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CAPACITY ANALYSIS OF WIRELESS MESH NETWORKS

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ABSTRACT

The next generation wireless networks experienced a great development with emergence of wireless mesh networks (WMNs), which can be regarded as a realistic solution that provides wireless broadband access. The limited available bandwidth makes capacity analysis of the network very essential. While the network offers broadband wireless access to community and enterprise users, the problems that limit the network capacity must be addressed to exploit the optimum network performance. The wireless mesh network capacity analysis shows that the throughput of each mesh node degrades in order of 1/n with increasing number of nodes (n) in a linear topology. The degradation is found to be higher in a fully mesh network as a result of increase in interference and MAC layer contention in the network.
Key words: Wireless mesh network (WMN), Adhoc network, Network capacity analysis, Bottleneck collision domain, Medium access control (MAC) layer

1. INTRODUCTION

Wireless mesh networking (WMN) is an option of scaling wireless networks. A wireless mesh network is a type of wireless network in which each node can communicate directly with one or more peer nodes. Also is a form of ad hoc network that forms mesh of wirelessly interconnected nodes. The difference between this type of network and the ad hoc network is the nature of packet movement in the network which is always from the client to the gateway node and vice versa, while, the packet movement in ad hoc networks is between arbitrary pair of network nodes (Hossain, 2008). In wireless mesh networks the host nodes (typically stationary) can also serve as routers to forward the clients' traffic in a multi-hop fashion to the destination (normally gateway nodes connected to the internet) when the network is deployed to provide internet access shown in Figure 1.

Wireless mesh networks offer the following advantages over the conventional wireless networks; easy deployment, greater reliability, self-configuration, self-healing, and scalability. The nodes in the network are able to establish and maintain mesh connectivity automatically (Akyildiz, 2010).

Wireless mesh network technology has drawn considerable attention as a promising broadband access technology despite increase in the number of internet access technologies. Very large areas can have broadband wireless access using wireless mesh networks without need for costly infrastructures. Wireless mesh networks can also be employed for wide variety of applications such as cellular radio access networks or WLAN hotspot multi-hopping, citywide surveillance systems, wireless sensor networks (WSNs), broadband home and office indoor networking, intelligent transport system networks, community and neighbour networking, micro base station backhaul and many others (Hethley, 2009).

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WMNs have been deployed in some countries including Australia and South Africa. The deployment of village telco (VT) (Adeyeye, 2011) in Cape Town in South Africa had proven efficient and cost effective solution for voice over IP (VoIP) over mesh networks. VT architecture uses a mesh network of mesh potatoes (MPs) to form a peer-to-peer network to relay telephone calls without landlines or cell phones towers. The MPs operate in two modes (Adeyeye, 2011): the adhoc mode which allowed the interaction with nearby MP and infrastructure mode that either acts as a client to obtain internet access, or as an access point which allows other WiFi devices and the nano stations to obtain network access as illustrated in Figure 2. The capacity of wireless mesh networks is affected by many factors such as network architecture, node mobility, node density, traffic pattern and number of channels used (Zhang and Luo, 2007). Other factors include the changing wireless condition and channel interference, packet losses and delay due to interference (Adeyeye, 2011). These could significantly degrade the quality of service of the network.

The capacity of wireless mesh networks and the network performance will be increased if the issue of unfairness behaviour of the flows in the network is addressed. The fair sharing of network resources can be achieved by giving the flows from distant source nodes crossing many network hops to the destination priority at each node queue over the flows from hops close to the destination (gateway) (Gumel, 2011). This reduces the end-to-end delay of the traffic flow and makes all the source nodes in the networks to have equal share of the network resources irrespective of their distance from the destination.

