QoS Performance Management in Mixed Wireless Networks

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ABSTRACT

This paper presents a model for Quality of Service (QoS) management in a mix of fixed Ground Station (GS) and ad-hoc telemetry networks, and introduces an enhanced clustering scheme that jointly optimizes the performance of the network using multiple distance measures based on the location of the wireless nodes and the traffic level. It also demonstrates that a "power" performance measure is an effective tool for modeling and managing QoS in Mixed Networks. Simulation results show that significant QoS performance improvements can be obtained and maintained even under severe traffic conditions.

KEYWORDS

Quality of Service (QoS), Mixed Network, Clustering, Power Performance Measure , iNET

I. INTRODUCTION

The iNET effort was launched to create a telemetry network that will enhance the traditional IRIG-106 point-to-point telemetry link from TAs to ground stations[1]. Research conducted at Morgan State University (MSU) has focused on providing solutions for two important critical needs identified by the Central Test and Evaluation Investment Program (CTEIP). They are: "the need to be able to provide reliable coverage in potentially high capacity environments, even in Over-The-Horizon (OTH) settings", and "the need to make more efficient use of spectrum resources through dynamic sharing of said resources, based on instantaneous demand thereof".

The Mixed Network architecture developed by MSU, combines fixed or GS/cellular networks with mobile ad-hoc networks (MANETs) and reflects the future of wireless networks. Performance in mixed networks is especially difficult to characterize because serving users with real time applications is a challenge as multiple elements complicate "Quality of Service" (QoS) guarantees. The original mixed network used clustering techniques to partition the aggregate network into clusters or sub-networks based on properties of each TA which included signal strengths and location [2][3]. This paper starts with an overview of the mixed network architecture followed by a discussion of the power performance measure and how it can be used to establish the appropriate operating point in the mixed network in order to provide Quality of Service (QoS) guarantees for time critical applications as a function of the traffic level. It then introduces an enhanced clustering scheme that jointly optimizes the performance of the mixed network using multiple distance measures based on the Signal to Noise Ratio (SNR) of the wireless nodes and the overall traffic level of the mixed network [4]. Finally, it presents extensive simulation results to prove that using our mixed network model provides significant QoS performance improvements that can be maintained even under severe operating conditions. This paper concludes by showing that the proposed enhanced clustering scheme can be extended to include additional distance measures such that the mixed network can be jointly optimized based on QoS, Spectrum, or Interference management requirements.

II. MIXED NETWORK ARCHITECTURE

The design and implementation of a mixed wireless network is a very challenging task because both systems, MANET and Cellular operate using different design constraints that are not directly compatible[5][6]. Changes have to be made in the Internet protocol (IP) at the different layers in order to provide a seamless integration between the two communication systems. The goal of the mixed network is to combine the advantages of both sub-networks by using the high capacity cellular network to enhance the MANET and use the MANET to extend the coverage of the cellular network. The Mixed Network designed by MSU is based on the following assumptions. It uses an optimized two-stage clustering scheme developed by Babasola [2] to divide the network into a cellular with a GS and one or more ad-hoc sub-networks also known as cluster cells (CC). It is assumed that the GS is located at the center of the cellular network, and that several CCs are located around it as shown in Figure 1.

