Comparative Performance Analysis of Single-Server and Multiple-Server Markovian Models

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ABSTRACT
This research paper compares M/M/1 and M/M/N Markovian models to determine a more suitable queuing model for the enhancement of a wireless system's performance. Data traffic was collected from the wireless MikroTik router connecting the overhead satellite to the university Wireless Campus Area Network (WCAN) using "Winbox" software monitoring tool for a period of 11 months from 31th January 2011 to 30th December 2012. The computation of this data traffic gave the average arrival rate of 176.5 kilobits per second, and the average service rate of 746 kilobits per second. By using these values in the analyses, M/M/1 was found to be better than M/M/2 and even far better than M/M/3. The results shows that the higher the number of servers in a queuing model, the more the number of unserviced entities in the system, and in the queue waiting for service, and also the system has slower response time and longer waiting time in the queue.

Keywords
WCAN, Router, M/M/1, M/M/N, Queue Discipline.

1. INTRODUCTION
Arrival and service processes guided by protocols are very important in computer communication because they facilitate the reception of transmitted information [7]. These processes are applicable to any network whether wireless or wired because in any form of communication there must be arrival and service processes to receive the transmitted information. The arrival and service processes of entities are taken in turn because of the following reasons [6]:

(i) No two or more items can arrived simultaneously, but only one at a time.

(ii) Also, no system can service two or more items at the same time. Service is done in turn.

Therefore, entities arrive at the service system in a line following each other in a queue and are serviced and dispatched to the receiver in turn. This is referred to as a first come first serve queuing discipline. However, there are other service disciplines such as priority queuing, class-base queuing, weighted–fair queuing and many more available to change the order of service for the queue, depending on the application. The number of entities to be served remains one at each moment of time the service process is available and ready [6]. To enhance the performance of such queuing systems requires the implementation of an appropriate queuing model. Some of these queuing models are [4]:

(i) **M/D/1** Deterministic same length of arrivals and constant service time single server model.

(ii) **M/G/1** General independent arbitrary probability distribution for arrival and service time single server model.

(iii) **M/M/1** Markovian negative exponential probability distribution for a single server Poisson interarrival or service time model.

(iv) **M/M/N** Markovian negative exponential probability distribution for a multiple-server Poisson interarrival or service time model.

For the purpose of this paper, only two common Markovian models, (M/M/1 and M/M/N) of items (iii) and (iv) were considered to determine the appropriate queuing model that is faster and has lesser number of entities in the system waiting for service for the WCAN investigated. In other words, the paper finds out the queuing model that better enhances the performance of a wireless queuing system. Furthermore, two cases of M/M/N were considered to show clearly the difference between models. However, the first three models of items (i) through (iii) can also be compared but by using a technique that employs the scaling factor {i.e., the ratio of the standard deviation of service time to the service time (σ_{T_S} / T_s)}.

To achieve enhancement of the performance of the queuing system, researchers employed many mechanisms. Some researchers concentrated on improving packet error rate and loss rate, some on reducing congestion of the system by using a suitable service discipline, while others combined these methods [5] with cross-layer design as is evident in the following works reviewed.

In their work, [1] were set to achieve guarantees on delay separation between traffic flows and fair access to scarce shared wireless channels. To get the desired results they defined a wireless fair service model and a generic framework in order to design a wireless fair queuing algorithm for adaptation to the wireless domain. They also employed the scheduling model to reduce delay separation between flows by using fair queuing access to the wireless channel. The results obtained gave some degree of guarantees on delay and fair access to the wireless channel. However, the model was not robust enough to enable wireless fair queuing swap time slots between flows based on channel error and transmission to and from the base station and also, channel prediction accuracy was not covered.

In their green radio research to optimize energy efficiency in radio networks [3] embarked on finding the tradeoffs between deployment efficiency and energy efficiency as well as spectrum usage, bandwidth allocation and delay against power consumption. They discovered that results obtained in practice deviated from derived ones using Shannon's formulae and accepted that one limitation of their work was because of the lack of cross-layer optimization technique using scheduling algorithm for resources allocation. Resources (data rate, energy, bandwidth, etc) were not properly managed (not dynamically allocated to avoid underutilization and wastage) and the use of an appropriate queuing discipline was not evident.