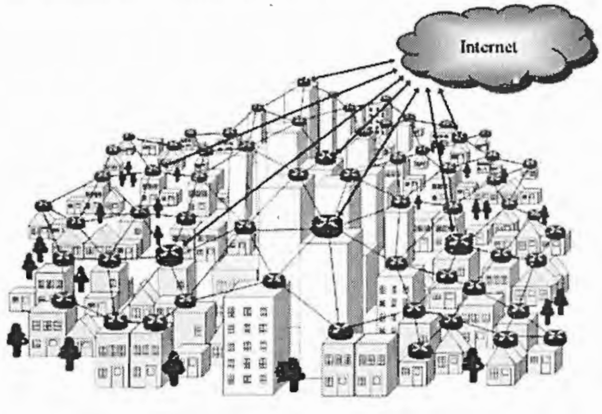

Figure 1: Wireless Mesh Network for Broadband Internet Access (Hossain, 2008)

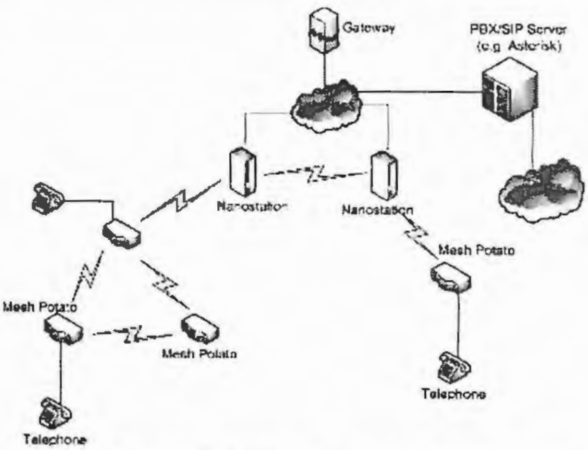

Figure 2: Village Telco Architecture (Adeyeye, 2011).

The capacity analysis in this research is based on the effect of mesh forwarding, interaction at the MAC layer and interference on the network. The research is done using simulations of three wireless mesh network scenarios (scenarios 1, 2 and 3). The aim of this research is to analyse the capacity of wireless mesh networks using OPNET (Optimized Network Engineering Tool) Modeller 14.5. The paper is organized as follows: section 2 reviews the related work on the capacity analysis of WMN. Section 3 gives details on the simulation environment and the simulation parameters used; and details on the network scenario are presented in Section 4 and finally Section 5 concludes the paper.

2. RELATED WORK

The capacity of wireless ad hoc networks is studied by Gupta and Kumar (2000). The paper provides the upper and lower bounds of the capacity of wireless ad hoc networks. In it, wireless nodes are randomly located and each node communicates using a common wireless channel. The paper shows

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that the capacity of wireless ad hoc networks depends on the number of wireless nodes in the network and there is a considerable reduction in the capacity with an increase in the number nodes. It concludes that, the maximum achievable throughput of randomly placed n identical nodes, each with a capacity of W bits/second is
$O\left(\frac{W}{n * \log n}\right)$ under non-interference protocol model, and even under optimal circumstances the maximum achievable throughput is only $O\left(\frac{W}{\sqrt{n}}\right)$ bits/second.
Significant work of analysing ad hoc networks was carried out by Hassanein (2010). In wireless mesh networks traffic flows are generally either from, or to the gateway nodes in the network unlike ad hoc networks where the traffic flows between arbitrary pairs of nodes (Aoun, 2010). So, the presence of gateway nodes in the network makes the capacity analysis of ad hoc networks different from that of wireless mesh networks. Jun (2010) addresses the issues of finding the accurate wireless mesh network capacity. In the paper, wireless mesh network scenario with only one gateway is used and the traffic load sent by each node in the network is varied. Using simulations it is concluded that the throughput of each node decreases as $O\left(\frac{1}{n}\right)$ where n is the total number of nodes in the network; the network throughput increases in direct proportion to the number of gateways in the network, and, addition of gateways also improves the network reliability. Jun and Sichitiu (2003), have analysed the capacity of wireless mesh networks but neglected the issue of unfairness and its effect on network capacity. It has assumed the network to be fair to all traffic flowing in the network. They have worked on the wireless mesh network capacity based on the determination of the bottleneck collision domain only and neglected the effect of interference on the network. They have also used a static route in their analysis and neglected the issue of routing which will introduce routing overhead (Gumel, 2011) in the network that can affect the network capacity.

