MOBILITY AND POWER AWARE DATA INTEREST BASED DATA REPLICATION FOR MOBILE AD HOC NETWORKS

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ABSTRACT

MOBILITY AND POWER AWARE DATA INTEREST BASED DATA REPLICATION FOR MOBILE AD HOC NETWORKS

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One of the challenging issues for mobile ad hoc network (MANET) applications is data replication. Unreliable wireless communication, mobility of network participators and limited resource capacities of mobile devices make conventional replication techniques useless for MANETs. Frequent network divisions and unexpected disconnections should be handled. In this thesis work, a novel mobility and power aware, data interest based data replication strategy is presented. Main objective is to improve data accessibility among a mission critical mobility group. A clustering approach depending on mobility and data interest patterns similarities is introduced. The investigated replica allocation methodology takes care of data access frequency and data correlation values together with mobile nodes' remaining energy and memory capacities. Performance of the proposed approach is analyzed in terms of data accessibility; cache hit ratio and traffic metrics. Improvements are observed by data interest based clustering in addition to mobility awareness over sole mobility aware clustering. Advantages of power aware replica allocation are demonstrated by experimental simulations.

Keywords: Mobile Ad Hoc Network, Data Replication, Data Accessibility, Power Aware, Data Interest Based

ÖZ

GEZGİN TASARSIZ AĞLARDA HAREKETLİLİK VE GÜÇ BİLİNÇLİ VERİ İLGİSİ TABANLI VERİ YEDEKLEME

ARSLAN, Seçil
Yüksek Lisans, Bilgisayar Mühendisliği Bölümü
Tez Danışmanı: Prof. Dr. Müslim BOZYİĞİT

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Veri yedeklemesi gezgin tasarsız ağ (GTA) uygulamalarındaki zorlayıcı konulardan biridir. Güvenilir olmayan kablosuz iletişim, gezgin araçların sınırlı kaynak kapasiteleri geleneksel veri yedekleme tekniklerini GTA için geçersiz kılmaktadır. Sık ağ bölünmeleri ve beklenmedik ayrılmaların ele alınması gerekmektedir. Bu tez çalışmasında, hareketlilik ve güç bilinçli, veri ilgisi tabanlı yeni bir veri yedekleme yaklaşımı sunulmaktadır. Esas amaç, görev kritik yapıda oluşturulmuş gezgin grup üyeleri için veri erişilebilirliğinde iyileştirme sağlamaktır. Düğümlerin hareketlilik ve veri ilgi yaklaşımlarındaki benzerliklerine dayandırılan gruplama mantığı kullanılmıştır. Bunun yanı sıra, veri erişim sıklığı ve veriler arası ilişki bilgileriyle birlikte gezgin düğümlerin kalan enerjileri ve kalan hafıza kapasiteleri göz önünde bulundurularak yapılan bir yedek yerleştirim yöntemi incelenmiştir. Önerilen veri yedekleme yaklaşımının başarım analizi; veri erişilebilirlik, önbellek erişim oranı ve trafik ölçümlerine göre gerçekleştirilmiştir. Sadece hareketlilik bilinçli gruplama yöntemine kıyasla ek olarak veri ilgisi tabanlı gruplamanın getirdiği iyileştirmeler gözlenmiştir. Güç bilinçli yedek yerleştirme yönteminin yararları deneysel benzetimlerle gösterilmiştir.

Anahtar Kelimeler: Gezgin Tasarsız Ağlar, Veri Yedeklemesi, Veri Erişilebilirliği, Güç Bilinçli, Veri İlgisi Tabanlı

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LIST OF ABBREVIATIONS

AM	Actual Motion
C-DAFN	Correlated - Dynamic Access Frequency and Neighborhood
C-DCG	Correlated - Dynamic Connectivity based Grouping
C-SAF	Correlated – Static Access Frequency
DAFN	Dynamic Access Frequency and Neighborhood
DAG	Directed Acyclic Graph
DCG	Dynamic Connectivity based Grouping
DIT	Data Interest Threshold
DPL	Data Priority List
DRV	Data Replication Value
ECR	Exponential Correlated Random
GM	Global Motion
GOP	Global Optimal
LOP	Local Optimal
MANET	Mobile Ad Hoc Network
MoPoAwDIB-DR	Mobility&Power Aware Data Interest Based Data Replication
NAM	Network Animator
NS	Network Simulator
PR	Priority Value
RM	Random Motion
RPGM	Reference Point Group Mobility
SAF	Static Access Frequency
SOP	Stable Optimal
TDS	Time and Distance Sensitive

CHAPTER 1

INTRODUCTION

1.1 Background

Evolution of wireless communication has led to an increasing popularity in mobile networks. Unlike traditional, fixed stationary networks; there is an unstructured organization of network participators. This networking is named as mobile ad hoc network (MANET) [35]. MANETs are composed of small and portable but capacity limited mobile devices (nodes). MANET applications are widely used in many areas such as crop monitoring, disaster management, rescue operations and various military applications [5, 6, 7, 9].

