exponential, Pareto, and Poisson arrivals are almost independent of loads. However, the mean throughput for CBR increases with traffic load. The maximum throughput (2.89 Mbps) is achieved at full loading. One can observe that the mean throughput for Pareto is slightly higher than that of Exponential. Clearly, the network mean throughput is reduced for Poisson arrivals. This lower throughput is as a result of less network congestion.

The effect of traffic arrival distributions on network mean throughput for UDP traffic is illustrated in Fig. 2. The network mean throughput for Exponential, Pareto, and CBR increases with traffic load and becomes saturated at 90% loads. Of the four traffic models used, the network achieves best mean throughput under all loads for CBR and worst for Poisson.

Figures 1 and 2 show that Poisson and CBR have the largest difference and Pareto and Exponential have the smallest difference in their effect. The main conclusion is that if UDP is used in place of TCP, the network mean throughput improves significantly for all traffic arrival distributions considered except Poisson.

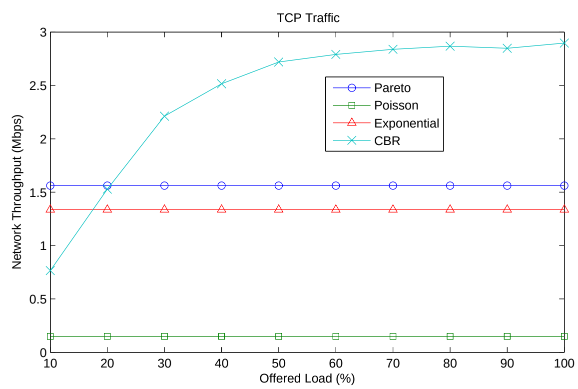
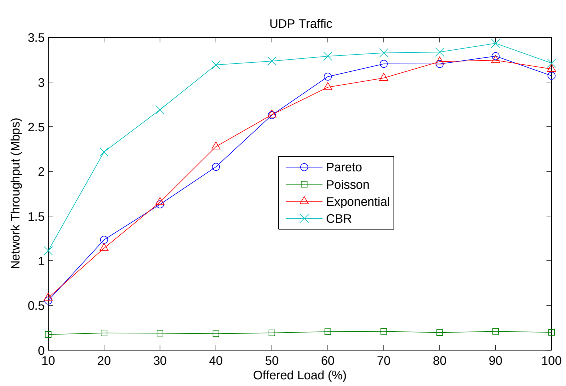


Figure 1. Network throughput versus offered load for TCP traffic.



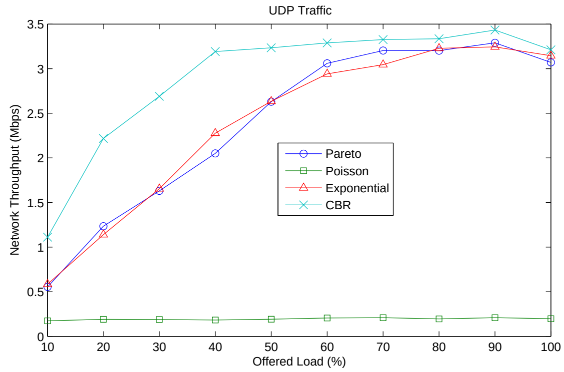


Figure 2. Network throughput versus offered load for UDP traffic.

B. *Effect of arrival distributions on packet delay*

Figure 3 plots network mean packet delay against traffic load for Exponential, Pareto, Poisson, and CBR arrivals for TCP. The mean packet delays for Exponential, Pareto, and Poisson processes are almost independent of traffic load. However, the mean packet delays for CBR increases with traffic load. By comparing the mean delays of all four traffic models used, one can observe that the network experiences shortest mean packet delay under medium-to-high loads for Pareto and longest under CBR.

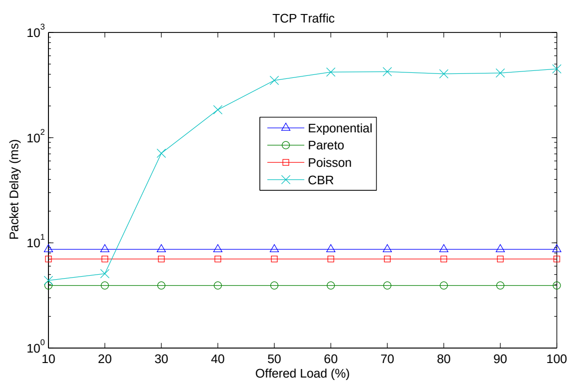


Figure 3. Mean packet delay versus offered load for TCP traffic.

Figure 4 compares mean packet delays for Exponential, Pareto, Poisson, and CBR for UDP. The mean packet delays for both Exponential and Pareto increase with load, especially under medium-to-high loads. The network experiences longer packet delays for CBR than those of Exponential, Poisson, and Pareto under all loads. The mean packet delays for Poisson are significantly better (in terms of lower packet delays) than those of Exponential, Pareto, and CBR, especially under medium-to-high loads. The packet delay is better because network is less congested in the Poisson case.