3. SIMULATION ENVIRONMENT SET-UP

The simulation environment has been set up using an empty OPNET (Optimized Network Engineering Tools) initial topology and campus network scale, with 10 km^2 x 10 km^2 areas. The mobile adhoc network (MANET) technology is used throughout in this research. Wireless mesh network scenarios have been deployed in the OPNET Modeller environment and simulations were performed.
All the simulations have been done using the MANET raw traffic generation, and each set node is assumed to have unlimited amount of traffic to send to the gateway node. The packets inter arrival rate follow the exponential distribution with mean $1/\lambda$ where, λ is the arrival rate. The start packet generation time was set to 5 seconds while the end-time was set to the end of the simulation. Each simulation was run for 5minutes. Table1 shows the other parameters used.

Table I: Simulation Parameters

Parameters	Values
Data rate	11 Mbps
Packet payload	12000 bits
Transmission Range	1250 m
RTS Threshold	250 byte
Transmit power Tx	7 dBm
Receiver Sensitivity Rx	-95 dBm
Fragmentation	None
Buffer size	[illegible]
Simulation time	[illegible]
[illegible]	[illegible]

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4. NETWORK SCENARIO SIMULATION

4.1 Network Scenario 1

The capacity analysis in this work started with a linear wireless mesh network scenario as shown in Figure 3, with adjacent nodes placed 1250 m apart. This scenario is used to investigate the impact of mesh forwarding on the network capacity. The network scenario is simulated with only one node transmitting at a time and at different positions. When node_1 is transmitting, the distance of the source node is only 1 hop to the gateway. When node_2 is transmitting, the distance is 2 hops to the gateway. Node_3 is 3 hops, node_4 is 4 hops, while node_5 is 5 hops to the gateway.

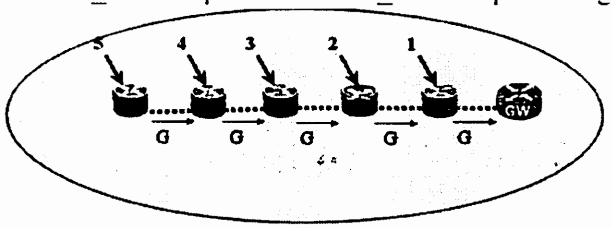

Figure 3: Linear Wireless Mesh Network Scenario to Analyse the Effect of Mesh Forwarding on the Network Capacity

When node_1 is the only node transmitting in the network, the network behaves like a single hop network. The throughput depends on the efficiency of the MAC layer used. IEEE 802.11b was used Table 1 shows the simulation parameters. The throughput is expected to be up to 11 Mbps. but this is not possible due to the exchange of control traffic packets (e.g. RTS/CTS/ACK) which introduces significant overhead into the network. If node_2 is the only node transmitting in the network and at 2 hops distance to the gateway (its traffic must pass through node_1 to the gateway), the links utilization in the network is *0.5* since node_1 cannot receive and transmit at the same time. Node_1 only transmits when node_2 finishes transmission (Ball, 2010). So, the maximum throughput is the maximum throughput achieved by a single hop network divided by 2. If node_4 is the node transmitting in the network, the throughput in the network degrades due to the issue of hidden and exposed node problem. Node_2 is outside the sensing range of node_4 but is within the interference range of the node_3 which receives from node_4: so, collisions degrade the throughput. The same problem occurs if node_5 is the transmitting node in the network.

4.1.1 Simulation Result

The simulation results in Figure 4 show the impact of mesh forwarding on the capacity of the network due to links constraints. The result is obtained from the simulation of the scenario shown in Figure 3 as a function of the offered load G (packet generated) in the network.