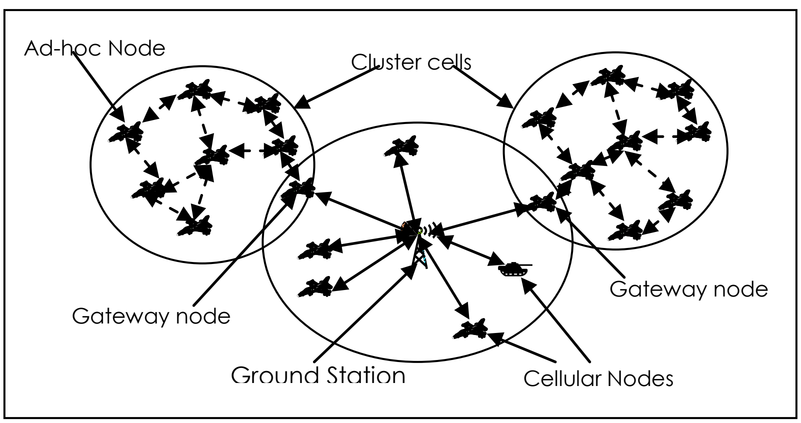


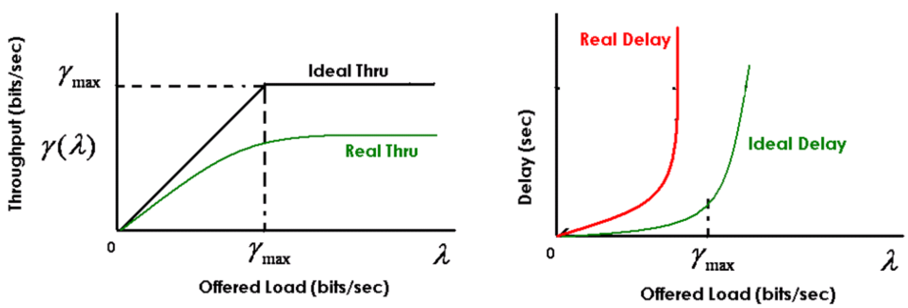
Figure 1: Mixed Network Overview (source [2])

All TAs are equipped with dual interface Network Interface Cards (NIC) that allows them to operate in cellular mode (CM), ad-hoc mode (AHM) or gateway mode (GM) depending on their location from the GS. Gateway nodes (GN) are capable of communicating in both cellular and ad hoc mode simultaneously and they can be used to relay data from TAs that are operating in OTH settings to the GS or vice versa. More information regarding the architecture of the mixed network and the basic clustering scheme can be found in [2] and [3].

III. PARAMETERS FOR QOS APPLICATIONS

A. Choice of QoS Parameters

QoS is defined as a scheme with priorities that assures that real time data is delivered in real time. A QoS scheme has to assure that critical or high priority applications are guaranteed the network resources they need, regardless of traffic conditions in the network. One of the key issues discussed in this paper is how to implement QoS guarantees in a mixed wireless network . Since QoS guarantees can take different forms [7][8], the approach used in this paper focuses on two parameters: throughput and delay. The throughput of a wired or wireless network represents the average rate that data packets can be successfully delivered from all the sources to all the destinations over the communication channel. A QoS guarantee of throughput assures both the source and destination that a minimum data transfer rate will be maintained throughout their exchange of data packets. Delay refers to the time delay in seconds data packets experience as they travel through the communication network from their source to their destination. A QoS guarantee of delay assures both the source and destination that the delay experienced by the packets they exchange will not exceed some agreed upon threshold time. The throughput and delay curves shown in Figure 2 indicate that the performances start deteriorating when the traffic load approaches the maximum capacity $_{max}$ of the network. This implies that a QoS guarantee is easier to implement when the traffic level is very low. Maintaining QoS guarantees becomes very challenging when the traffic level becomes very high.



(a) Throughput Performance (b) Delay Performance

Figure 2: Throughput and Delay Performance Curves (source [4])

B. Analytical Derivation of QoS Parameters

The most important challenge associated with providing QoS guarantees is congestion. Since the sources of congestion vary significantly between wired and wireless networks, different approaches are needed for wireless networks. Congestion control in wireless networks is more challenging than wired networks. A closer look of the region of our mixed network where the GNs are located indicates that the performance of the mixed network depends on the interaction between the TAs in the two sub-networks. There are two important parameters that affect the performance of each sub-network and have an impact on congestion: contention between the TAs in the mobile ad-hoc network, and queuing at the Gateway TAs that serve as the link between the mobile ad-hoc and the Cellular networks.

