THE OPTIMIZATION OF NODE CONFIGURATION IN A MIXED NETWORK FOR QUALITY OF SERVICE

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ABSTRACT

Morgan State University's iNET project is the development of a complete network architecture to enhance telemetry performance. Existing telemetry standards employ an RF link standard which allows only unidirectional data transfer from a test article (TA) to a ground station over a dedicated channel per TA. This limits the capacity of the system as resources are not efficiently utilized. Additionally, this standard does not allow data exchange between Over the Horizon TAs and the ground station. Their data must be recorded for subsequent retrieval by test engineers. The growth of telemetry demands that spectrum resources are maximized to increase transfer capacity. Real time data exchange capability is essential to success in telemetry. Bidirectional streaming of data to both near and over the horizon TAs is desired with no compromise of Quality of Service for real time applications. The network approach addresses these demands by allowing telemetry data to be multiplexed over a shared radio channel to and from the TAs. A mixed cellular and mobile adhoc network (mixed network) has been shown to satisfy the capacity and coverage elements of iNET requirements. This paper begins with an introduction to the iNET objective, continues with some background information on the major technical elements applied in this endeavor and finally shows that an optimum node configuration can be achieved and maintained in this mixed network using clustering techniques to include the joint optimization of the Quality of Service, Signal-to-Noise ratio, and Interference requirements as outlined by the iNET Needs Discernment.

INTRODUCTION

Telemetry is a technological process that allows the remote measurement and reporting of such object characteristics as an aircraft's wing oscillation to system designers or operators over various distances for immediate or delayed analysis [1], over various distances, and via various media. Telemetry facilitates the monitoring of design integrity during various maneuvers and conditions which dictate the capabilities of the aircraft. Today's telemetry is characterized by a large number of measurements. It is becoming increasingly impractical to transmit each of these along a dedicated transmission channel. It is the desire that measurements are grouped and transmitted as a single stream. At the test engineer stations, the stream will be decoded for analysis.

Navy test articles (TAs) rely heavily on such telemetry systems in their design and test environments. In these environments, it is imperative that a telemetry system reliably provides Quality of Service (QoS). The data needs to be delivered without delay, jitter, or error. Furthermore, network coverage needs to be maintained reliably regardless of distance from the base station and the number of TAs communicating with that base station. Additionally, the information needs to be secured and resilient to interception and decoding by foreign parties. The Integrated Network Enhanced Telemetry (iNET) study [2] thus serves to develop telemetry systems with network technology, to satisfy the aforementioned requirements and accommodate the increasing telemetry demands of measurements and communication ranges.

Babalola [3] proposed and demonstrated the mixed network architecture as being the building block for achieving the iNET requirements of robust performance, capacity, and coverage. The cellular standard provides a high capacity network with spectral efficiency [4]. Its limitation is that coverage is limited to a defined radius which is a function of the power of transmission and the path loss in the signal through channel fading effects and multipath. The result is that throughput decreases exponentially with distance from the point of transmission according to the Free Space Propagation Model as given in [4]. The ad hoc network standard provides the coverage characteristics desired. With no centralized control mechanism, dynamic routing protocols allow these nodes to configure routing strategies based on the network architecture and congestion at a given time. Babalola demonstrated a hybrid of these networks in [3]. Figure 1 illustrates the proposed implementation.

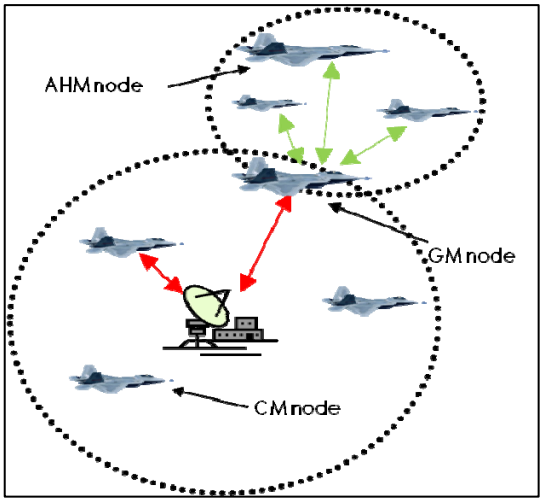

Figure 1: Mixed Network Overview

Quality of Service (QoS) defines the maintenance of the real time requirement in the exchange of time-critical telemetry data between TA and base station under the proposed mixed network. QoS is necessary as ad hoc networks are contention based networks. In ad hoc mode (AHM), data arriving from an Over the Horizon (OTH) TA is queued with other data from other OTH TAs using the same gateway node (GN) TA. Given the number of TAs transmitting comparable data streams through that common GN, delay is expected and will vary. Ad hoc networks are currently implemented under IEEE 802.11 or wireless LAN protocol. While TCP is the dominant transfer protocol in 802.11, from [5], it is not well suited for QoS. Queuing disciplines attempt to address this shortcoming by processing packets arriving at the GN from all TAs on the basis of QoS labels to ensure timely delivery. The Contention and Queuing model was explored by Chaney in [5] and addresses minimizing the expected delay associated with an ad hoc network.

