OPTIMAL CONFIGURATION FOR NODES IN MIXED CELLULAR AND MOBILE AD HOC NETWORK FOR INET

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ABSTRACT

As part of Morgan’s iNET development, the Mixed Cellular and Mobile Ad hoc Network (MCMN) architecture has been proposed to provide coverage to over-the-horizon test articles. Nodes in MCMN are assigned to one of three possible modes: Ad hoc, Cellular or Gateway. We present architecture for the proposed MCMN and some performance analysis to characterize the network. The problem of organizing nodes in this mixed network with optimal configuration is significant. This configuration gives nodes ability to know the best mode to operate and communicate with other nodes. Node organization is critical to the performance of the mixed network and to improve communication. The configuration of nodes required to optimally organize nodes in MCMN is demonstrated. The problem of evaluating configuration parameters for nodes in a mixed network is a nonlinear and complex one. This is due to the various components like the number of nodes, geographical location, signal strength, mobility, connectivity and others that are involved. Clustering techniques and algorithms have been used in literature to partition networks into clusters to support routing and network management. A clustering technique is employed to dynamically partition the aggregate network into Cluster Cells (CCs). A gateway node is selected for each CC which relays traffic from the cellular to the Ad hoc and vice versa. A trade-off analysis of the cellular boundary is presented using the maximum of the minimum data rate in the network. Numerical analysis and experiments are provided to show that the coverage can be extended to test articles in over-the-horizon region. It is also shown that, when the network is well organized, performance is improved.

KEYWORDS

MANET, cellular, coverage, throughput capacity, Ad Hoc, iNET

1 The choice of a cellular/ad hoc structure precedes INET’s choice of an IEEE802.11 model. This work still applies with the assumption that the WLAN Access Point substitutes for the cellular base station.
INTRODUCTION

MCMN was proposed after a comparison study of ad hoc and cellular networks [1]. In mixed or hybrid networks concept, the cellular networks and mobile ad-hoc networks interoperate to form an aggregate network. Advancements in technology have revealed the feasibility of the proposed solution by using the emerging dual-mode interface to equip nodes. This allows nodes to communicate in one of the three possible modes. These modes are ad hoc mode (AHM), cellular mode (CM) and gateway mode (GM). This concept provides mobile nodes more flexibility and system performance enhancement by providing seamless roaming between cellular networks and ad hoc networks. This research focuses on an efficient way of computing the configuration for each node in a mixed network. This includes their CC identity, gateway node to relay their traffic, and information about other nodes in the network. As routing schemes are important to effectively route traffic in the network, this work will include techniques for routing within each cluster and routing between the cellular and MANETs. The CC to which a node belongs is evaluated based on the information sent to the Base Station (BS) by the node. The focus in this work is the aeronautical environment where nodes have high mobility, reduced path loss due to free space or line of sight communication, and high coverage areas. The first section presents the MCMN architecture, the next section presents performance analysis in terms of throughput and coverage. The last section presents node organization scheme using a 2-stage clustering technique. Numerical analysis is presented to validate the performance of the network and a conclusion is given.

MCMN ARCHITECTURE

The MCMN is a pure hybrid network when compared with most of the other proposed hybrid networks [2, 3]. In MCMN, both cellular and ad hoc communications are possible. This means that both cellular and ad hoc nodes can originate and receive data. MCMN also includes the ad hoc mode (AHM) nodes, these nodes communicate in multi-hop mode and they dynamically route their own traffic using standard routing protocols like AODV, DSR, and DSDV. For Nodes operating in CM to continue communication in the network they switch to AHM (multi-hop) when their signal strength drops to a certain threshold. This is similar to the hand-over process in a conventional cellular system. The difference is that, while a node searches for another BS to connect to in cellular networks, nodes in MCMN search for an alternate mode or route using their other interface (ad hoc interface). A third category of nodes in MCMN is the gateway node (GN). These nodes are capable of communicating in both cellular and ad hoc mode simultaneously and they relay cellular traffic to ad hoc and vice versa.