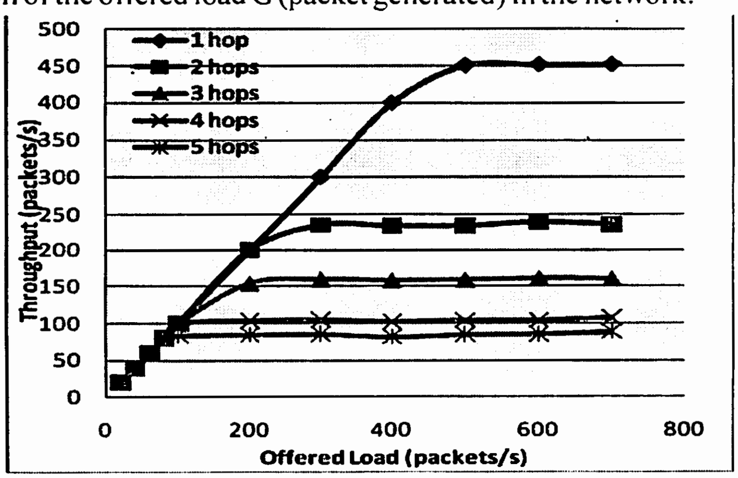

Figure 4: Effect of Mesh Forwarding on Wireless Mesh Network Capacity

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When node_1 is the node transmitting in the network the throughput in the network increases with increasing offered load (packet generated by the node) up to the maximum, which is about 450 packets per second, from where it remains almost constant at the maximum network capacity. Since 12000 bits was used as a packet size multiplied by the throughput in packets per second we have around 5.4 Mbps throughput. This is almost equal to the result of Jun et al. (2010) which says that the maximum throughput that can be achieved is 5.2 *Mbps* using 11 Mbps data rate and 12000 bits packet size. The throughput decreases to about 230 packets per second when node_2 at 2 hops distance to the gateway is transmitting. This agrees with the theoretical analysis given above which says the link utilisation will be *0.5* when node_2 is transmitting. Figure 4 show that the throughput decreases to about 160 packets per second when node_3 is the node transmitting. But when node_4 is transmitting the result indicates a slightly larger degradation, since the throughput is only about 100 packets per second. This is due to interference caused by the hidden node problem. The same thing occurs when node_5 is the node transmitting and the maximum throughput is about 80 packets per second. The wireless mesh network capacity analysis above shows that the throughput of a linear network decreases by $1/n$ where n is the number of hops to the gateway node. This is also true if the number of nodes is not more than 3, beyond which the degradation will be slightly larger as a result of interference caused by hidden node(s) in the network.

4.2 Network Scenario 2

In Scenario 2 illustrated by Figure 5, all the nodes in the network are set to generate traffic to the gateway node simultaneously. Assuming the traffic sent by each node is G, the load will double after each node. Link 5-4 load will be G, link 4-3, 2G up to link 1-GW which will be 5G.

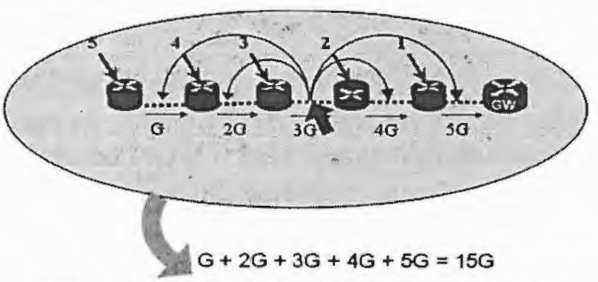

Figure 5: A Linear Wireless Mesh Network Scenario to Analyse the Effect of Bottleneck Collision Domain on the Network Capacity