BACKGROUND

In the proposed mixed network, where the gateway node is the shared link to the base station, it is important to manage contention within the MANET to maintain QoS. Clustering is the partitioning of a set of mobile devices or nodes into subsets or (cluster) cells based on some

identified common attributes such as location. "k-means clustering" first defines k number of cells into which nodes are grouped based on the similarity between their attribute value and that of the k^{th} cluster [6]. Babalola's mixed network was implemented using a modified k-means clustering scheme which is detailed in [3]. It first established which nodes were within transmission range of the base station and were thus classified as cellular nodes or cellular mode (CM). The outlying nodes were classified as ad hoc nodes or ad hoc mode (AHM) and formed the MANET to which the k-means clustering was applied; from these clusters, a gateway node (GN) was determined.

A distance measure is a parameter or function which uses a scalar distance between two arguments to establish similarity or dissimilarity between them. The Euclidean norm distance measure was used to establish the spatial similarity among nodes and thus form clusters based strictly on their spatial orientation via the clustering parameter $CPar_i = [r_i,\theta_i]$. The details are presented in [3]. The focus of this project is to modify the k-means clustering method to incorporate spatial orientation as well as the node attributes or characteristics such as volume of traffic, contention among nodes, the priority of data, and the observed signal to interference (SIR) characteristics. This requires distance measures to be developed which use these aforementioned node characteristics as parameters in conjunction with the existing distance measure. Thus, the clustering parameter will be extended to something such as $CPar_i = [\theta_i,r_i,tr_i,pr_i,QoS_i,SIR_i,\ldots]$.

The development of these distance measures as described above is the key to the successful modification of the clustering algorithm. "k-means clustering" groups elements based on a minimum difference value between the investigated attribute value of node and that of the centroid or point of interest. This makes the clustering technique very efficient for spatial parameters as nodes can be grouped in tiered fashion based on their proximity to centroids given their values $\boldsymbol{\theta}$ and $\boldsymbol{r}$. With the node attributes such as QoS and SIR, the need is to evenly distribute these values among clusters. Therefore, the distance measure in the modified clustering scheme must be designed to produce an effect opposite to clusters tiered based on these attributes. Tiering of these attributes is counterintuitive to our objective. Developing a distance measure in this effort demands that a node's attribute or the node's attribute relative to that of its neighbors is used to seemingly affect either its spatial orientation or the spatial orientation of the nodes in close proximity to it. This will change the way in which the nodes will be clustered.

METHODOLOGY AND DESIGN IMPLEMENTATION

The starting point for the modification of the clustering distance parameters is the point at which a group of nodes has been classified into Cellular Nodes and Adhoc Nodes as achieved by Babalola [3]. In this network configuration, the Adhoc Nodes are clustered based on the spatial parameter *CPar*. Figure 2 illustrates this network configuration from the original group of mobile nodes. In this network configuration, the gateway nodes have also been determined for each of the clusters as indicated by the large blue dots in each cluster.

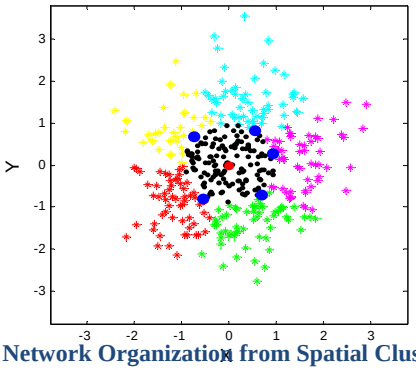

Figure 2: Original Network Organization from Spatial Clustering

Quality of Service Distance Measure and Optimization

The Quality of Service (QoS) requirements as outlined by the iNET Needs Discernment identifies the major considerations as:

- Data of various levels of priority will be exchanged between the TAs and the base station.
- A real time exchange of selected levels of priority data must be facilitated.
- The network will operate under very specific spectrum allocation limited the spectral resources available for data sharing.