The research work of [5] compared the combined hybrid automatic repeat request (HARQ) with adaptive modulation and coding (AMC) schemes against the combined automatic repeat request (ARQ) with AMC. They discovered that the former combination gave better results on spectral efficiency, PER and end-to-end throughput. These results were achieved through cross-layer communication design which allowed individual protocol layers co-operate and share information of their retransmission schemes and parameters defining each service class. They also found that the AMC with HARQ combination was also more suitable for real time service than AMC with ARQ combination. Though they were able to identify the suitable model to achieve optimization, the model failed to address the effect of parameters optimization on the characteristics of each service class and queuing service discipline implemented.

In view of the limitations mentioned, in our approach to determine the best performance enhancement technique of a queuing system, we compared queuing models to identify the most suitable one for the university WCAN. The objectives are to save time and to reduce the number of entities waiting for service in the system.

2. MATERIALS AND METHODS

Traffic data used in the analyses was collected from the university network shown in Figure 1. The Mikro Tik router in Figure 2 linking the university network to the overhead satellite serves as a queuing system for traffic data captured over a period of 11 months from 31 January 2011 to 30 December 2012.

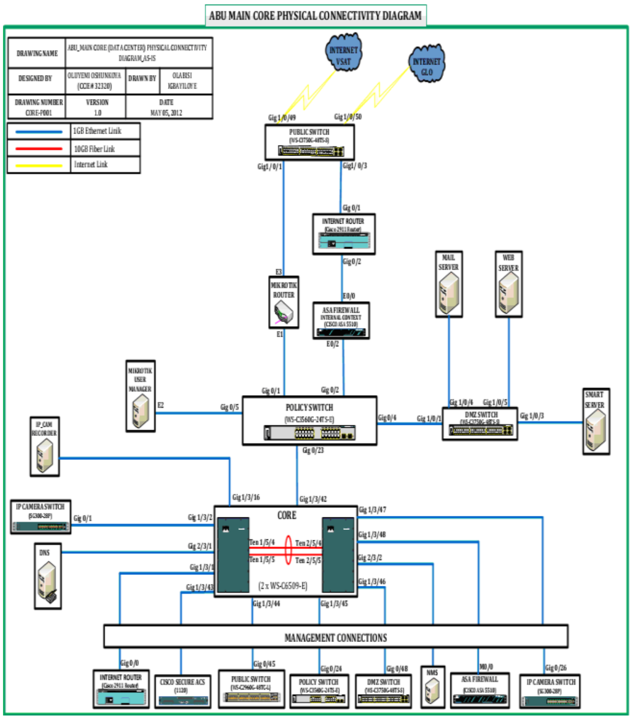

Figure 1: Topology Diagram of ABU Network

For the structural university network shown in Figure 1, the overhead satellite feeds only one main wireless access router that in turn forwards both interactive (video live streams, etc) and non-interactive (e-mails, etc) to other wireless routers distributed over various campuses, as well as the CAN connecting these campuses. This satellite-router arrangement shown Figure 2 can be taken as a queuing system. The arriving mix traffic from the overhead satellite follows Poisson distribution at an average arrival rate of λ packets per second (pps) and the wireless router is considered as a server system with an average service rate of μ pps [8]. Congestion occurs when arrivals are faster than outgoings and packets queue for service at the router to avoid drop. Once the interface is free, they are serviced and delivered.

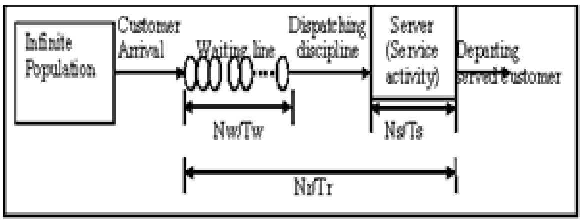

Figure 2: Piosson Queuing System [8]

2.1 Data Collected Process

The process of data collection was done on a daily basis from Mondays to Fridays only, excluding Saturdays and Sundays when the place would have been closed. At this MikroTik router, arriving packets in kilobits per second (kbps) and transmitted packets also in kbps were captured from 9 am to 4 pm at an interval of two hours, that is, 9 am, 11 am, 1 pm, 3 pm, respectively and represented in a table form as illustrated in Appendix 1. This period was chosen because this was the time the system was always fully utilized.

Information contained in Appendix 1 was computed to give the average arrival rate (λ) and average service rate (μ) represented in Table 1.

Table 1: Average Arrival and Service Rates

RATE	TOTAL 3	TOTAL 4	GRAND TOTAL	AVG in 260Days	USED DATA
μ	133933.5	45117.8	179051.3	746.0471	746
λ	26138.2	16217.75	42355.95	176.4831	176

The totals of Appendix 1 referred to as T1 and T2 were rearranged and their summations computed as represented in Appendix 2. The totals of Appendix 2 are known as TOTAL 3 and TOTAL 4, respectively. Finally, Table 1 obtained from Appendix 2 contains the average arrival rate (λ kbps) and average service rate (μ kbps) for the 11 months period as represented in Appendix 3.