The iNET scenario is illustrated in figure 1 where Test Articles (TA) collect data and send them to ground systems for further processing. The words nodes and TAs are used interchangeably for the rest of this paper to refer to wireless terminals. The figure shows TAs communicating in AHM as well as CM using both the ad hoc and cellular technologies for communication. TAs are grouped into \( K \) MANETs CCs. Each CC has its own GN to relay traffic between the cellular and MANET nodes in the CC. The BS is located at the center of the cellular network (single cell cellular system), and \( K \) CCs are located around it as shown in figure 2. The GNs can be a
bottleneck in the network so the choice of GNs is critical to the performance of MCMN. Every node can become a GN depending on its configuration. It is also assumed that each node is aware of its geographical location through GPS or other positioning mechanism.

![Figure 1 MCMN Architecture](image1)

![Figure 2 MCMN Layout](image2)

The architecture and protocol stack for a node in MCMN is presented in figure 3 below. The two interfaces use the same upper layers – application, transport, and network. The network layer plays the role of interfacing between the lower layers and upper layers. The network layer is also responsible for the complex task of routing between the two different interfaces with consideration of mobility and connection management.

Every node in the network is equipped with dual interface as shown in figure 3. Any node in the network can become a gateway at any time depending on its geographical location, signal strength and proximity to both the BS and ad hoc nodes. GNs communicate using the two interfaces simultaneously as shown in figure 4. This is a more complex task because it integrates the two technologies and also deals with the routing problems. Every CC can have one or more GNs, but for this analysis and simplicity, it is assumed that every CC has one GN for relaying traffic.
Based on the node organization and grouping (next section), the BS develops a configuration table for all nodes in the network. The BS builds up a routing table and sends the routing information of every node in each CC to the GNs respectively; every node in the network is attached to GN for its CC. GNs keep and maintain the routing information, and share it among other GNs. In addition, each GN forwards the routing information of all nodes in its CC to every member of the cell. Using this information every node in the same CC can communicate with one another without necessarily passing through GN. To communicate with the nodes outside the CC or CM node, a node will have to transmit through the GN. Even though a node cannot communicate with nodes outside its CC, every node can receive ‘where do I belong’ (WDIB) message from other nodes. This message is meant for the BS and contains node parameters that will be used to compute its configuration; every node can receive and forward the WDIB message until it arrives at the destination which is the BS.

PERFORMANCE ANALYSIS

Two common network performance metrics are coverage and throughput. These have been extensively covered in literature for the cellular and ad hoc networks separately. Coverage is defined as the geographical area in which successful communication can be provided. For
MCMN, the coverage provided by the $k$th CC results in a cumulative effect on the total coverage of MCMN. Estimation for the overall coverage is given as:

$$\text{Cov}_{\text{MCMN}} = \text{Cov}_{\text{cellular}} + \sum_{k=1}^{K} \nu_k \text{Cov}_{N_{CC_k}}$$  \hspace{1cm} (1)

Where $\nu_k$ is a constant reflecting the border effect which is due to the fact that CCs are non-overlapping [4]. The Cov$_{\text{cellular}}$ is the cellular coverage, Cov$_{N_{CC_k}}$ is the coverage provided by $k$ CCs with $N_{CC_k}$ nodes in each CC. Throughput is defined as the aggregate amount of data that can be successfully transported in a network over time. The GN is assumed to be a super user and can have more time slots from the BS to accommodate demand. The BS monitors the demand on the GN and increases its time slots dynamically. The overall throughput for MCMN is given as:

$$S_{\text{MCMN}} = \begin{cases} S_{CM} + \sum_{k=1}^{K} S_{CC_k} (N_{CC_k}) & \text{if } S_{\text{Cell}_{\max}} \geq S_{GN} > S_{CC_k} \\ S_{CM} + \sum_{k=1}^{K} S_{GN_k} & \text{if } S_{\text{Cell}_{\max}} \geq S_{CC_k} > S_{GN} \end{cases}$$  \hspace{1cm} (2)

Where $S_{GN}$ is the throughput of a GN, $S_{CC_k}$ is the expected throughput in a CC with $N_{CC_k}$ nodes, $S_{CM}$ is the throughput of the cellular network. Details of these analyses are provided in [5].