For a starting point, it was assumed that TAs simultaneously present a single data packet for transmission at time, *t*. The distribution of relative priorities of the data is expected to follow an exponential distribution as illustrated in Figure 3. The data of highest relative priority among the set would be representative of data for which the real time exchange cannot be compromised. These values from 0 to 1 are called the QoS labels. The distribution of Fig. 3 was simulated as a random exponential distribution with a mean of 0.3, applied to the set of Adhoc nodes on the domain of [0, 1]. In this ideal distribution, the QoS labels are relatively evenly distributed. Therefore, a priority queuing scheme [4] can adequately manage the packet arrival and maintain the QoS requirements.

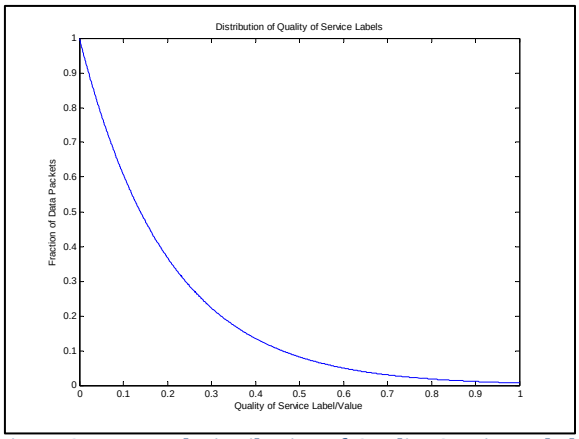

Figure 3: Expected Distribution of Quality Service Labels

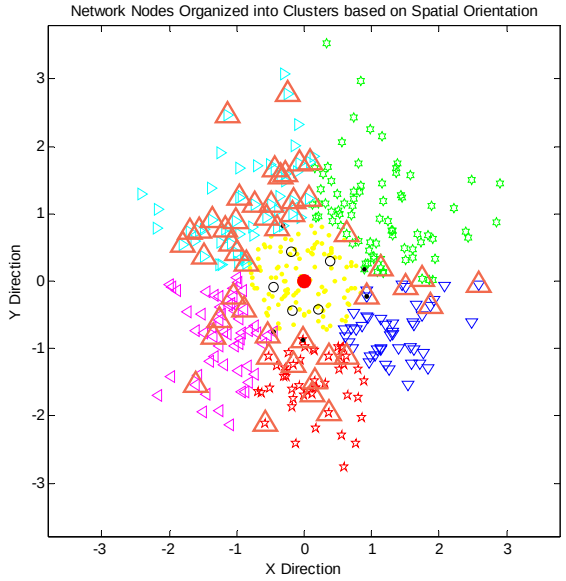

Figure 4: Flooding of a Single Cluster with High QoS Labeled Data Packets

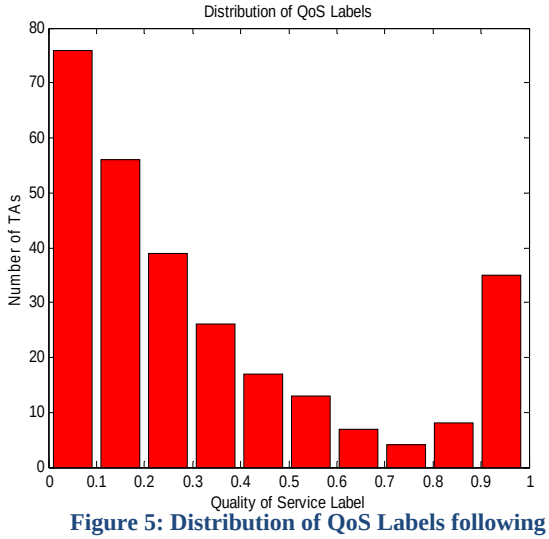

Figure 5: Distribution of QoS Labels following Flooding of a Single Cluster with High QoS Data Packets

The problem arises where a particular cluster may experience a larger than normal influx of high priority data packets at a given time. To simulate this, a selected cluster was flooded with high QoS labeled data packets and this is illustrated in Figure 4. Figure 5 shows the resulting QoS label distribution bar graph. Using the triangle outline to highlight the high QoS labeled packets, in the cluster to the northwest, colored light blue/cyan, there is an overwhelming presence of nodes presenting high QoS packets. The

gateway node in this cluster is no longer able to maintain the QoS requirements by priority queuing. The clusters need to be modified to maintain the QoS requirements within that cluster.
The QoS parameter, *QoSPar* is determined as a function of the acceptable delay which a packet can tolerate, its QoS label, and the mean QoS label present in the cluster to which it belongs. $QoSPar_{i,j}$ represents the *QoSPar* for the subject node, *i*, which is currently a member of cluster *j* and is calculated according to Equation (1) where the acceptable delay of the data packet normalized to a scale of 0 – 1, $\hat{AccDelay}_i$, is given as $\hat{AccDelay}_i = 1 - QoS_i$.