Each link in the network has a collision domain, which is the set of all links that must be inactive for the link to transmit successfully (set of links that are within its interference range). The collision domain that forwards most of the traffic in the network is called a bottleneck collision domain (Yu, 2010). Some nodes in the network can transmit simultaneously (e.g. node_1 and node_5); but, for node_3 in the centre to have successful transmission all the nodes in the network have to be inactive. So link 2-3 (carrying node_3 transmission) collision domain (with 15G sum of traffic load as shown in Figure 5) is the bottleneck collision domain of the network and this limits the throughput of each node at the destination. The throughput of individual nodes in the network will be the throughput of a single hop network divided by the sum of the traffic load of network bottleneck collision domain (Yu, 2010). Scenario 2 in Figure 5 has been simulated to analyse the wireless mesh network capacity using the same approach as in scenario 1. The offered load (packets generated) by an individual node is varied from 10 packets per second to 80 packets per second in steps of 10. To differentiate flows from individual mesh node, five nodes have been placed at the gateway position to receive traffic flows from individual mesh node in the network. Traffic flows from node_1, node_2, node_3, node_4 and node_5 are to be received by node_0, node_6, node_7, node_8 and node_9 respectively

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placed at the same position (gateway position).

4.2.1 Simulation Result

The simulation results obtained (average throughput of the individual node over the simulating period) was exported to an Excel spreadsheet and plotted against the offered load (packets generated) as shown in the Figure 6.

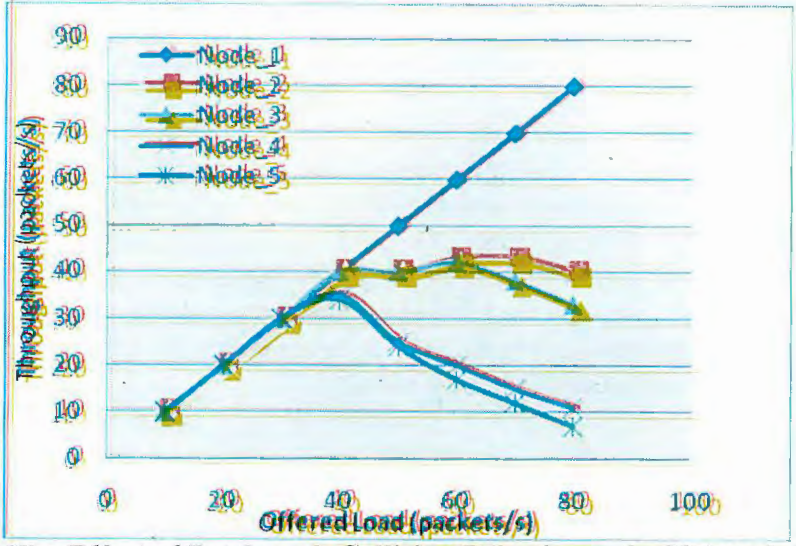

Figure 6: The Effect of Bottleneck Collision Domain on the Network Capacity

At the initial stage, when the total traffic in the network is low, each node achieves 100% throughput of its generated traffic, this continues until the offered load by the nodes is around 32 packets per second. Beyond an offered load of 32 packets per second the unfairness becomes pronounced in the network and this occurs when the traffic load in the network is beyond the network capacity. The maximum throughput of 32 packets per second of each individual node traffic flow agrees with the analysis above which says that the maximum throughput of individual nodes in the network will be the maximum throughput in a single hop network divided by the sum of the traffic load of the network bottleneck collision domain, that is 450 packets per second divided by 15. The bottleneck collision domain in a wireless mesh network is the major drawback that limits the capacity of the network.

4.3 Network Scenario 3

The scenario in Figure 7 is used to analyse the effect of interference on the network throughput. All the nodes in the network generate traffic to the gateway node simultaneously; and all the nodes, except node_5, are within the gateway node interference range.

Figure 7: Wireless Mesh Network Scenario to Analyse the Effect Of Interference on the Capacity of the Network.