MANET specific issues involve environmental factors, mobility and mobile device related factors. First of all, wireless environment makes communication unreliable and provides low data transmission rates due to low bandwidth. Secondly, as nodes are mobile, frequent disconnections are unavoidable. Ad hoc networking cannot guarantee predefined infrastructure so it is impossible to prevent abrupt topology changes and network divisions. Lastly, mobile devices that have energy, memory and processing capacity limitations also trigger unexpected disconnections and topology changes. Applications for MANETs and traditional networks are alike but these environment, mobility and mobile device based issues makes them different for MANETs.

One of the most common issues is sharing the data within a network. In this study, we focus on improving data availability for MANETs using wireless communication. As data is owned by some mobile nodes but should be shared by other mobile nodes, it is crucial to make data items accessible as long as possible. As mentioned before, mobility of nodes cause frequent network partitioning and disconnection. In addition, capacity constrained mobile devices are very likely to result in unexpected failures. Therefore, improving data availability requires special considerations for MANETs.

Initial research suggests caching of data for increased accessibility. Cache management, cache invalidations and cache coherency problems are widely investigated for MANETs [25, 26, 27, 28, 29]. Furthermore, many studies are interested in data management for MANETs especially handling disconnections [30, 31, 32, 33, 34]. Some of these studies keep data in distributed file systems constructed upon MANETs [33, 34]. They [33, 34] aim to solve disconnection based file system management problems.

Dissemination of information is achieved by caching accessed data at local nodes. However, since mobile devices have memory constraints, caching every data item locally is not possible. Hence, data replication is observed to be a much more effective approach in order to enhance data availability. Data replication alleviates capacity problems. Namely, not every accessed data item can be cached; instead a collaborative scheme is adopted to replicate data items on caches [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 36, 37, 38]. Data replication approaches in the literature can be grouped with respect to communication methodologies. A group of studies depend on client-server model [1, 2, 7] whereas others are developed for peer-to-peer communication model [3, 4, 5, 6, 8, 9, 10].

1.2 Scope and Objectives

In this study, a *Mo*bility and *Po*wer *Aw*are *D*ata *I*nterest *B*ased *D*ata *R*eplication (MoPoAwDIB-DR) strategy is developed for MANETs communicating via wireless links. Our motivation is group based data sharing, especially in mission critical application domains. Mobile nodes that come together to complete a mission, are grouped for completing sub-parts of the overall mission. Mobile nodes that are grouped by sub-missions move together and have similar data interest patterns.

Main objective of this study is to suggest a data replication strategy for MANETs that improves data accessibility. We define a collaborative approach which is supported by clustering mobile nodes with respect to their historical mobility and data interest pattern similarities. In addition, every mobile node is weighted as a combination of remaining energy and memory capacities together with data access frequency and data correlation values to detect the most suitable replica holder.

1.3 Contributions

Main contribution of the study lies in clustering of mobile nodes depending on not only mobility pattern similarity but also data interest pattern similarity. Data interest similarity approach is not applied by any of the previous works in the literature. As our problem domain states, mission critical group members are likely to be interested in similar data items. Therefore different mobility groups moving closer for a period of time are not distinguished by sole mobility aware clustering. However, our approach is able to estimate possible disconnections since mobile nodes are members of different sub-mission groups based on their interests.

Another contribution we have made on replica allocation is that data items are replicated on mobile nodes in regard to choosing the replica holder that has enough energy and memory in addition to access frequency and correlation parameters. Thus, weak candidates are not able to hold the most frequently accessed data items, thus unexpected failures are prevented.