$$QoSPar_{i,j} = \left| \left(\hat{AccDelay}_i \times QoS_i^{\,f} \right) - \hat{mean(QoS)}_j \right| \quad (1)$$

By comparing the value of normalized $AccDelay_i$ to the normalized $mean(QoS)_j$ the minimum difference attracts a node to the gateway where the delay is most comparable with that which it can tolerate. This attracts a high QoS labeled node to a gateway where delay is very low. Likewise, the tendency is that very low QoS nodes will be relocated to gateways with very high delays. However, the concern here is to move primarily the nodes with the highest QoS demands. As QoS values decrease, there needs to be a comparable decrease in the amount of movement that such nodes experience. $QoS_i^{\,f}$ provides this effect. The product $\hat{AccDelay}_i \times QoS_i^{\,f}$ allows the *QoSPar* to decrease in significance as the nodes' value of QoS decreases. By the use of the exponent, *f*, applied to QoS, we can alter the degree to which the changing QoS value affects the degree by which *QoSPar* is used in re-clustering the subject node.
Next, the parameters $QoSPar_{i,j}$ and the node's corresponding spatial parameter, $CPar_{i,j}$ are scaled for comparability. This is done by normalizing both values to scales of 0 – 1 and is calculated as

$$\hat{QoSPar}_{i,j} = \frac{QoSPar_{i,j}}{\max(QoSPar_{i,j})} \; and \; \hat{CPar}_{i,j} = \frac{CPar_{i,j}}{\max(CPar_{i,j})} \quad (2).$$

Finally, the two parameters are integrated as a product in which each parameter is raised to a weight factor. This weighting factor establishes the ability to trade off one parameter against the other. This allows the user to push the optimization technique in the direction which he desires, either towards the QoS optimized cluster configuration or towards a spatially optimized cluster configuration. Equation (3) illustrates this.

$$QoSmeas_{i,j} = \left(\hat{CPar}_{i,j} \right)^{w_1} * \left(\hat{QoSPar}_{i,j} \right)^{1-w_1} \quad (3)$$

The weights have been selected such that they sum to 1. Analytical methods may be employed in determining the optimum weights to be applied to achieve the best configurations, thereby replacing weights *w* and *1-w* with w_1 and w_2 respectively.

By implementing $QoSmeas_{i,j}$ as our clustering parameter, the spatial clustering is now modified by the QoS attribute. The clustering process continued until convergence. The resulting optimized node configuration from this method is illustrated in Figure 6.

The result shown in this figure is obtained at the following weight values implemented in equations (1) and (3): $f = 1$; $w = 0.4$. From Figure 6, it can be seen that the nodes presenting the