2.2 Analyses of Queuing Models

In queuing analysis, some vital assumptions are normally considered as itemized underneath, [2, 8]:

1. **Infinite queue size**, where no item is dropped or lost, then the value of the arrival rate (λ) is the same as that of the service rate (μ) (i.e., $\lambda = \mu$).
2. **Infinite population size**, where the population loss does not affect the arrival rate.

3. **System is stable**, where utilization (offered load) is less than unity, i.e., $\rho < 1$ or $\lambda < \mu$, since $\rho < \lambda/\mu$.

Using values of average arrival rate $(\lambda = 176.5kbps)$ and average service rate $(\mu = 746kbps)$ obtained from data collected, the average number of entities resident in the system (N_r) and those waiting in the queue (N_w), as well as the average response time (T_r) and average waiting time (T_w) of the system were calculated and tabulated in Table 1.

2.2.1 M/M/1 Single Server Queuing Model

The theoretical maximum input rate (λ) for a single-server, single-queue model with utilization (ρ) and traffic service time (T_S) are related as follows [8]:

$$\lambda = \frac{\rho}{T_S} \qquad (1)$$

Since $\rho < \lambda/\mu$ then equation (1) becomes:

$$T_S = \frac{1}{\mu} \qquad (2)$$

For M/M/1 system, different set of equations are obtained [8] for calculating the following parameters used for comparison:

$$N_r = \frac{\rho}{1-\rho} \qquad (3)$$

where N_r is average number of entities in system.

Since utilization $\rho = \lambda/\mu$, then equation (3) becomes:

$$N_r = \frac{\lambda}{\mu-\lambda} = \frac{176.5}{746-176.5} = 0.31$$

$$N_w = \frac{\rho^2}{1-\rho} \qquad (4)$$

where N_w is average number of entities waiting in the system.

Since utilization $\rho = \lambda/\mu$, equation (4) becomes:

$$N_w = \frac{\lambda^2}{\mu(\mu-\lambda)}$$

$$= \frac{(176.5)^2}{746(746-176.5)} = 0.07$$

$$T_r = \frac{T_s}{1-\rho} \qquad (5)$$

where T_r is the average time entities spend in the system.

Since, $\rho = \lambda/\mu$ and $T_s = 1/\mu$, equation (5) is now:

$$T_r = \frac{1}{\mu-\lambda}$$

$$= \frac{1}{746-176.5} = 1.8\ \mu\text{sec}$$

$$T_w = \frac{\rho T_s}{1-\rho} \qquad (6)$$

where T_w is the waiting time in the system.

With $\rho = \lambda/\mu$ and $T_s = 1/\mu$, equation (6) becomes:

$$T_w = \frac{\lambda}{\mu(\mu-\lambda)}$$

$$= \frac{176.5}{746(746-176.5)} = 0.4\ \mu\text{sec}$$

2.2.2 M/M/N Multiple Server Queuing Model

Similarly, the system assumes Poisson arrival rates, exponential service times and a dispatch discipline that follows First-In-First-Out algorithm, where all servers are assumed to be equally loaded, have the same service time and no entity is dropped from the queue [8].

With these assumptions, the Poisson ratio function is given by [8] as:

$$K = \frac{\sum_{j=1}^{N} \frac{(N\rho)^j}{j!}}{\sum_{j=1}^{N+1} \frac{(N\rho)^j}{j!}} \qquad (7)$$

If two servers are used for the queuing system, where N = 2, then:

$$K = \frac{\frac{(2\rho)^1}{1!} + \frac{(2\rho)^2}{2!}}{\frac{(2\rho)^1}{1!} + \frac{(2\rho)^2}{2!} + \frac{(2\rho)^3}{3!}}$$

$$= \frac{3+3\rho}{3+3\rho+2\rho^2} \qquad (8)$$

When all servers are occupied, the probability that any new arrival will meet the servers busy and be placed in a queue is defined by the Erlang-C function as in [8]:

C = $\dfrac{1-K}{1-\rho K}$ (9)