In our queuing model, we assume for a system with QoS requirements that a packet will be dropped if its queue time T_q is greater than some maximum threshold wait time T_{max}. Contention in MANET is evaluated by looking at the Medium Access Control (MAC) protocols. The MAC protocol plays a critical role in allowing different users to share a common communication medium. Collision occurs when two or more users transmit at the same time using the same communication medium. There are two ways of managing and controlling the multiple access and collision problems. The first approach uses the Aloha or Slotted-Aloha contention protocols that resolve collision problems after they occur [9]. The second approach uses contention protocols that try to avoid collisions before they occur. The most important collision avoidance protocol is the Carrier Sense Multiple Access contention protocol. Our previous research work [3], was based on the slotted Aloha contention protocol and a simple queuing model. In this paper, we extend our research work by deriving the analytical equations using the more advanced CSMA contention protocol. Since there are various versions of the CSMA protocol we base our analysis on the non-persistent CSMA protocol because it provides us with excellent throughput/delay characteristics [10]. The following section presents a summary of the analytical solutions we derived for the throughput and delay equations for both sub-networks. A detailed explanation of the steps taken to derive the final analytical equations can be found in [4].

Since contention and queuing affect the overall performance of the mixed network, the aggregate throughput due to both parameters can be computed as shown in equation (1).

$$Aggr\_Thruput = Thruput_{cont} * Thruput_{que}$$

$$Aggregate\_Throughput = \left(\frac{aGe^{-aG}}{\left(1 - e^{-aG}\right) + a} \right) \left(G \left[1 - e^{-(1-G)T_{max}/T_s} \right] \right) \qquad (1)$$

where: "G" represents the traffic demand, "a" represents the propagation delay normalized in time units, "T_s" is the service time in the queue, and "T_{max}" is the maximum wait time in queue. Similarly, the aggregate delay equation due to both parameters is shown in equation (2).

$$Aggr\_Delay = Delay_{cont} + Delay_{que}$$

$$Aggregate\_Delay = \left(1 + a + \frac{G - S}{S} \left(1 + 2a + \alpha + \delta\right) \right) + \left(\frac{T_s}{1 - G} \right) \qquad (2)$$

where: "G" represents the traffic demand , "S" is the throughput, "a" represents the propagation delay normalized in time units, "α" is the normalized acknowledgment time for packets that have been received, and " " is the normalized retransmission delay.

The next step is to do a trade-off analysis in order to identify the best throughput versus delay combination. In the ideal case, a network manager wants the maximum throughput with lowest possible delay. Since that is a very difficult task to achieve, the more realistic option is to come up with an approach that tries to balance the two parameters by identifying the appropriate operating point such that the overall network performance is optimized with an emphasis on either throughput or delay. In this paper, we propose using the "power" performance measure to achieve that goal. A detailed explanation of our approach is presented in [4].

IV. NETWORK MANAGEMENT FOR QOS APPLICATIONS

A. Power Function to Manage QoS

The throughput and delay performance measures were initially derived separately for the contention and queuing networks in the previous section. The "power" performance measure shown in equation (3) can be used to combine the two parameters into one, and evaluate trade-offs between competing performance metrics such as throughput and delay [11]. The name power when applied to a communication system is derived from a physics analogy where throughput represents energy and delay represents time. Note that : $0 \le \text{Power} \le 1$ because $\text{Throughput} < 1$ and $\text{Delay} > 1$.

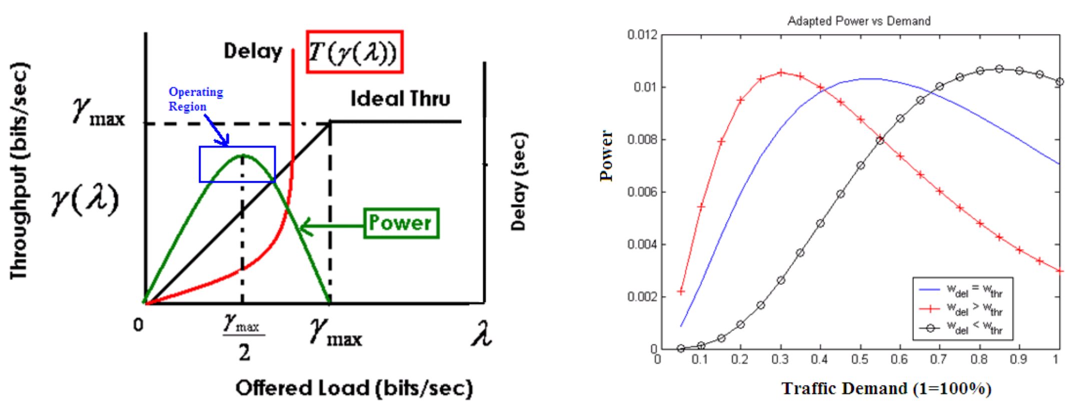
$$Power = \frac{Energy}{Time} = \frac{Throughput}{Delay} \qquad \textbf{(3)}$$