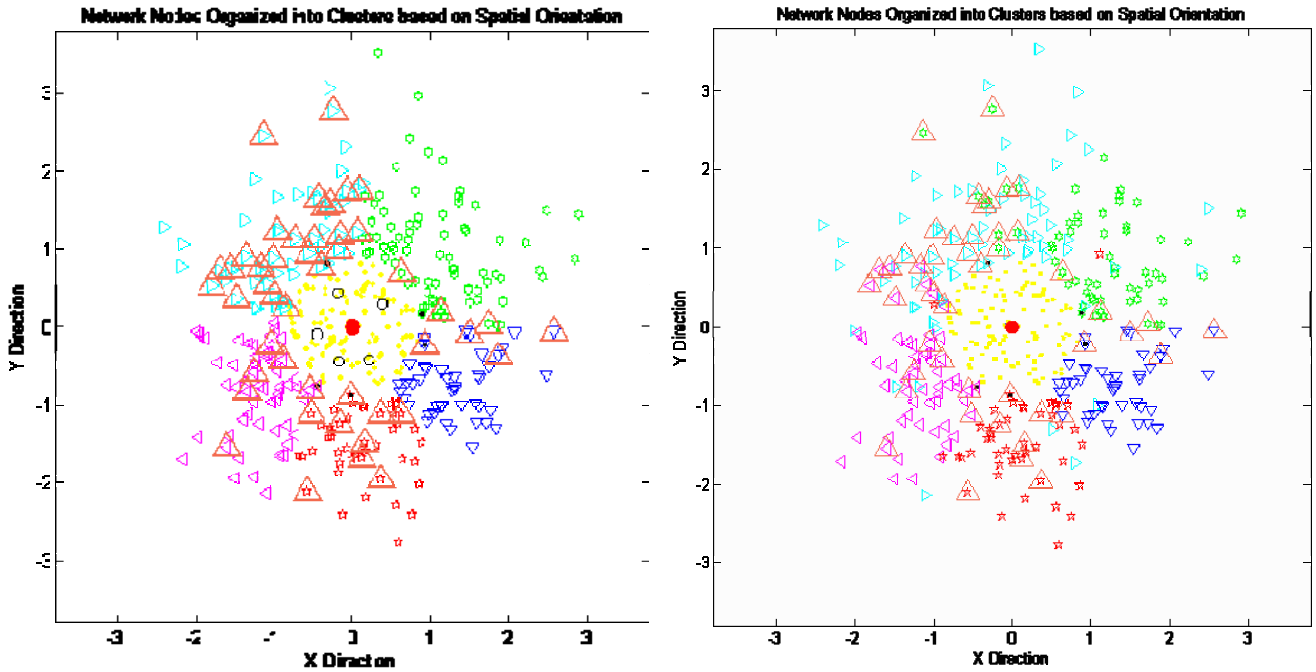

Figure 6: Network Configuration Before and After QoS Based Clustering is Applied

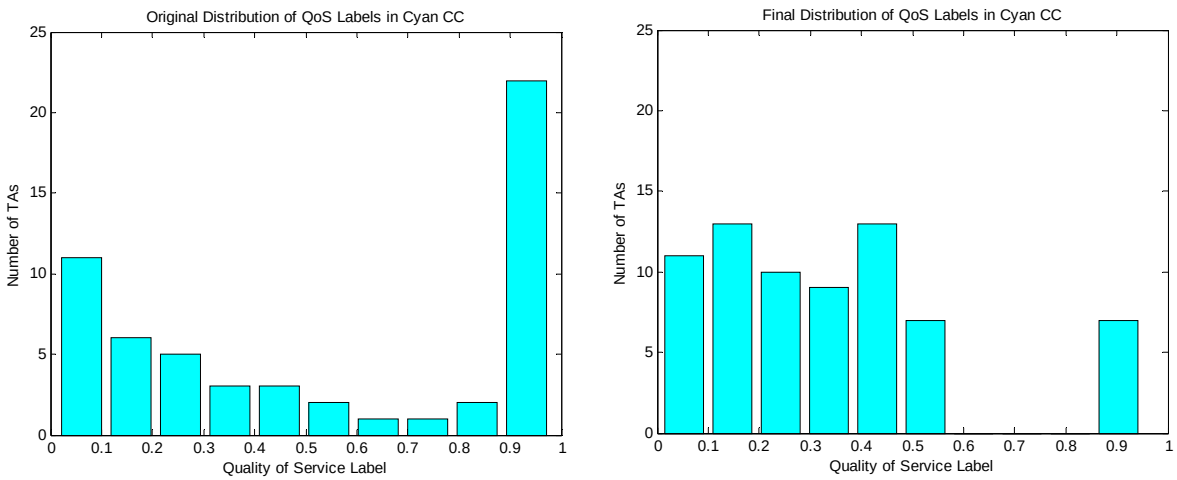

Figure 7: Re-Distribution of TAs with High QoS Labeled Nodes

high QoS labeled data have been distributed over the adjacent green and fuchsia colored clusters. Also prevalent in this result is that the majority of the nodes being reassigned to clusters different from their original clusters are nodes with high QoS labels. This verifies that the distance measure produces the desired effect.

An examination of the distribution of the high QoS data packets in these three clusters verifies the result. Figure 7 above shows compares the distribution of high QoS nodes in the flooded (cyan colored) cluster before and after the optimzation using the QoSmeas parameter. In this comparison, the before bar graph (left) shows a very large number of TAs presenting data packets with QoS labels above 0.9. The result of the optimization is that many of these TAs have vacated this cluster. In their place, a few lower QoS labeled TAs, capable of accepting delay have been

moved into this cluster. This is necessary in maintaining an overall good balance among the TAs and achieving convergence for the algorithm. Figures 8a and 8b then illustrate the distribution of TAs with high QoS labeled packets in the adjacent clusters following the QoS based optimization. Both of these bar graphs show a comparable increase in the numbers of TAs in the very high QoS