1.4 Document Organization

This thesis work includes 5 chapters. Chapter 2 is about the state-of-art on data management of MANET applications. The studies that we have been motivated from are described in details in this chapter. Chapter 3 defines the data replication strategy (MoPoAwDIB-DR) suggested by this thesis work. First, the problem domain and approach are defined and explained in details including sample execution scenarios. Then the simulation environment (ns-2) we have used for implementing the proposed strategy and the performance metrics accepted to evaluate our approach are introduced. Chapter 4 evaluates our approach in terms of the performance metrics defined. It involves graphical results of the simulation runs for our model in comparison with other models. Chapter 5 concludes the thesis work and states future work.

CHAPTER 2

RELATED WORKS

2.1 Leader Election Strategies

Leader election is one of the mostly studied issues for both wired and wireless networks. Defining one of the nodes as a leader is crucial in cases that a global control or management is required. In addition to leader election in static networks, there are also several algorithms developed for mobile and wireless networks [16, 17, 18, 19, 20, 21]. Conventional leader election algorithms aim to form a single spanning tree from neighborhoods and select the root of the tree as leader node.

Leader election algorithms for mobile and wireless networks are classified into two categories. Similar categorization is also valid for conventional approaches. It is possible to divide algorithms as extrema-finding and non-extrema-finding algorithms.

Extrema-finding algorithms [17, 19, 21] aim to maximize or minimize a weight value dedicated to each node. Lowest-ID, Highest-ID methodologies are well-known extrema-finding leader election algorithms. Some approaches maximize leader stability by considering mobile devices' resource limitations. [17, 19, 21] propose much more sophisticated leader election algorithms which have higher messaging overheads. Non-extrema-finding algorithms [18] select leader depending on connection states. This class of algorithms forms directed acyclic graphs (DAG) so that each graph is a component in the network. This strategy resembles conventional spanning tree approaches in the sense that graph formation is applied, but differs in the way that component disconnections and merges are handled.

Leader election algorithm adopted in this thesis work is explained in section 2.4.

2.2 Mobility Models

Wireless communication among network participators has brought up freedom in positioning of users. Mobility of users has become a crucial aspect in wireless networks since it affects all application scenarios and makes conventional approaches inapplicable. Quality of the communication is severely affected by mobility of nodes in the MANETs [11, 12, 13, 14]. Initial mobility models are related to individual motion patterns of nodes [11]. However, as the term of mobile ad hoc network has developed, mobility modeling of groups of mobile nodes appeared [11, 12, 13, 14]. Mobility models have the goal of imitating movements of mobile nodes as in real world cases. Mobility models are divided into two categories such as entity mobility models and group mobility models. Following sections describe these two categories of mobility models.

2.2.1 Entity Mobility Models

Entity mobility models deals with movements of mobile nodes that do not depend on each other [11]. Random Walk Mobility Model mimics movements of nodes whose movements cannot be estimated. Mobile nodes change position from one point to another in random directions and speeds. Each change is triggered at specific time periods [11, 13]. Similar to Random Walk, in Random Waypoint Model, mobile nodes choose random directions and speeds but they pause for a period of time at the new location. Thus, movements of mobile nodes consist of motion and pause periods [13, 15, 16] which is much more realistic than Random Walk Model. Random Waypoint Mobility Model results in node density at the center of movement area. In order to overcome this situation, mobile nodes are not allowed to change direction and speed until they reach the borders of movement area [11, 13]. That model is called Random Direction Mobility Model. There are also other variations of this models that differ in determining randomness level and change periods. Boundless Simulation Area Mobility Model, Gauss-Markov Mobility Model and Probabilistic Version of Random Walk Model are some examples of the variations [11]. Among independent mobility models Random Waypoint Model is the most popular and widely used one since it gives the closest patterns of real world mobile users.

2.2.2 Group Mobility Models

Mobile network applications, especially MANETs, are based on cooperation of a number of mobile nodes. Cooperative applications bring movement patterns of mobile nodes that are dependent on each other [11, 12, 13, 14]. Thus, mobile nodes tend to move in groups for cooperation purposes. A novel category in mobility models is formed for groups of mobile nodes, named as group mobility models.

There are five types of group mobility models. These are;

- Exponential Correlated Random Mobility Model
- Column Mobility Model
- Nomadic Community Mobility Model
- Pursue Mobility Model
- Reference Point Group Mobility Model

Exponential Correlated Random (ECR) Mobility Model is the first suggested group mobility model in the literature as stated in [12]. ECR uses a functional relation to produce next movement steps of mobile nodes. Mobile nodes' next positions in time depend on their current positions. Change rate of position and motion divergence are controlled by parametric values in the functional relation. However, Exponential Correlated Random Mobility Model is not able to produce expected group movement by only adjusting these parametric values [11, 12].