Therefore, substituting for K from equation (8) into equation (9), C becomes:

$$C = \frac{1-\dfrac{3+3\rho}{3+3\rho+2\rho^2}}{1-\rho\left(\dfrac{3+3\rho}{3+3\rho+2\rho^2}\right)}$$

$$= \frac{\left(3+3\rho+2\rho^2\right)-\left(3+3\rho\right)}{\left(3+3\rho+2\rho^2\right)-\rho\left(3+3\rho\right)}$$

$$= \frac{2\rho^2}{3-\rho^2} \quad (10)$$

The average number of entities in this two-server queuing system, waiting and being served is [8]:

$$N_r = C\frac{\rho}{1-\rho}+2\rho \quad (11)$$

Substituting C from equation (10) into equation (11) gives the average number of entities in the system as:

$$N_r = \left(\frac{2\rho^2}{3-\rho^2}\right)\left(\frac{\rho}{1-\rho}\right)+2\rho$$

Since $\rho = \lambda/\mu$, therefore, N_r can be rewritten as follows:

$$N_r = \left(\frac{2\lambda^2}{3\mu^2-\lambda^2}\right)\left(\frac{\lambda}{\mu-\lambda}\right)+2\left(\frac{\lambda}{\mu}\right)$$

Since arrival rate for each server is λ = 176.5 kbps and there are two servers available in this M/M/2 system, then total arrival rate is 2λ = 353 kbps. Therefore:

$$N_r = \left(\frac{2(353)^2}{3(746)^2-(353)^2}\right)\left(\frac{353}{746-353}\right)+2\left(\frac{353}{746}\right) = 1.1$$

Similarly, the average number of items in this two-server queuing system, waiting to be served is [8]:

$$N_w = C\left(\frac{\rho}{1-\rho}\right) \quad (12)$$

Substituting C and expressing it in terms of terms of average arrival rate (λ) and average service rate (μ), N_w is:

$$N_w = \left(\frac{2\rho^2}{3-\rho^2}\right)\left(\frac{\rho}{1-\rho}\right)$$

$$= \left(\frac{2\lambda^2}{3\mu^2-\lambda^2}\right)\left(\frac{\lambda}{\mu-\lambda}\right)$$

Similarly, with the total arrival rate of 2λ = 353 kbps for this M/M/2 system, N_w is:

$$N_w = \left(\frac{2(353)^2}{3(746)^2-(353)^2}\right)\left(\frac{353}{746-353}\right) = 0.14$$

The average time entities spend in the system in terms of service time (T_s), utilization (ρ) and Erlang-C function is given as [8]:

$$T_r = \left(\frac{C}{N}\right)\left(\frac{T_s}{1-\rho}\right)+T_s \quad (13)$$

Substituting C from equation (8), $(T_s = 1/\mu)$, $\rho = \lambda/\mu$ and expressing equation (13) in terms of average arrival rate (λ) and average service rate (μ), T_r is:

$$T_r = \left(\frac{2\rho^2}{6-2\rho^2}\right)\left(\frac{T_s}{1-\rho}\right)+T_s$$

$$= \left(\frac{\lambda^2}{3\mu^2-\lambda^2}\right)\left(\frac{1}{\mu-\lambda}\right)+\frac{1}{\mu}$$

Since, the total arrival rate for this M/M/2 system 2λ = 353 kbps, then T_r is:

$$T_r = \left(\frac{(353)^2}{3(746)^2-(353)^2}\right)\left(\frac{1}{746-353}\right)+\frac{1}{746} = 1.8\ \mu\text{sec}$$

The average waiting time of entities expressed in terms of service time (T_s), utilization (ρ) and Erlang-C function is as follows [8]:

$$T_w = \left(\frac{C}{N}\right)\left(\frac{T_s}{1-\rho}\right) \quad (14)$$

Substituting C from equation (10), $(T_s = 1/\mu)$, (ρ = λ/μ) and expressing equation (14) in terms of average arrival rate (λ) and average service rate (μ), T_w is:

$$T_w = \left(\frac{C}{N}\right)\left(\frac{T_s}{1-\rho}\right)$$

$$= \left(\frac{\lambda^2}{3\mu^2-\lambda^2}\right)\left(\frac{1}{\mu-\lambda}\right)$$

Similarly, with the total arrival rate of 2λ = 353 kbps for this M/M/2 system, T_w is:

$$T_w = \left(\frac{(353)^2}{3(746)^2-(353)^2}\right)\left(\frac{1}{746-353}\right) = 0.4\ \mu\text{sec}$$