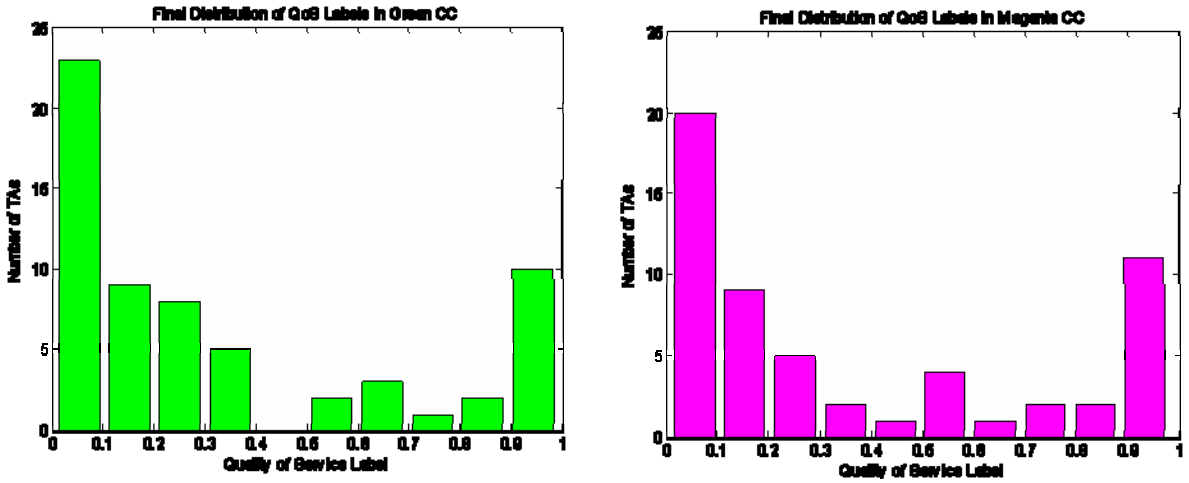

Figure 8a and b: Updated Distribution of TAs' QoS Labels in Neighboring Clusters

label to that of the originally flooded cluster. This indicates that the optimization has done a good job of distributing the high QoS load of the flooded cluster over the immediately adjacent clusters.

Signal to Interference Distance Measure and Optimization

In this mixed clustered network, a common characteristic is frequency re-use. There will typically be a greater number of clusters than different frequency bands available. This creates a potential for significant interference between clusters if the same frequency is used within close proximities. The optimization for Signal to Interference Ratio (SIR) is based on the original starting network configuration as depicted in Figure 2. For this configuration, we consider the availability of three different communication frequencies. Figure 9 shows the resulting frequency re-use which characterizes the original spatially optimized configuration. This network configuration is asymmetrical in the use of the frequencies. Given the relative proximity of the clusters re-using the frequencies denoted by green and orange colors, SIR considerations must be employed if performance is to be optimized for Quality of Service considerations.

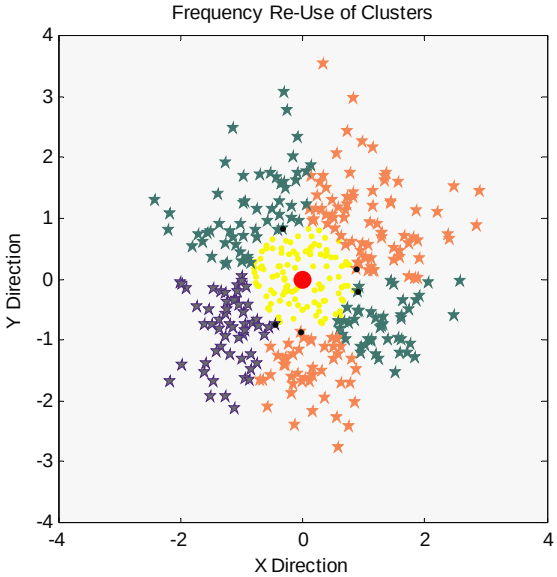

Figure 9: Frequency Re-use in Original Network Configuration

The optimization of this network configuration for SIR considerations involves each node assessing whether it will encounter a better SIR by transitioning to one of the clusters adjacent to its current cluster thereby optimizing the configuration. The SIR distance measure was determined given the following determinations:

- The signal to noise ratio SNR from the subject node to each cluster's gateway is determined given the transmission power of the gateway and the precise location in space of the node.
- The subject node can measure the interference received from every other node transmitting on the same frequency as the gateway to which it considers transmitting.

$SIRPar_{i,j}$, was calculated according to Equation (4) as the SIR parameter between the subject node i and any given gateway node, j.

$$SIR\,Par_{i,j} = \frac{SNR_{i,j}}{\sum_{1}^{N} I_{j_n}},\ where\ I_j\ comes\ from\ N\ nodes\ using\ frequency\ of\ GN_j$$

$$I_{n,j} = SNR, \eta,\ at\ node\ j\ from\ node\ n \qquad (4)$$

$$\eta = \frac{P_{t_n} G_t G_r \lambda^2}{16\pi^2 L}\left(\frac{d_0}{D(n,j)}\right)^{\varphi} - Log - Dist\ Path\ Loss\ Equation$$