Remaining four models are variations of Reference Point Group Mobility (RPGM) Model. RPGM model is proposed and explained in [12]. According to RPGM, mobile nodes move in groups in the movement area. Each group's movement pattern is directed by a manager mobile node. This manager node is the reference point for all other group members. Movement of group members is defined by direction and speed of the reference point. In addition to obeying mobility pattern of the group, mobile nodes move randomly in the circular area centered at reference point with a radius of ε. Motion of the reference point is represented by the Global Motion Vector ($\overrightarrow{GM}$). Member nodes' motion vectors are called as Random Motion Vector

($\overrightarrow{RM}$). $\overrightarrow{RM}$ is limited with respect to $\overrightarrow{GM}$ in that resultant position of the member node should be in the circular area centered at reference point. Moreover, direction of the random motion vector should be in [0, 2π] range [12]. Details of RPGM mobility pattern is given in section 2.3.2.2 since mobility aware clustering approach highly depends on RPGM model.

In Column Mobility Model, mobile nodes of the same group move on a straight line. Therefore column mobility model is a special case of RPGM in that reference point's motion forms a straight line. Nomadic Community Mobility Model sets group members free in movement direction. Reference point determines the time and direction of the next motion but does not limit the movement area. Member nodes reach the position of the reference node but are able to roam around that point [11]. Pursue Mobility Model is like RPGM in that a reference point exists but differs in that mobile nodes and reference point do not move at the same time. Instead as the name implies a target is followed by group members. Thus direction and speed of group members is controlled by the target node [11].

Group mobility model adopted in this thesis work is explained in section 2.4.

2.3 Data Replication Models

Improvements in mobile networking environments have brought up several issues related to communicating sides. There are common aspects between mobile wireless networking and conventional wired networks. One of those issues is sharing of the information that is distributed over different parts of the network. As data is shared and required by multiple users of a MANET, data availability also becomes a consideration point. Solution for increased data availability is replication of shared data on different participators of the overall network. Data replication is then the key for enhanced data access performance.

Data replication in MANETs has evolved in different environmental and architectural scenarios. First of all, cache management strategies for a MANET are investigated. Studies on replicating data in MANETs are derived from the cache management strategies. Thus, this section includes related works on both caching mechanisms that have direct influence on existing data replication models and data replication mechanisms offered so far.

Data replication studies on MANETs differ in terms of underlying architectural design. The existing works are related to either client-server or peer-to-peer communication. This study adopts peer-to-peer interaction of mobile nodes via wireless communication.

2.3.1 Client-Server Based Models

Mobile nodes that are in the communication range of each other are evaluated as partners and many data replication strategies take the advantage of this availability in case of both caching and data replication. In other words, resource limitations such as low memory capacity of mobile nodes are enhanced via forming a composite resource pool.

In [1], a cooperative caching strategy for push-based information systems is stated. System environment is mentioned to be a single server and multiple client system where client nodes institute a MANET. A typical shopping center case is applicable for this strategy. Users are able to access broadcasted advertisements of stores as they walk around. This study emphasizes the importance of response time for each data access request. Unlike our target environment, the system assumes an ever existing data provider server, thus there is no data availability problem. Since data is always accessible, data access latency is mentioned as the performance metric. This work establishes the improvement by cooperation of mobile nodes. The study suggests three caching strategies LOP (Local OPtimal strategy), GOP (Global OPtimal strategy) and SOP (Stable OPtimal strategy). Suggested cache replacement methodology is mentioned to obtain shortest average response time. Therefore, mobile nodes are grouped into sets and cache replacement is applied on cache resources of all set members. LOP consists of a single mobile node, where as GOP includes all connected mobile nodes in a single set. Due to the disconnection possibility of mobile nodes, SOP groups mobile nodes as biconnected components and thus more stable grouping is achieved. A Priority Value (PR) is assigned for each data item to determine the cache replacement policy. This study uses a combination of access frequency, remaining time for next data broadcast period and network topology changes in order to find this PR value. Similar to our approach, access frequency and network topology factors are considered together with cooperation of mobile nodes. However, data accessibility is not an issue.