Similarly, if three servers are used for the queuing system, where N = 3 in this case, then from equation (7):

$$K = \frac{\frac{(3\rho)^1}{1!}+\frac{(3\rho)^2}{2!}+\frac{(3\rho)^3}{3!}}{\frac{(3\rho)^1}{1!}+\frac{(3\rho)^2}{2!}+\frac{(3\rho)^3}{3!}+\frac{(3\rho)^4}{4!}}$$

$$= \frac{\frac{(3\rho)}{1}+\frac{(3\rho)^2}{2}+\frac{(3\rho)^3}{6}}{\frac{(3\rho)}{1}+\frac{(3\rho)^2}{2}+\frac{(3\rho)^3}{6}+\frac{(3\rho)^4}{24}}$$

$$= \frac{72\rho+108\rho^2+108\rho^3}{72\rho+108\rho^2+108\rho^3+81\rho^4}$$

$$= \frac{8+12\rho+12\rho^2}{8+12\rho+12\rho^2+9\rho^3}$$

But from equation (7):

$$C = \frac{1-K}{1-\rho K}$$

$$= \frac{1-\left(\frac{8+12\rho+12\rho^2}{8+12\rho+12\rho^2+9\rho^3}\right)}{1-\rho\left(\frac{8+12\rho+12\rho^2}{8+12\rho+12\rho^2+9\rho^3}\right)}$$

$$= \frac{9\rho^3}{8+4\rho-3\rho^3} \qquad (15)$$

From equation (11), the average number of entities in this three-server queuing system, waiting and being served is:

$$N_r = C\frac{\rho}{1-\rho}+2\rho$$

where C is obtained from equation (15) to give N_r as:

$$N_r = \left(\frac{9\rho^3}{8+4\rho-3\rho^3}\right)\left(\frac{\rho}{1-\rho}\right)+2\rho$$

Since $\rho = \lambda/\mu$, therefore, in terms of λ and μ, N_r is:

$$N_r = \left(\frac{9\lambda^3}{8\mu^3+4\mu^2\lambda-3\lambda^3}\right)\left(\frac{\lambda}{\mu-\lambda}\right)+2\left(\frac{\lambda}{\mu}\right)$$

Since the arrival rate for each server is $\lambda = 176.5kbps$ and there are three servers in this M/M/3 system. Therefore, total arrival rate is $3\lambda = 529.5kbps$, thus giving N_r as:

$$N_r = \left(\frac{9(529.5)^3}{8(746)^3+4(746)^2(529.5)-3(529.5)^3}\right)\left(\frac{529.5}{746-529.5}\right)+2\left(\frac{529.5}{746}\right)$$

= 2.2

Similarly, from equation (12), the average number of items in this three-server queuing system, waiting to be served is:

$$N_w = C\left(\frac{\rho}{1-\rho}\right)$$

Hence, substituting C from equation (15) and expressing it in terms of λ and μ, taking into account that arrival rate for M/M/3 system is $3\lambda = 529.5kbps$, then N_w becomes:

$$N_w = \left(\frac{9\lambda^3}{8\mu^3+4\mu^2\lambda-3\lambda^3}\right)\left(\frac{\lambda}{\mu-\lambda}\right)$$

$$N_w = \left(\frac{9(529.5)^3}{8(746)^3+4(746)^2(529.5)-3(529.5)^3}\right)\left(\frac{529.5}{746-529.5}\right)$$

= 0.8

Also, from equation (13), the average time entities spend in the system in terms of service time (T_s), utilization (ρ) and Erlang-C function for M/M/3 system is given as:

$$T_r = \left(\frac{C}{N}\right)\left(\frac{T_s}{1-\rho}\right)+T_s$$

Since $(T_s = 1/\mu)$, (ρ = λ/μ) and C can be obtained from equation (15), T_r is now:

$$T_r = \left(\frac{9\rho^3}{3\{8+4\rho-3\rho^3\}}\right)\left(\frac{T_s}{1-\rho}\right)+T_s$$

$$= \left(\frac{9\lambda^3}{3\{8\mu^3+4\mu^2\lambda-3\lambda^3\}}\right)\left(\frac{1}{\mu-\lambda}\right)+\frac{1}{\mu}$$

T_r = = 1.9 μsec

$$\left(\frac{9(529.5)^3}{3\{8(746)^3+4(746)^2(529.5)-3(529.5)^3\}}\right)\left(\frac{1}{746-529.5}\right)+\frac{1}{746} = 0.8$$

Similarly, from equation (14), the average waiting time of entities expressed in terms of service time (T_s), utilization (ρ) and Erlang-C function is:

$$T_w = \left(\frac{C}{N}\right)\left(\frac{T_s}{1-\rho}\right)$$

This can be expressed in terms of λ and μ, given that $(T_s = 1/\mu)$, $(\rho = \lambda/\mu)$ and C can be obtained from equation (15).