The power performance measure can be used to characterize the overall performance of the mixed network. It will be used to establish the best operating point or region for the mixed network as shown in Figure 3(a), such that the clustering algorithm organizes the wireless nodes for optimum traffic management and QoS delivery. The aggregate power equation for the non-persistent CSMA protocol is shown in equation (4) .

$$Aggr\_Power(G) = \frac{\left(\dfrac{aGe^{-aG}}{1-e^{-aG}+a}\right)\left(G\left[1-e^{-1-G\;T\max/Ts}\right]\right)}{1+a+\dfrac{G-S}{S}\;1+2a+\alpha+\delta\;+\left(\dfrac{T_s}{1-G}\right)} \qquad \textbf{(4)}$$

The simple power function allows the user to identify only one particular operating point for the network. We modified it by adding weights to each distance measure as shown in equation (5), so that we are able to select and vary the operating point based on the network management requirements that puts an emphasis on throughput or delay as shown in Figure 3(b).

$$New\_Aggr\_Power(G) = \frac{(Aggr\_Thru)^{w\_thr}}{(Aggr\_Delay)^{w\_del}} \qquad \textbf{(5)}$$



(a) Original Power Function

(b) Adapted Power Function

Figure 3: Original and Adapted Power Function Performance Curves (source [4])

B. Enhanced Clustering Algorithm

Clustering is the grouping of a set of nodes into subsets or clusters cells based on some identified common attribute such as location, etc…The original clustering algorithm presented in [2] is based on a two stage "k-means" clustering scheme [12][13]. In the first stage, the algorithm groups the nodes into either the cellular or the ad-hoc network based on their location from the ground station. In the second stage, it groups the nodes in the ad-hoc network into *k* cluster cells (CCs) based on an Euclidean distance measure by computing the minimum distance between each node and the k-centroids. Although the k-centroids are initially chosen randomly, the algorithm converges when the location of the k-centroids doesn't change anymore indicating that they have reached their optimum position. In this paper, we present an enhanced clustering algorithm shown in Figure 4 that operates in two modes by modifying the second stage. It can either cluster the nodes based on their spatial location only, or it can use the operating point determined by the power function to group nodes and set traffic levels in the ad-hoc network such that the traffic level in each CC is optimally distributed and QoS guarantees can be met in all CCs. We experimentally select the appropriate weights to establish the trade-off between the distance and traffic parameters as shown in equation (6).

$$Aggregate\,Clust\,Par = Spatial\,Clust\,Par^{w1} * Traffic\,Clust\,Par^{w2} \qquad \textbf{(6)}$$

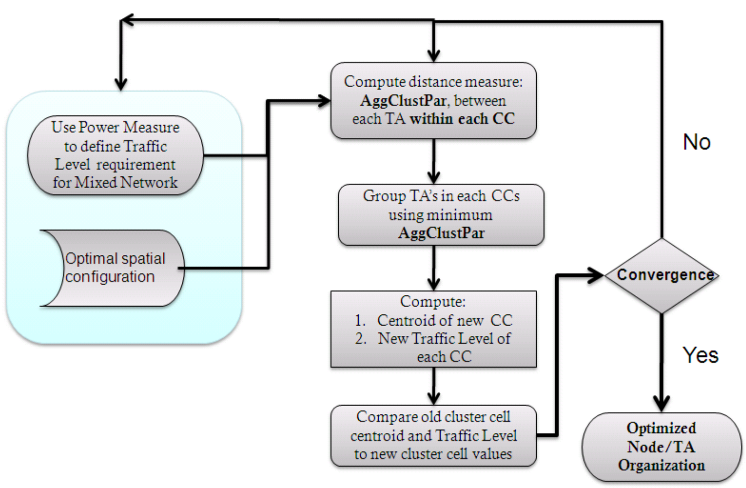


Figure 4: Enhanced Clustering Algorithm (source [4])