The signal to noise ratio, *SNR* or η is determined based on the Log–Distance path loss model and equation. Next, the parameters $SIRPar_{i,j}$ and the node's corresponding spatial parameter, $CPar_{i,j}$ are made comparable by normalizing both values to scales of 0 – 1 and is calculated as

$$\hat{SIR}\,Par_{i,j} = \frac{SIR\,Par_{i,j}}{\max(SIR\,Par_{i,j})}\ and\ \hat{CPar}_{i,j} = \frac{CPar_{i,j}}{\max(CPar_{i,j})} \qquad (5)$$

Finally, the two parameters are integrated as a product in which each parameter is raised to a weight. This weighting factor establishes the trade off of one parameter against the other. This allows a tradeoff towards either an SIR optimized or a spatially optimized configuration.

$$SIRmeas_{i,j} = \left(\hat{CPar}_{i,j}\right)^{w_1} * \left(\hat{SIR\,Par}_{i,j}\right)^{1-w_1} \qquad (6)$$

Analytical methods may also be employed in determining the optimum weights to be applied to achieve the best configurations, thereby replacing weights w and 1-w with w_1 and w_2.

By implementing $SIRmeas_{i,j}$ as the clustering parameter, the spatial clustering is now modified by the SIR characteristic. The clustering process is continued until convergence. The optimized node configuration resulting from this implementation is illustrated in Figure 10 where a weight w = 0.5 implemented in equation (6).

From Figure 10, a reduction in size in clusters 4 and 5 is observed. The original members of cluster 4 are very close to the gateway node of Cluster 3 as is seen in the original configuration (top). With the large interference experienced from cluster 1, many of the nodes present in cluster 4 gain an increase in SIR by migrating to cluster 3 which is not re-used. Similarly, the nodes of cluster 5 are close to the gateway node of cluster 3. Compared with the interference experienced from cluster 2, many of these nodes gain SIR by migrating to cluster 3. The outcome of this optimization is the increased utilization of frequency 3 which undergoes no re-use. The re-use of frequencies 1 and 2 is reduced in clusters 4 and 5 and this mitigates the error in packet transmission from interference.

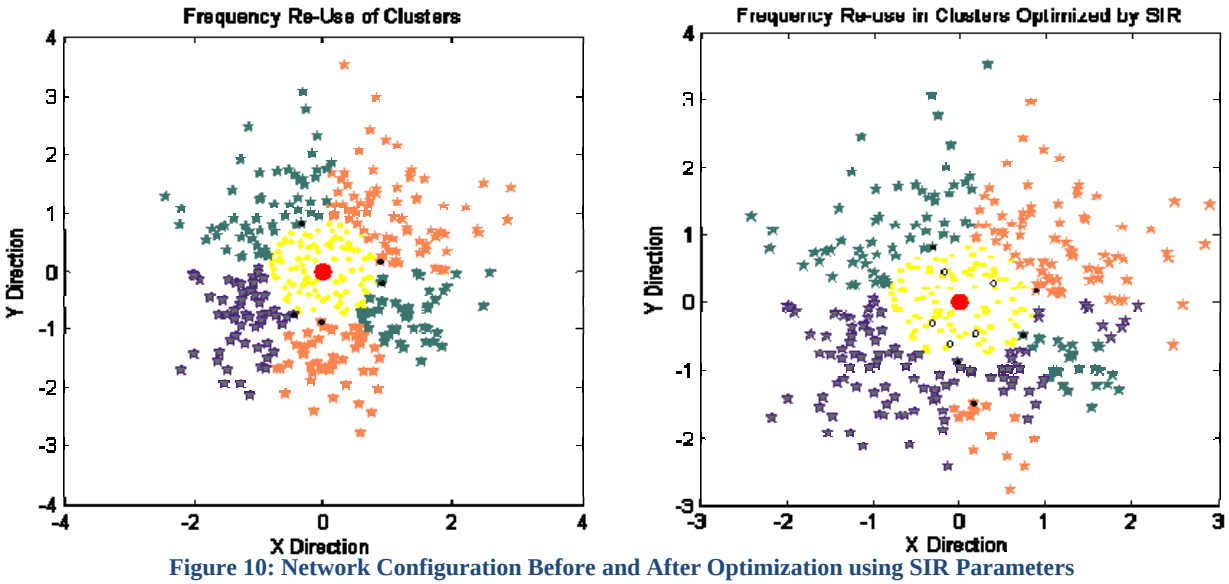

Figure 10: Network Configuration Before and After Optimization using SIR Parameters

Aggregate Optimization

The aggregate optimization fuses the optimizations of QoS attributes and SIR considerations with the original spatially optimized configuration to provide a clustering parameter based on three degrees of freedom. The Aggregate clustering parameter, $AggrPar_{i,j}$ is defined as

$$AggrPar_{i,j} = \left(\hat{CPar}_{i,j}\right)^{w_1} * \left(\hat{QoSPar}_{i,j}\right)^{w_2} * \left(\hat{SIRPar}_{i,j}\right)^{w_3} \quad (7).$$