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Since there is decrease in the number of hops (chain reduced) to the gateway, the effect of mesh forwarding on the network decreases. Then, the network capacity is expected to increase, but interference and MAC layer contention increase in the network since the gateway node can hear the transmissions of all the nodes except node_5. When the gateway is receiving from node_1, node_2 must hold off since the gateway node cannot receive and transmit simultaneously. Likewise, node_3 and node_4 cannot transmit simultaneously since they must forward their traffic to node_1. However, node_1 transmission corrupts node_5 transmission at node_4. So, for node_5 to have successful transmission node_1 must hold off transmission. The transmission of node_3, which is within the interference range of the gateway causes collision at the gateway while it's receiving from node_2. Apart from node_5 which can transmit while node_2 is transmitting, when any node in the network wants to transmit, all the other network nodes have to hold off transmission for that node to have a successful transmission. The scenario 3 has been simulated to analyse the effect of interference and MAC layer contention on a wireless mesh network capacity using an approach similar to that of scenario 2. To differentiate flows from individual mesh nodes, five nodes have been placed at the gateway position to receive traffic flows from individual mesh nodes in the network as explained above.

4.3.1 Simulation Results

Figure 8 shows overlaps in the mesh nodes transmission with RTS/CTS disabled in the network.

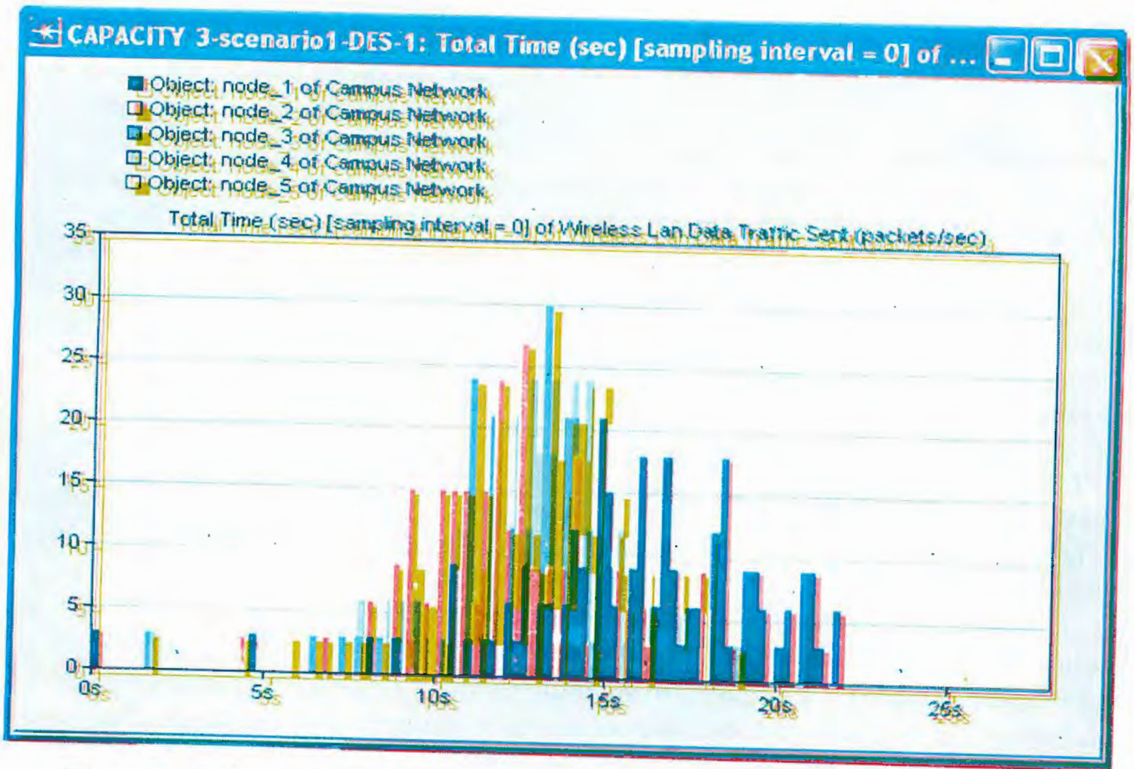

Figure 8: Effect of Interference on the Nodes Transmission in the Network

Figure 8 shows the effect of interference on the network, which results in overlaps in the mesh nodes transmission, causing collisions and increasing packet loss. The collision in the network can be avoided by employing RTS/CTS in the network, though it does not prevent a reduction in throughput as shown in Figure 9.