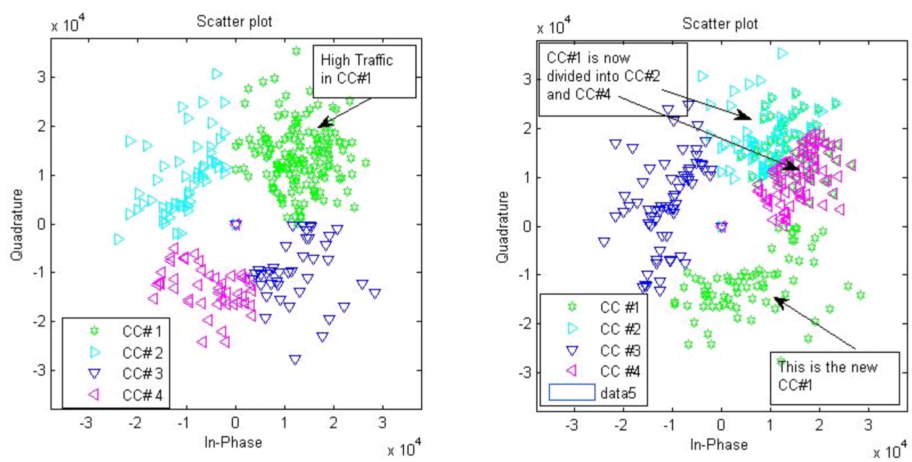
V. SIMULATION RESULTS AND DISCUSSION

A. Designing the Experiment

The goal of a network manager is to get the real throughput and delay performance curves shown in Figure 2 as close as possible to the ideal curves by choosing the appropriate operating point and maintaining the performance even under severe traffic conditions. In this section, we will use the simulation results to show that our QoS management model is efficient at achieving that goal. Our simulation experiment is designed as follows. First, we organize nodes in a mixed network using the original clustering algorithm based on spatial location only. Second, we purposely create conditions for congestion in one of the CCs by creating high traffic conditions. In the third step, we evaluate the throughput, delay, and power performance measures in the high traffic cell and all other CCs before and after the enhanced clustering scheme is applied to prove that the enhanced clustering algorithm has relieved the congestion in the mixed network and improved the overall performance. All the simulations are done using the Matlab software, and additional detailed results can be found in [4].

B. Simulation Results using Original and Enhanced Clustering

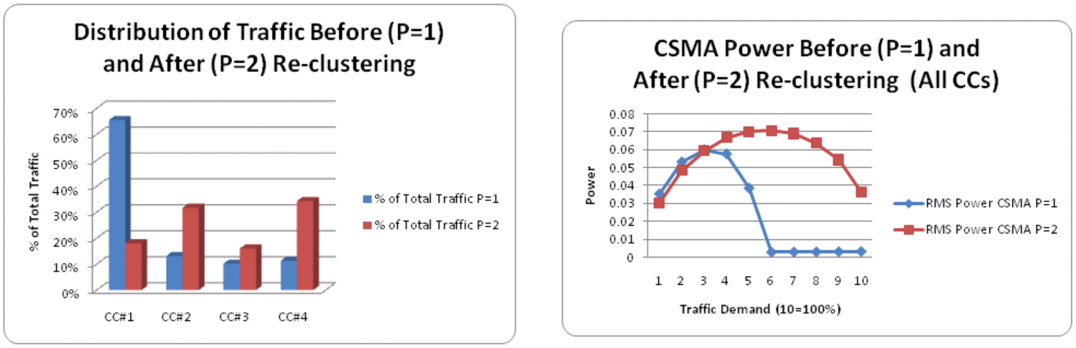
Figure 5(a) shows the mixed network after the original clustering algorithm that is only based on the Euclidean distance measure and k = 4 CCs is applied. To show the impact of congestion on the throughput and delay performance measures that are important to QoS guarantees, CC#1 is purposely flooded with nodes that have a high traffic demand with high QoS requirements. The new re-clustered mixed network that uses the enhanced clustering algorithm based on equation (6) is shown in Figure 5(b). Figure 5(b) shows that the enhanced clustering algorithm that is based on both location and traffic level, did the most practical thing in order to tackle the congestion in CC#1. It divided CC#1 into two separate clusters CC#2 and CC#4 such that the overall high traffic demand that used to be present in CC#1 only is now shared by the two neighboring CCs. The amazing part about the algorithm is that it did the re-clustering and the new re-assignment of the CCs on its own without prior pre-conditioned demands from the user. The next step is to evaluate the effect of the enhanced clustering algorithm on the traffic distribution, throughput, delay and power performance measures in all CCs.