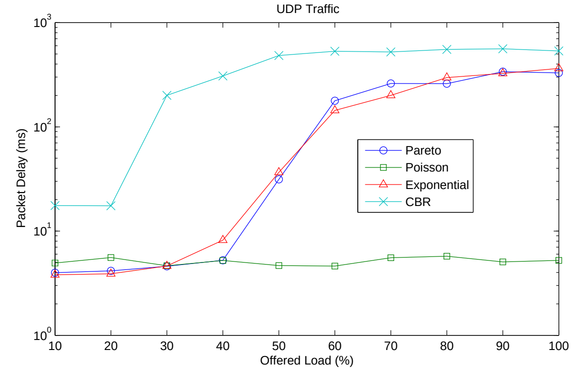


Figure 4. Mean packet delay versus offered load for UDP traffic.

The main conclusion is that (Figs. 3 and 4) if UDP is used in place of TCP, the network mean packet delay degrades slightly for the four traffic models used. The reason for packet delay degradation is that an UDP source does not adapt to network traffic congestion and therefore it wastes transmission bandwidth by sending packets that will not reach the destination stations.

C. *Effect of arrival distributions on MDT Fairness*

In Fig. 5, the MDT fairness is plotted against traffic load for Exponential, Pareto, Poisson, and CBR models for TCP. The MDT fairness for Exponential, Pareto, and Poisson processes are almost independent of traffic load.

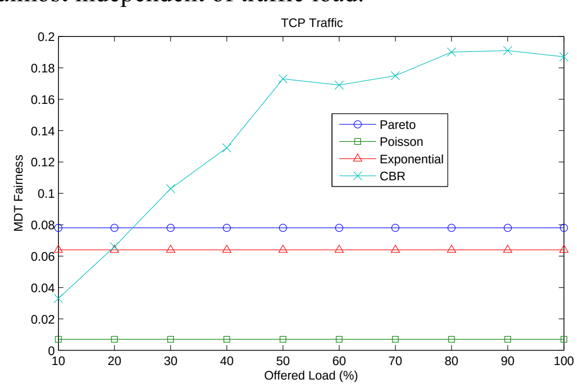


Figure 5. MDT Fairness versus offered load for TCP traffic.

We observe that the network suffers severe unfairness for CBR arrivals especially under medium-to-high loads. The network achieves slightly better fairness (in terms of lower MDT) for Exponential than for Pareto. Of the four traffic models used, Poisson results in the best fairness performance under all loads. The reason for this superior fairness is that Poisson fails to model adequately the burstiness of data traffic.

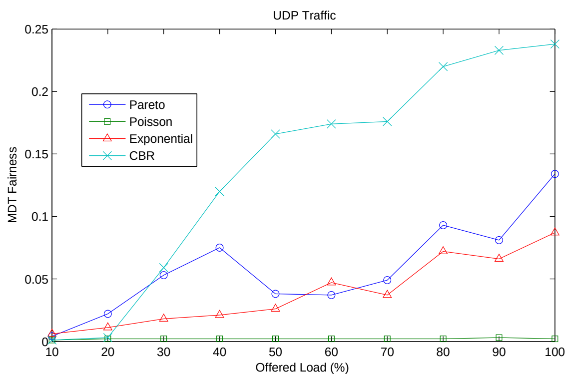


Figure 6. MDT Fairness versus offered load for UDP traffic.

Figure 6 compares the MDT fairness for Exponential, Pareto, Poisson, and CBR for UDP. Clearly, the network suffers severe unfairness (with respect to allocating bandwidth among active stations) for CBR, especially under medium-to-high loads. This unfairness performance is due to the statistical properties of CBR in which more packets are generated at the stations (traffic congestion), especially under high loads contributing to worse packet delay and MDT fairness. However, the network achieves the best (almost 100%) MTD fairness for Poisson processes. Our findings are in accordance with the work of other network researchers [4, 22].

The conclusion can be drawn from Figs. 5 and 6 is that when UDP is used in place of TCP, the network MDT fairness degrades slightly for all traffic models used except Poisson.

D. Effect of arrival distributions on packet drop ratio

Figure 7 plots the network mean packet drop ratio against traffic load for Exponential, Pareto, Poisson, and CBR with TCP. The mean packet drop ratios for Exponential, Pareto, and Poisson are almost independent of traffic load. However, the packet drop ratio for CBR sharply increases at loads of 20% and tapers off at 40%. Of the four arrival distributions used, the packet drop ratio is better (in terms of fewer packets being dropped) for Poisson under all loads.