Mission critical groups working on push/pull mobile environments have been mentioned in [2]. Authors apply profile based caching techniques for enhanced data availability. One of the mobile nodes is defined as server. Mobile server node is responsible for extracting group data interests and push related data to corresponding groups. Moreover, mobile clients run a cache replacement policy depending on a utility value parameter. Utility value for each broadcasted data item is calculated as a weighted combination of size of the data item, access count, and profile utility factors. Profile utility factor is mentioned to be a server determined parameter for each data item, but there is no much detail on obtaining that parameter. User profile includes both automatically generated and user provided information on access frequency of data items. The profiles for each user are inputs for extracting group interest function of the server node. Then, interested data items are pushed to related group members. Compared to [1], there is no cooperation in [2], so this system cannot prevent data duplications. However, it is one of the crucial studies in the literature in the way that it considers profile based data caching. Having mentioned mission critical applications of mobility groups, authors assume that mobility groups are known by the server mobile node. Therefore, different from our approach, this approach lacks node mobility extraction and does not take precaution for possible node disconnections due to mobility.

A recent study on information dissemination in dense MANETs is proposed by [7]. An environment specific middleware is implemented. This middleware (REDMAN) is capable of ensuring replica management. System model is based on data resources providing information to mobile users located in a wide area. Basically, replica degree manager module of the middleware finds a mobile node located near the center of the MANET and allocates the required replica at that node. In addition, one further improvement is supplied by keeping replica holder information at intermediate nodes. Hence, access latency is reduced and usage of limited resource capabilities of mobile nodes is optimized. This work has a novel contribution in that it does not solely replicate data but also holder information. This methodology is valid and appropriate for densely located MANETs where server-client architecture is applied. In case of our mission critical networking scenario mobile nodes are separately located, thus the idea of keeping replica holder would not work when mobility groups become apart.

2.3.2 Peer-to-Peer Based Models

Studies on client-server based models are developed for decreasing data access latency since a data broadcasting server is assumed to be always available. Conversely, in peer-to-peer based models data is held by different mobile nodes. As data is not guaranteed to be always available, improving data availability is much more important.

Chen and Nahrstedt ([3]) state a data lookup and replication scheme. A proactive data replication strategy is proposed so that partitioning is estimated and data is replicated accordingly. Location and movement direction of mobile nodes are used to find mobile nodes that will become out of communication range of each other. Future locations of mobile nodes are calculated from movement direction and speed values. Thus, this work mentions a predictive data replication scheme. Network disconnections are predetermined. The study does not consider movement patterns of mobile nodes. Hence, data replication scheme in [3] is not applicable for mission critical mobility groups moving around a specified region.

Most of the studies on peer-to-peer based approaches declare cooperation of mobile nodes. Therefore, there are various works considering data caching for peer-to-peer mobile ad hoc networking. Aggregate cache management is achieved in [4] by using number of hops to access a requested data item. A system parameter Γ demonstrates the hop count limit for deciding to cache the accessed item or not. If data is far from the requester more than Γ hops, then data is cached. Cooperation is applied in the way that neighboring nodes' data availability is checked on hop count. In addition, after deciding to cache the data item, each mobile node performs a cache replacement policy called Time and Distance Sensitive (TDS). TDS includes two main factors. First is the distance factor (δ) representing the number of hops for the requested data item. Another factor is time factor (τ). τ indicates how fresh the value of distance factor is. The work suggests three schemes for cache replacement policy; TDS_D, TDS_T, and TDS_N. Those schemes help in finding the candidate to remove from cache in order to replicate a new data item. Data items having the least ($\delta + \tau$), τ and (δ x τ) values are chosen to be replaced for TDS_D, TDS_T and TDS_N schemes respectively. Even though the study puts forward cooperation of mobile nodes, the problem of unexpected disconnections remains. Authors state rapid topology changes in MANETs and they account for time factor (τ) as a topology change indicator. Thus, the study does not behave in a proactive way in terms of data replication.

Another work on cooperation based caching is also presented in [5]. Three approaches for data caching are recommended called CachePath, CacheData and HybridCache. Primary goal of CachePath is to keep access path of data items at intermediate nodes. A mobile node keeps data path when it is more close to the node holding the replica rather than the source node. Hence, mobile nodes are said to collaboratively share and find required data quickly. Secondly, CacheData forces a node that takes data access requests for the same data item but from different nodes to cache that data in its own cache. CachePath is mentioned to give better results when data items have large size so that it is impractical to cache them. However, CacheData is considered more successful when data items are of small size. Consequently this approach introduces a combination of two methodologies named as HybridCache. In HybridCache data size and data hop count thresholds are used to switch between CachePath and CacheData strategies. The study demonstrates experimental results for both of three caching strategies. It is shown that HybridCache outperforms other methods in terms of access latency. Likewise other caching methods in MANETs ([1], [2], [4]), this study stresses data access latency improvement rather than increasing data availability.