$$T_w = \left(\frac{C}{N}\right)\left(\frac{T_s}{1-\rho}\right)$$

$$= \left(\frac{9\rho^3}{3\{8+4\rho-3\rho^3\}}\right)\left(\frac{T_s}{1-\rho}\right)$$

$$= \left(\frac{9\lambda^3}{3\{8\mu^3+4\mu^2\lambda-3\lambda^3\}}\right)\left(\frac{1}{\mu-\lambda}\right)$$

$$T_w = \left(\frac{9(529.5)^3}{3\{8(746)^3+4(746)^2(529.5)-3(529.5)^3\}}\right)\left(\frac{1}{746-529.5}\right)$$

$= 0.5\ \mu\text{sec}$

3. RESULTS AND DISCUSSIONS

Using equations (1) through (15), the values of respective parameters for each of the models were computed and tabulated as represented in Table 2. These parameters include, the average number (N_r) of entities being served, the average number (N_w) of entities waiting to be served, average time (T_r) entities spend in the system and average waiting time (T_w) of entities in the queue.

Table 2: Parameter Values of Different Mode

Model Type	No of Servers	Parameter values			
		Nr	Nw	Tr(μs)	Tw(μs)
M/M/1	**1**	**0.31**	**0.07**	**1.8**	**0.4**
M/M/2	2	1.1	0.14	1.8	0.4
M/M/3	3	2.2	0.8	1.9	0.5

From the parameter values represented in Table 2, a single server queuing model is preferred over a multiserver model because it has lesser average number of entities resident in the system and those in the queue waiting to be served, as well as lesser average response time and waiting time. Furthermore, M/M/1 is preferred because it represents the best case of the family of single server models with a unity scaling factor and well defined Poisson arrival rate and exponential service time [4].

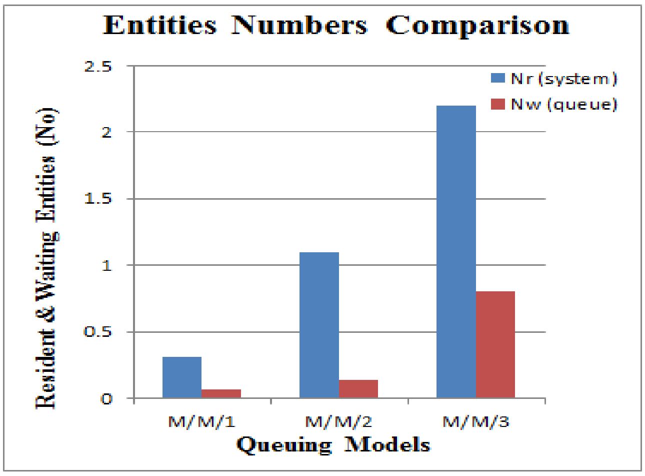

Fig. 3: Comparison of Mo Numbers of Entities

From Fig. 3, multiple server model has more entities in the queuing system than a single server model. Also, the number of entities in the system increases with an increase in the number of servers available. These are equally true for both entities resident in the system and those waiting in the queue for service.

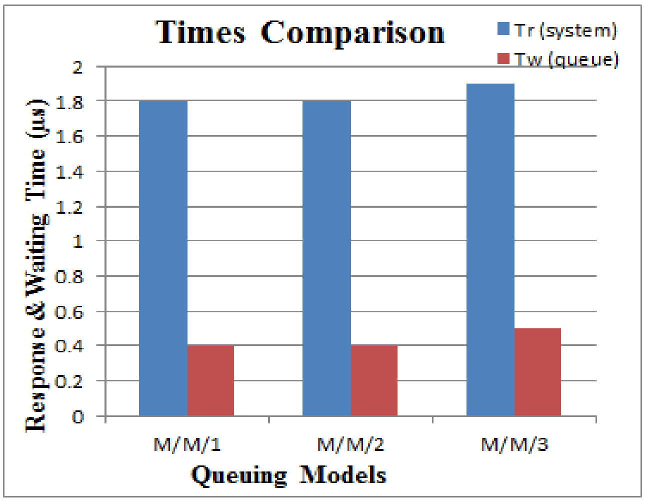

Fig. 4: Comparison of Response and Waiting Times

Time comparison of the models is not apparent when the number of servers is not more than two because both the single server and the double server models give the same response and waiting times. The superiority of the single server model becomes evident only when the number of servers is more than two. The single server model registers faster response time and lesser waiting time than the multiple (three) server model as represented in Fig. 4.