NODES ORGANIZATION IN MCMN

The technique for grouping nodes in MCMN into CCs (CCs) for optimum performance is developed in this section. This grouping of nodes is the key to the overall performance of a MCMN network. A method is presented to intelligently form CCs, select nodes to be gateway nodes (GNs) for each of the CCs, and develop a scheme to evaluate the optimal number of CCs that will be required for the network partitioning. Nodes are presented as points in a 2-dimensional Euclidean space ($\mathbb{R}^2$) and information about nodes in this space is contained in their statistics. Clustering procedures use a criterion function, such as the Euclidean distance and sum of squared distances from the cluster centers, and seek the grouping that optimize the criterion function [6]. A 2-stage clustering scheme is used in MCMN to organize nodes in the network; this is shown in figure 5a and 5b.

The clustering is done by the BS after collecting the required information from nodes in the network. In this analysis, only distinct clusters are considered with each node in a CC having a GN to connect to the cellular nodes as well as nodes in other CCs. The use of clustering for organizing nodes in MCMN offers several advantages. It improves manageability, increases throughput, reduces overhead and minimizes network congestion among other advantages. Every node is assumed to have the knowledge of its geographical location. Every node transmits its $X$-$Y$ geographical location to the BS where centralized coordination and management of the network takes place.
To organize nodes in MCMN, two heterogeneous parameters are defined for every node – the radius and angle. Radius measures the distance of each node from the BS (Centre of network) while the angle measures the spatial location of each node. It has been assumed that the radius and angle are uniformly distributed. The radius $R_i$ and angle $\theta_i$ of node $i$ are given as:

$$R_i = \sqrt{X_i - X_0 + Y_i - Y_0} \quad (3)$$

$$\theta_i = \tan^{-1}\left(\frac{Y_i - Y_0}{X_i - X_0}\right) \quad (4)$$

Where $X_0 - Y_0$ represent the geographical location of BS which is assumed to be the center of the network. Using the heterogeneous parameters defined above, clustering parameter $CPar_i$ is computed for each node in the network.

$$CPar_i = [R_i, \theta_i] \quad 1 \leq i \leq N_{AHM} \quad (5)$$

Where $N_{AHM}$ is the total number of ad hoc nodes in the network. The clustering parameter, $CPar$, can include as many parameters as possible and has been limited to $R_i$ and $\theta_i$ for simplicity. The first stage involves using the location information and the path loss model of equation (6) and (7) to compute the SNR of every node from the BS. This is a function of the distance from the BS which is the radius given in equation (3) above. The SNR decreases as a function of $R^{-\phi}$ where $\phi$ is the path loss exponent. A threshold is set for the SNR and any node with SNR greater than the threshold is considered a CM node and those with SNR less than the
threshold are considered as AHM node. This procedure partitions the aggregate network into the two main components of MCMN: Cellular network and ad hoc network.

\[
P_r(d) = P_r(d_0) \left( \frac{d_0}{d} \right)^\gamma, \quad d \geq d_0
\]  

(6)

Where \( P_r(d_0) = \frac{P_G G_r \lambda^2}{(4\pi)^2 d_0^2 L} \) and the SNR, \( \eta \) in wireless communications is given as

\[
\eta = \frac{P_r}{L} \quad \text{or} \quad P_r = \eta L
\]  

(7)

Where \( P_r \) and \( P_t \) are the receive and transmit powers respectively. The \( G_r \) and \( G_t \) are receive and transmit antenna gains, and \( L \) is the path loss.

Given a partitioning of CCs, \( \{CC_k\}_{k=1}^K \), \( K \) being the total number of CCs to partition the network into, the centroid, \( \mu_k \), for each CC is defined as:

\[
\mu_k = \left[ \mu_{R,k}, \mu_{L,k} \right]
\]  

(8)

The clustering problem is defined as

\[
CC_k = \arg \min \left( \sum_{\text{CPar} \in \text{CC}_k} D(\text{CPar}, \mu_k) \right)
\]  

(9)

Where CPar is the clustering parameter, \( CC_k \) is the \( k^{th} \) cluster cell, and \( \mu_k \) is the centroid for cluster cell \( k \).

**NUMERICAL ANALYSIS AND RESULTS**

This section presents some numerical analyses and experiments using MATLAB program. A MATLAB visualization program is developed to view the node organization. In addition, analysis is presented for gateway location and trade-off in the cellular boundary when the ad hoc component is dependent on the cellular component. A total of 400 nodes are randomly placed in a circular region with the BS located at the center of this network. The first task is to classify the aggregate network into either CM nodes or AHM nodes. Figure 6 shows the randomly placed nodes in a given area. Figure 7 shows the partitioned network after applying the threshold for SNR. It is seen that the whole network is separated into CM nodes and AHM nodes.