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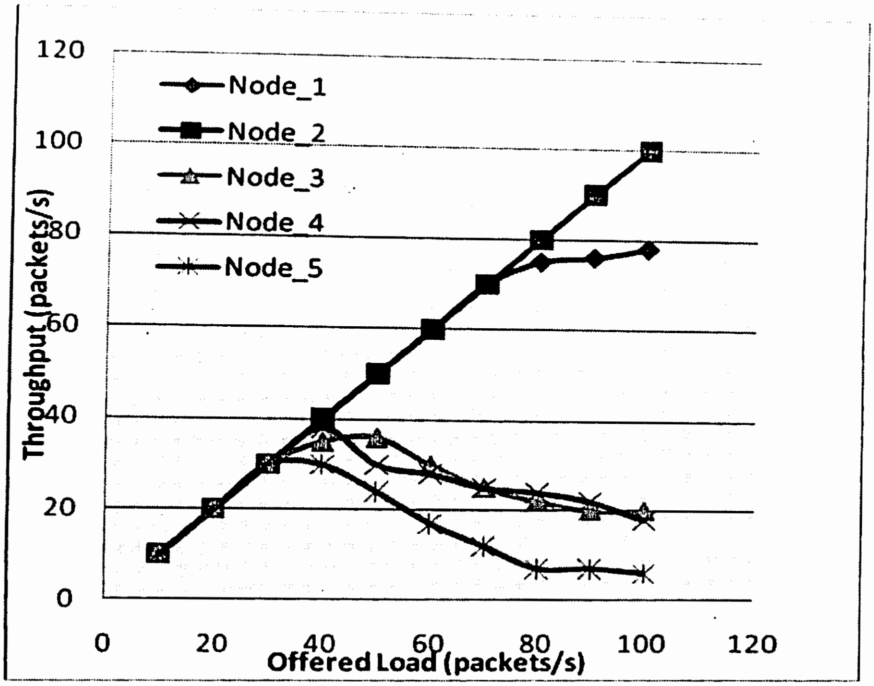

Figure 9: The Effect of Interference and MAC Contention on the Network Capacity

Figure 9 shows that node_2, closest to the gateway node, achieves 100% throughput of its generated traffic, up to when the generated traffic is 100 packets per second. Node_1 is also close to the gateway node but other node's traffic flows pass through it; the node's throughput starts decreasing when the offered load (packets generated) by each node is about 75 packets per second. Node_3 and node_4 achieve maximum throughput of only about 30 packets per second. When the offered load from the individual nodes in the network increases beyond 30 packets per second, the throughput of node_3, node_4 and node_5 start decreasing. This is due to the domination by node_1 and node_2 transmission, as they are closer to the gateway node. If the number of forwarding nodes in a wireless mesh network reduces, the throughput capacity of the network is expected to increase. But the increase in interference and MAC layer contention greatly affects the capacity of the network and makes the throughput degradation higher than that of a linear wireless mesh network.

5. CONCLUSION

Wireless mesh network technology has drawn considerable attention as a promising broadband access technology despite the increase in the number of internet access technologies. Very large areas can have access to broadband wireless using wireless mesh networks without need of costly infrastructures. The wireless mesh network capacity analysis, based on the effect of mesh forwarding, interference and contention at the MAC layer, and using simulations, shows that the throughput of each mesh node degrades in order of $1/n$ with increasing the number of nodes (n) in a linear topology, the degradation is even higher in a fully mesh network as a result of increase in the effect of interference and MAC layer contention in the network.