4. CONCLUSION

It was discovered that the average number of entities in the system to be served, and the average number of entities in the queue waiting for service for M/M/1 model are lesser than their corresponding numbers for both M/M/2 and M/M/3 models as shown in Table 2 and Fig. 3 and Fig. 4.

Furthermore, the average time entities spend in the system and the average waiting time of entities in the queue for M/M/1model are also lesser than those of M/M/3 model. However, there is no time difference between both M/M/1 and M/M/2 models. Hence, the scope of the study can include higher number servers in order to get a true picture.

Therefore, M/M/1 was found to be better than M/M/3 because of lesser {(2.2-0.31)/2.2*100 = 86%} number of entities in the system and lesser number of entities (91%) in the queue waiting for service, as well as having faster {(1.9-1.8)/1.9*100 = 5%) response time and lesser (20%) waiting time. Others were calculated likewise.

5. ACKNOWLEDGEMENTS

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7. APPENDIX

Appendix 1: Arrival and Service Rates with Received and Transmitted Packets for the Public Router of ABU WCAN Network and their total

31 Jan - 18 Feb									**T1**							
Items	**Mon**	**Tues**	**Wed**	**Thurs**	**Fri**	**Mon**	**Tues**	**Wed**	**Thurs**	**Fri**	**Mon**	**Tues**	**Wed**	**Thurs**	**Fri**	**T1**
µkbps	204.2	232.8	105.4	1664.4	822.1	1007.7	1013.8	1005.6	1005.2	822.1	897.3	1005.8	905.3	966.4	98.2	11756.3
λkbps	7.1	13.1	21.9	100.3	93.8	103.4	79.4	99.5	81.8	93.8	6000	35.9	32	31.7	10.8	6804.5
21 Feb - 11 Mar																
µkbps	346.1	180.5	382.7	105.5	637.6	603.7	790.6	361.9	332.2	995.8	1002.2	1003.7	1007.2	1001.2	1009.4	9760.3
λkbps	23.3	7.4	21.6	24.7	46.7	25.7	45.2	16.1	15.9	86.3	61	72.4	91.9	58.2	56.4	652.8
14 Mar - 1 Apr																
µkbps	1005.1	1002.2	1004.9	1006.9	1004.3	1007.4	1002.7	1005.3	1009.9	1009.9	1002.7	1009.4	1005.2	1004.8	964.9	15045.6
λkbps	64.7	67.8	64.4	57.8	69.7	77.9	60.6	96.9	78.2	81.7	60.6	106.8	91.2	82.1	177	1237.4
4 Apr - 23 Apr																
µkbps	788.7	888.3	878.1	762.4	6200	6300	6400	6300	6200	3600	519.7	517	511.7	523.5	513.1	40902.5
λkbps	139.1	203.3	158.5	204.5	953	786	829.1	799.9	870.3	885.8	87.8	108.9	76.8	67.7	72.9	6243.6
26 Apr - 13 May																
µkbps	511	515.9	507.3	520.7	526	7900	6200	5900	6400	836.2	619.8	475.8	281.4	519.5	730.9	32444.5
λkbps	95.5	46.7	107.3	52.4	48.8	1965.1	1438.8	1456.7	1027.3	69	83.4	62.6	23.3	51.6	91.2	6619.7
16 May - 3 June																
µkbps	541.4	420.6	339.4	230.5	926	969	861.3	920	831.3	956.2	1003.4	1003.3	713.2	664.1	1009.8	11389.5
λkbps	50.3	29.5	37.7	46.8	96.3	162.6	95.1	125.9	74.1	48.5	81.4	72.6	86.8	111.8	104.2	1223.6
6 June - 24 June																
µkbps	13.2	3.8	2.8	798	5.2	1002.7	1007.2	1002.6	1001.4	1004.1	86.5	150.8	79.7	213.8	140.9	6512.7
λkbps	14.2	6.6	6.3	3.5	4.5	44.1	56.1	57.9	53.2	57.6	41.5	32.7	43.1	42.9	42.1	506.3
27 June - 15 July																
µkbps	206.8	201.7	240.5	155	138.8	420.2	694.8	632.3	656.2	900.1	526.3	175.9	391.3	263.1	519.1	6122.1
λkbps	42.5	58.5	67	38.8	40.4	306.8	304.7	306.7	319.1	273.6	173	161.7	207.7	469.3	80.5	2850.3
18 July - 5 Aug									**T2**							
µkbps	6000	20.4	69.4	4.7	36.5	999.2	1001.9	1039.1	969.3	1005.8	998.2	1020.8	1039.6	970.9	1010.1	16185.9
λkbps	1300	9.1	36.5	9.6	17.6	335.8	324.5	230.7	334.4	454.3	201	275.7	329.7	391.7	234.2	4484.8
8 Aug - 26 Aug																
µkbps	74.1	82.8	74.9	93.4	107.9	99.1	114.2	145.7	203	120.2	48.8	49.3	27.2	6.1	20.3	1267
λkbps	13.2	12.9	15.9	18.4	12.8	30.7	11.4	48.1	31.7	40.4	24.4	9.1	4.8	3.1	8.9	285.8
29 Aug - 16 Sept																
µkbps	444.1	465.7	295.9	463.3	503.4	189.4	148.5	147.7	134.3	207.3	157.1	196	189	171.6	225.4	3938.7
λkbps	177.6	179.6	308.8	332.4	277.6	49.9	27.9	90.4	39.8	69.5	37.4	47.3	64.3	36.8	81.4	1820.7
19 Sept - 7 Oct																
µkbps	257.9	261.1	264.8	208.3	226.7	265.4	261.2	264.5	250.7	255.1	337.1	472.4	491.7	397.1	410.1	4624.1
λkbps	104.9	96.2	52.6	145.9	61.3	88.7	67.9	73.8	57.3	83.4	38.5	82.8	37	38	43.8	1072.1
10 Oct - 28 Oct																
µkbps	508.6	478.8	352.7	370.6	296.4	324	379.8	360.8	236.2	267.1	172.6	160.5	114.9	**254.8**	161.2	4439
λkbps	35.4	50.4	42.7	42.5	47.1	40.9	131.7	59.7	122.7	124.5	42	29.4	34.6	**31.6**	27.4	862.6
31 Oct - 18 Nov																
µkbps	717.7	514.2	524.4	514.7	**461**	516	509	517.3	515.1	254.8	227.5	461.1	470.8	395.7	418.1	7017.4
λkbps	169.5	61.6	74.3	53.2	**71.1**	43	97.1	87.4	66.7	31.6	542	703.1	690	688.8	601.1	3980.5
21 Nov - 9 Dec																
µkbps	503.7	517.8	504.4	497.7	436.4	511.9	490.3	515.4	512.3	512.8	**36.1**	513.6	453.6	461	470.8	6937.8
λkbps	549.8	589.5	573.1	657.7	617.9	44	54.5	51.9	35.3	43.8	**4.5**	49.1	42.6	71.1	32.6	3417.4
12 Dec - 30 Dec																
µkbps	**51**	12.6	25.6	21.2	29.7	25.7	29.5	33.3	36.1	25.5	76.2	76.1	81.1	107.1	77.2	707.9
λkbps	**49.1**	1.75	39.6	3.2	7.9	4.7	4.2	10.3	4.5	4.5	54.3	11.8	50.8	25.1	21.7	293.45