$AggrPar_{i,j}$ is utilized as the clustering parameter in the same manner as $QoSmeas_{i,j}$ and $SIRmeas_{i,j}$ were employed. The result is that the original spatial parameter clustering network configuration is modified by both factors with the weights w_1, w_2, and w_3 controlling the tradeoff between these

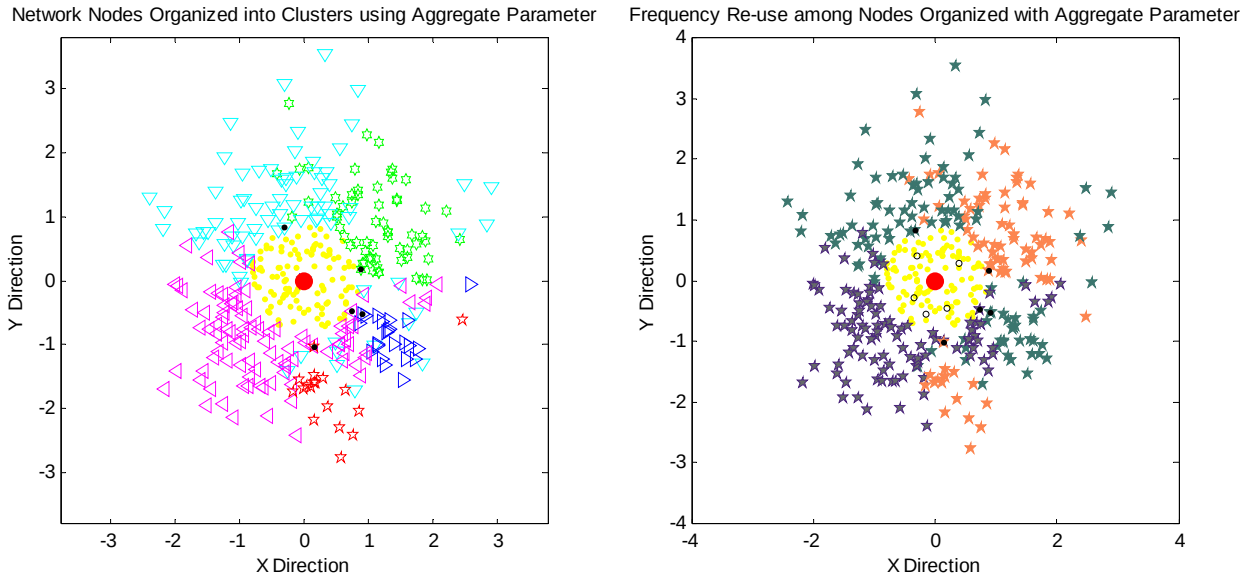

Figure 11: (a) Network Node Organization (b) Frequency Re-Use among Nodes for Aggregate Parameter Optimization

degrees of freedom. Figures 11a and b show the result of clustering implementing the aggregate

parameter at applied weights of $w_1 = 0.3$, $w_2 = 0.5$, and $w_3 = 0.3$. The aggregate parameter was applied to the network configurations illustrated in Figures 4 and 9.

In Figure 11(a), the node organization illustrates the grouping of the nodes to the gateways as determined by the aggregate parameter $AggrPar_{i,j}$ and from this, the overlap of cluster cells is visible. Figure 11(b) illustrates the frequency re-use among the nodes as determined by $AggrPar_{i,j}$. In this illustration, the overlap of cluster cells is now visible coinciding with the QoS optimization element present in $AggrPar_{i,j}$. These two images capture the effect of the aggregate parameter and the effect of varying the weighting values.

CONCLUSIONS

Two methods by which the node and network characteristics could be effectively utilized to optimize the modified k-means clustering scheme were developed. In this project, two such distance measures were developed and successfully utilized. A QoS label associated with each data packet was used to develop a distance measure which allowed the network configuration to be modified to facilitate changing QoS requirements. This also allows a tradeoff in favor of either an optimal QoS or an optimal spatial configuration. The second distance measure successfully modified the clustering parameter based on the Signal to Interference Ratio (SIR) experienced by a node in the network configuration in relation to the gateways was also used to develop a second distance measure which allowed optimization for SIR considerations and tradeoff an optimal SIR configuration against an optimal spatial configuration to be achieved. Finally, these two distance measures were successfully integrated to provide an aggregate parameter to implement both of these optimizations into the clustering mechanism in a manner which allows each of these three optimizations to be traded off against each other. These optimizations allow the management the iNET network requirements.

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