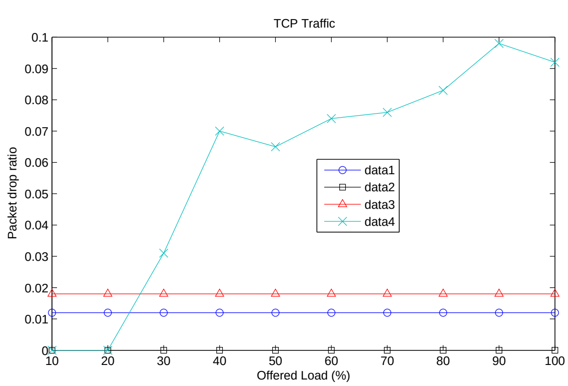


Figure 7. Packet drop ratio versus offered load for TCP traffic.

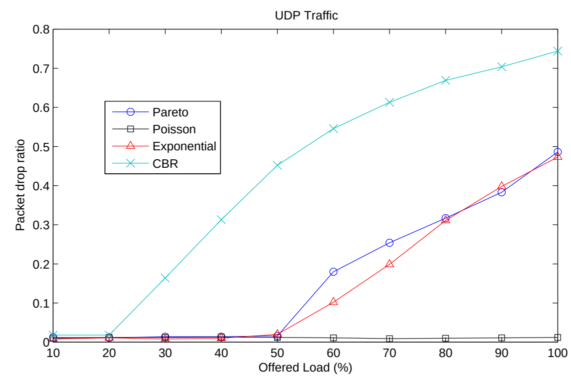


Figure 8. Packet drop ratio versus offered load for UDP traffic.

Figure 8 compares the mean packet drop ratios for Exponential, Pareto, Poisson, and CBR for UDP. Clearly, the mean packet drop ratio is best for Poisson and worst for CBR. The packet drop ratios for Exponential and Pareto steadily increase at loads > 50%.

The main conclusion is that (Figs. 7 and 8) if UDP is used in place of TCP, packets are dropped more frequently for all traffic models used except Poisson. The network achieves superior packet drop ratios for Poisson for both TCP and UDP because it fails to model the burstiness of data traffic.

V. Practical Implications

The results presented in Section IV provide some insight into the impact of the choice of traffic arrival distributions and transport protocols on WLAN performance. Results show that the traffic arrival distribution has a significant effect on network mean throughput, packet delay, MDT fairness and packet drop ratio of a typical 802.11b ad hoc network for TCP and UDP.

From a real application point of view a question may arise about the right traffic distribution model to use for a particular application. Figure 9 illustrates the best traffic model to use for an application to meet a certain QoS requirement (in terms of data rate and end-to-end packet delay). For instance, if an application requires high bandwidth (data rate), CBR is the best model to use for TCP and UDP. For another application requiring low mean packet delay for TCP traffic, Pareto is the best model to use for this application.

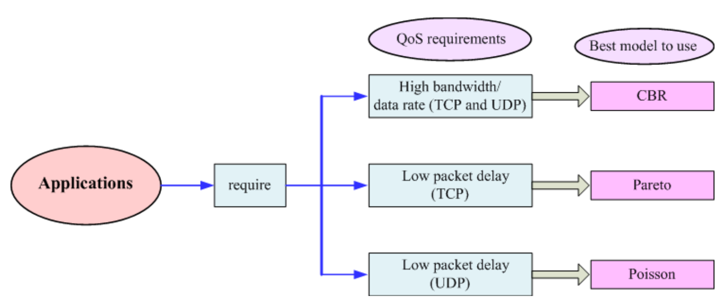


Figure 9. The best traffic distribution to use for a particular application.

VI. Conclusions

The effect of traffic arrival distributions and transport protocols on the performance of a typical 802.11 network has been investigated by extensive simulation experiments. In the investigation, Exponential, Pareto, Poisson, and CBR traffic models were used.

Experimental results have shown that the network achieved slightly higher mean throughput at packet length of 1500 bytes than that of 512 bytes packet length for both TCP and UDP traffic. The network mean throughput for UDP traffic is better than that of TCP under all loads. The network performance for Exponential, Pareto, and Poisson arrivals was found to be almost independent of traffic loads. On the other hand, the network performance for CBR was sensitive to traffic loads. Of the four traffic models used, the network achieved best and worst mean throughput with CBR and Poisson, respectively. The mean throughput of Pareto was found to be slightly better than that of Exponential for TCP under all loads. Overall, the best and worst packet delay, MDT fairness, and packet drop ratio were for Poisson and CBR, respectively. It was observed that Poisson and CBR had the largest effect on system performance, whereas Pareto and Exponential had the smallest effect.

When UDP is used instead of TCP, the network mean throughput improves significantly for all traffic models used except Poisson. However, when UDP is used in place of TCP, both the mean packet delays and packet drop ratios degrade slightly for all four traffic models types. An investigation of the impact of a traffic stream on the propagation dependent performance of a typical WLAN is planned as an extension of the study reported here.

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