(a) (b)

Figure 5: Original and Enhanced Clustering of Mixed Network (source [4])

The distribution of traffic among the four CCs before and after the enhanced re-clustering is shown in Figure 6(a). It indicates that using the original clustering (P=1), CC#1 carries nearly 67% of the total traffic in all ad-hoc CCs, which is a level of traffic that is 6 times higher than the next highest traffic level in CC#2 and CC#4. This will create a severe congestion in CC#1 that will be reflected in the performance curves of the throughput, delay and power. The results after the enhanced clustering is applied (P=2) indicate that CC#1 does not carry the majority of the total traffic in the ad-hoc network anymore. The enhanced clustering algorithm re-organized the Ad-hoc network such that the total traffic is more evenly divided among the four clusters with no one CC carrying more than 35% of the total traffic.

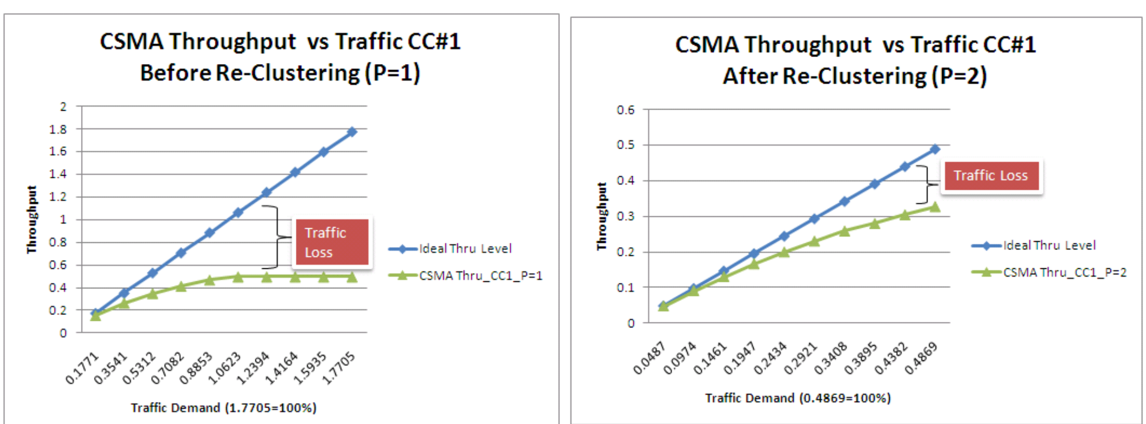


(a) (b)

Figure 6: Traffic Distribution and CSMA Power Function (source [4])

Figure 6(b) indicates the values of the power function before and after the enhanced clustering algorithm is applied. It should be noted that a level of 1 or 10 in the x-axis represents a maximum traffic demand level of 100%. It shows that the CSMA power reaches its peak at around 30% of the maximum traffic demand before the enhanced clustering is applied (P=1), and at around 60% of the maximum traffic level after the enhanced clustering is applied (P=2). It should also be noted that the CSMA power goes to zero around 60% of the traffic demand before the enhanced clustering is applied (P=1), and never goes to zero after the enhanced clustering (P=2) is applied. A power level that goes to zero implies that the delay has increased significantly due to congestion. The next step is to evaluate the effect of the enhanced clustering on the throughput and delay distance measures.