A validity measure is developed to obtain an estimation for the optimal number of CCs, \( K \), that the ad hoc nodes are divided into. This is given as:

\[
\text{Validity measure} = \arg \min \left( \frac{\text{wicler}}{\text{excler}} \right)
\]  

(10)

Where wicler is the ‘within cluster error’, it measures the average of all distances between a node and the centroid of its CC, and it can be used to determine whether the CC is compact or not. The external error, excler, measures the relationship between the CCs that make up a given partitioning and is computed as the minimum distance between the centroids in partitioning. The
goal is to minimize the validity measure, the values of validity measure for each $K$ is plotted and the partitioning with the minimum value of validity measure gives the optimum partitioning. The value of $K$ for this partitioning is the optimum number of CCs to partition the AHM nodes. The result is shown in figure 8 and for the network scenario considered in this analysis, the value of validity measure is minimum at $K = 5$.

To effectively choose GNs in MCMN, similar parameters used in partitioning the network must be considered in selecting appropriate GNs. The BS, in addition to performing the clustering, computes the GNs selection metric, $ngmetric$, for all active nodes in a CC. This is given as:

$$ ngmetric_j = \frac{w^* SNR_j}{N_{CC_k} \sum_{i=1}^{N_{CC_k}} D(node_i, node_j) + D(node_i, BS)} $$

where $D(node_i, node_j)$ is the distance between node $i$ and node $j$ in the same CC, and $D(node_i, BS)$ is the distance between node $i$ and the BS. In addition to the distances, the signal-to-noise ratio, SNR, of nodes in the CC with reference to one another is computed. Figure 9 represents the complete MCMN system with every node knowing the CCs they belong to in the network and their GN ID. Using this organized network, the BS has detailed information about all the nodes in the network.

The minimum network rate, $R_{\text{min}}$, is computed as the minimum rate of cellular nodes, gateway node, and ad hoc node. This is represented as

$$ R_{\text{min}} = \arg \min (R_{CM}, R_{GM}, R_{AHM}) $$

Where $R_{CM}$, $R_{GM}$, $R_{AHM}$ are the rates for cellular mode, gateway mode, and ad hoc mode. And finally, the maximum of the minimum rate is used to define the boundary for cellular and ad hoc mode.
network in MCMN. This represents the optimal location for the GNs and also the optimal boundary for cellular and ad hoc networks. This analysis has taken into consideration the dependency of the ad hoc network on the capacity of cellular network.

Figure 8 Optimal Number of Cluster to Partition MCMN

Figure 9 Gateway Nodes for CCs

Figure 10 shows the trade-off between rates and distance from base station for the different components of MCMN. The figure also shows the cellular and gateway throughput decreasing as the distance from the BS increases until the optimum point is reached and continues to decrease at the minimum rate. But because the network is well organized, the cellular node changes into ad hoc mode and its throughput begins to rise.

Figure 10 Trade-off for Boundary and Gateway Location
CONCLUSIONS AND FUTURE WORK

A solution to the problem of coverage of nodes using a mixed cellular and ad hoc network has been presented. It has been shown that when combining the features of traditional infrastructure-based cellular networks with that of ad hoc networks an improved mixed network can be formed. We have designed a novel architecture for our proposed MCMN. We presented both theoretical and numerical analysis to evaluate the performance improvement that MCMN can provide to a network. It has been shown that coverage can be extended beyond the limitation of a cellular base station. It has also been shown that throughput can be enhanced while extending the network coverage. A solution to the problem of organizing nodes in MCMN has been presented through a 2-stage clustering scheme. The modified K-means scheme incorporates the non-homogeneity of network nodes into the network partitioning. A solution for choosing the optimum number of CCs to partition the ad hoc nodes into was developed. A scheme for selecting gateway nodes to relay traffic from one cluster to another was developed. And finally, the trade-off analysis in selecting the GN location and cellular boundary has been presented. The solution easily adapts to iNET system by incorporating iNET chosen technologies to operate in multihop and single hop to form the MCMN. This will enhance throughput and extend coverage to OTH TAs in iNET. Finally, it is important to acknowledge the support provided by NAVAIR without which this work could not have happened.

REFERENCES