Appendix 2: Totals of arrival and Service Rates with Received and Transmitted Packets for the Public Router of ABU WCAN Netwo

Items	31Jan-18Feb	21Feb-11Mar	14Mar-1Apr	4Apr-23Apr	27Apr-13May	16May-3Jun	6Jun-24Jun	27Jun-15July	TOTAL3=SUM T1
µkbps	11756.3	9760.3	15045.6	40902.5	32444.5	11389.5	6512.7	6122.1	133933.5
λkbps	6804.5	652.8	1237.4	6243.6	6619.7	1223.6	506.3	2850.3	26138.2
Tx Pkt	1449	803	1223	4142	3614	1047	535	946	13759
Rx Pkt	1628	901	1609	3733	3396	1085	573	1057	13982

Items	18July-5Aug	8Aug-26Aug	29Aug-16Sep	19Sept-7Oct	10Oct-28Oct	30Oct-18Nov	21Nov-9Dec	12Dec-30Dec	TOTAL4=SUM T2
µkbps	16185.9	1267	3938.7	4624.1	4439	7017.4	6937.8	707.9	45117.8
λkbps	4484.8	285.8	1820.7	1072.1	862.6	3980.9	3417.4	293.45	16217.75
Tx Pkt	1645	109	442	460	428	1333	1385	65	5867
Rx Pkt	1752	197	732	646	541	3151	3111	140	10270

Appendix 3: The Arrival and Service Rates values used in the Analysis

Table 4.1: Average Arrival and Service Rates

ITEM	TOTAL 3	TOTAL 4	GD TOTAL	AVERAGE	USED DATA
µkbps	133933.5	45117.8	179051.3	746.04708	746
λkbps	26138.2	16217.75	42355.95	176.48313	176.5