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REFERENCES

Adeyeye, M. and Gardner-Stephan, P. (2011). The Village Telco Project: A Reliable and Practical Wireless Mesh Telephone Infrastructure. EURASIP Journal of Wireless Communication and Networking, available on http://jwcn.eurasipjournals.com/content/2011/1/78.

Aoun, B. and Boutaba, R. (2010). Max-Min Fair Capacity of Wireless Mesh Networks 2006. University of Waterloo, Waterloo, ON N2L3G1 CANADA retrieved on 21 May, 2010 bcr2.uwaterloo.ca/~rboutaba/Papers/Conferences/MASS06.pdf

Akyildiz, I. Wang, X, and Wang, W. (2005). Wireless Mesh Networks: A survey. In: Computer Networks' 47 (47): 445-487. Retrieved on 31 Feb, 2010 from http://www.sciencedirect.com

Ball, P. (2010). Broadband Wireless Networks. Unpublished Lecture Notes. Oxford Brookes University, UK.

Gumel, M. I.; Faruk, N. and Ayeni, A. A. (2011). Investigation and Addressing Unfairness in Wireless Mesh Networks. Journal of Emerging Trends in Computing and Information Sciences, 2 (10): 514-524.

Gume.l M. I.; Faruk, N. and Ayeni, A. A. (2011). Routing With Load Balancing in Wireless Mesh Networks.

International Journal of Current Research, 3 (7): 087-092.

Gupta, P. and Kumar, P. (2000). The Capacity of Wireless Ad hoc networks. IEEE Transactions on Information Theory, 46 (2). Retrieved on 29 March, 2010 from http://nesl.ee.ucla.edu/pw/ee206a/gupta_infotheory00.pdf

Hethley, S. (2009). Essentials of Wireless Mesh Networking. Cambridge Wireless Essentials Series, Cambridge University Press, New York, USA.

Hossain, E. and Leung, K. (2008). Wireless Mesh Networking Architecture and Protocols. Springer Science Business Media, New York, USA.

Hassanein, H. and Zhou, A. Routing with Load Balancing in Wireless Ad hoc Networks. Department of Computing and Information science, Queues University, Kingston Ontario, Canada. Retrieved on 31 March, 2010 from portal.acm.org/citation.cfm?id=381614

Jun, J. and Sichitiu, M. Fairness and QoS in Multihop Wireless Networks. Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC 27695-7911, USA. Retrieved on 29 March, 2010 from, www4.ncsu.edu/~mlsichit/Research/Publications/fairnessVTC.pdf

Jun, J.; Peddabachagari, P. and Sichitiu, M. (2003). "Theoretical Maximum Throughput of IEEE 802.11 and its Applications. Proceedings of the Second IEEE International Symposium on Network Computing and Applications (NCA'03). Retrieved on 15 February 2010 portal.acm.org/citation.cfm?id=824470.825340

ISSN......... 0189-9546
Faculty of Engineering & Technology, University of Ilorin, Ilorin, Nigeria.

Jun. J. and Sichitiu. M. (2003). The Nominal Capacity of Wireless Mesh Networks. Wireless Communications. IEEE 10 (5): 8–14. Retrieved on 29 February 2010 http://wwwieeexplore.ieee.org/iel5/7742/27826/01241089.pdf

Li Yu. F. and Li. X. (2010). Gateway Placement for Throughput Optimization in Wireless Mesh Networks. Department of Computer Science. University of North Carolina. Charlotte. USA. Retrieved on 29 February 2010 portal.acm.org/citation.cfm?id=1413939.1413954

Zhang. Y. and Luo. H. H. (2007). Wireless Mesh Networking Architecture. Protocols and Standards. Wireless Networks and Mobile Communications Series. Auerbach Publications. New York. USA.