The results in Figure 7(a) indicate that before the enhanced clustering is applied (P=1), the throughput performance for the CSMA contention protocol in CC#1 is negatively affected by congestion. This can be seen by comparing the CSMA throughput performance to the ideal throughput curve where throughput equals demand and evaluating the level of traffic loss.

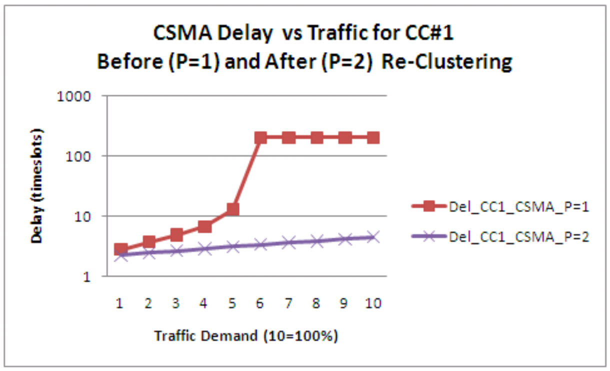


(a) (b)

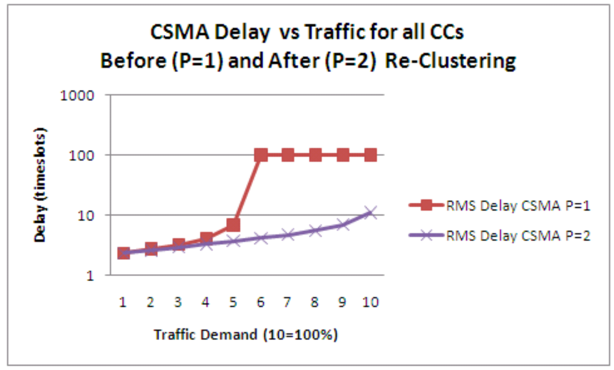
Figure 7: CSMA Throughput Before and After Enhanced Clustering (source [4])

Figure 7(b) shows that the CSMA throughput performance in CC#1 after the enhanced clustering is applied (P=2) has increased significantly. This can be validated by looking at the traffic loss in Figure 7(b) and noticing that it has decreased significantly compared to that in Figure 7(a).

Figure 8 indicates that before the enhanced clustering is applied (P=1), the average delay for CC#1 in 8(a) and all the CCs in 8(b) reaches saturation around 60% of the maximum traffic demand. After the enhanced clustering is applied (P=2), the average delay in CC#1 in 8(a) and among all CCs in 8(b) is around 1/10 of the maximum delay before re-clustering and never reaches saturation indicating once again that the congestion is under control.



(a)



(b)

Figure 8: Delay Before and After Enhanced Clustering (source [4])

VI. CONCLUSION AND FUTURE WORK

In conclusion, we provided a valid model to implement QoS guarantees in a mixed wireless network by focusing on two parameters: throughput and delay. The two parameters were combined into one using the power performance measure because it allowed us to evaluate trade-offs between the two competing performance metrics. We provided analytical equations for the power function and proved using simulation results that it can be used to establish the appropriate operating point in the mixed network in order to provide Quality of Service (QoS) guarantees for time critical applications as a function of the traffic level. We applied the enhanced clustering algorithm and proved using extensive simulation results that it can manage congestion in the ad-hoc network and can therefore jointly optimize the performance of the mixed network using multiple distance measures such as spatial location and the overall traffic level in the ad-hoc network. The analytical and simulation results prove that the proposed enhanced clustering scheme can be extended to include additional distance measures such that the mixed network can be jointly optimized based on QoS, Spectrum, or Interference management requirements. This will be the focus of our future work.

Acknowledgments

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