Explorations for data accessibility in MANETs are strongly dependent on the devices used. As mobile devices are poor of resources such as energy, memory and processing capacities, solutions regarding device conditions are appreciated. Boulkenafed and Issarny ([6]) come up with a new middleware that has the purpose of enhancing data availability. The notion of collaborative mobile ad hoc groups sits in the center of their research. This work differs from previous studies in the sense that profile information is the main input for data management. Each mobile node keeps track of its own profile. Peers profiles are described as a combination of available energy, expected time within the group, and available storage capacity. Every mobile node within the same group is aware of other nodes' profiles. Peers are categorized with respect to their profiles as *optimal*, *acceptable* and *weak*. Data management module of the middleware has the responsibility of replicating data on stronger peers derived from profiles. When a mobile node decides that it has a weak profile, then it triggers a data replication procedure for creating Preventive Replicas on stronger peers. Stronger peers are the ones having optimal or acceptable profiles. The study focuses on the effects of profile information for enhancing data availability in collaborative mobility groups. The work accepts predetermined collaborative groups and therefore dynamic formation of mobility groups is out of scope of the study. This work also mentions disconnections and aims to guess these disconnections from expected time within the group. However there is not an automatic middleware driven methodology to estimate that expected time, instead this information is assumed to be provided by the user itself. In this respect, our approach is similar to [6] in the way that it uses profile information but is different from [6] in that our approach derives both device and user profiles from user logs and has the capability of dynamic mobility group formation.

[3], [4], [5] and [6] are all peer-to-peer based data replication models offered for MANETs. However these studies lack main considerations of our work. First of all, target problem domain of our thesis work depends on correlation of a set of data items. In other words, access relation of data items is extracted and a much more optimal replication is achieved by using data correlations. Secondly, proposed approach gains its strength from dynamic group formation prior to data replication. There are some studies that consider data correlation and group mobility constraints. Following parts give details about these studies in the literature. These studies are categorized into two. First of all, the studies that point out data correlation, data access frequency are mentioned [8, 9]. Secondly, studies that group mobile nodes dynamically according to mobility patterns are explored in [10]. Our work is motivated from the studies of Hara [8], [9] and Huang [10]. As methodologies and algorithms are based on those in [8, 9] and [10], they are described in details.

2.3.2.1 Data Correlation Awareness

T. Hara first deals with improving data accessibility in MANETs [8]. The studies conducted by [8], [9] are similar to [1], [5], [7] in that they also bring about the effects and advantages of mobile host collaboration in data replication. Main purpose of these studies is to increase data availability instead of access latency. For instance, Figure 1 demonstrates a possible network topology scenario where a network partitioning occurs. In case of a division, data items existing on disconnected parts of the network become inaccessible. Therefore, it is important to determine the data items to be replicated before the division. Network connectivity status is evaluated for estimating possible disconnections and determining data items that need to be replicated. In addition, data access frequency of each data item is used as a factor to find where to replicate them. Three replica allocation methodologies are suggested in [8]. Those methods are extended in [9] with data correlation included.

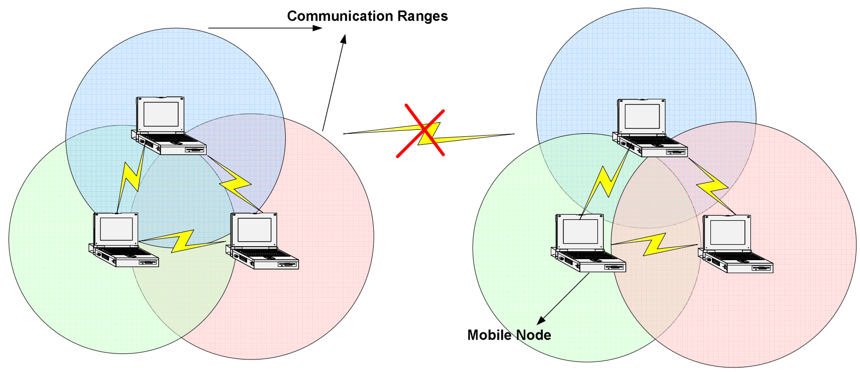


Figure 1 – Network Topology Status

A System Model Suggested by Hara [8, 9]:

A system model of an ad hoc network of mobile hosts communicating wirelessly is described in both [8] and [9]. Each mobile host keeps one data item as the original accessed by others. Some of the assumptions in [8] are as follows:

- Mobile nodes have limited memory size so they cannot cache or replicate every data item.
- Data items are read-only and not updated even by owner of the item.
- Mobile hosts have static access frequencies for each data item and the frequencies remain the same.

As network topology changes frequently, finding an optimal replica allocation is costly, a heuristic approach is applied in [8], [9], based on the following rules:

- Data items are replicated at predetermined periods called *relocation period*s.
- Data items are replicated on mobile hosts according to the access frequencies of mobile nodes and snapshot of the network topology at the relocation period.

Replica Allocation Strategies:

Hara presents three approaches that differ in the level of collaboration [8];

- *SAF (Static Access Frequency):* At replica allocation periods, every mobile host performs its own replica allocation strategy. Mobile hosts allocate replicas of the data items in access frequency order. Namely, most frequently accessed items are allocated until local cache is full. Extra message exchanges are not required since each mobile host is responsible of own cache management only. Although this strategy has no communication overhead, it results in many replica duplications. Mobile hosts having similar access patterns replicate the same data items even if they are within the communication range of each other. Network topology changes are not taken into account.

- *DAFN (Dynamic Access Frequency and Neighborhood):* This method is a further improvement in terms of collaboration level compared to SAF method. Mobile hosts notify each other about their access frequencies for data items, in the beginning of the relocation period. Then every mobile host applies SAF method initially. Furthermore, in order to eliminate replica duplication, mobile hosts reevaluate data item replications in breadth first order beginning from the lowest id. If a mobile host detects that the same data item is also replicated by a neighboring mobile host having higher access frequency, then that mobile host replicates another data item. DAFN has much more message overhead than SAF method, since data access frequency information is disseminated. However, DAFN method is verified to result in higher data accessibility rates compared to SAF method.

- *DCG (Dynamic Connectivity based Grouping):* DCG strategy extends collaboration level to overall network topology. Mobile hosts are grouped into sets that have lower disconnection possibility. Replica allocation is performed on the cumulative cache of strongly connected groups. At relocation period, a leader node is elected and this leader node has the responsibility of grouping nodes as *biconnected components*. Biconnected components of the network are not disconnected even if one of the mobile hosts leaves the network. When grouping is completed, access frequency of data items for each group is calculated as summation of all access frequencies of mobile hosts belonging to the group. Data item replicas are allocated with respect to the total access frequency values. Data item to be replicated in the group is allocated at the mobile host which has the highest access frequency. Whenever cache of a mobile host is full, data is replicated on another candidate. Candidates are ordered by access frequencies. Data access frequency and replica allocation cause more messaging overheads, and thus DCG has the highest overhead among the other two methods. On the contrary, DCG reaches the best data accessibility rate because it performs replica allocation for the overall biconnected component group.

Hara's next study [9] differs from [8] in that replicas are allocated according to not only access frequencies but also data correlation values. It has been accepted that data items do not stand alone and there exists a correlation between data items. For instance, in case of a rescue situation both pictures and text information about disaster area are required. Therefore those data are strongly correlated and the probability of accessing related data items sequentially is high. Hence [9] aims to guess possible data accesses due to correlation prior to access requests.

A further assumption over the ones in [8] is that correlation of two data items is known and does not change. Correlation value for data items *j* and *k* at mobile node M_i is represented as follows;

$$p_{i-jk} \qquad (i = 1 \ldots m,\ j,k = 1 \ldots n)$$

where m and n stand for total number of mobile nodes and data items respectively. Data correlation is the ratio of number of times data items j and k are accessed simultaneously to the total data access count at mobile node M_i.

This work ([9]) redefines replica allocation strategies of [8] with the help of a novel concept data priority. Each data item is given a data priority. Priorities of data items at a mobile node M_i are evaluated according to the following rules [9];

1. Data items are ordered in decreasing access frequency. From the first $\lfloor n / x \rfloor$ data items, two items having strongest correlation are selected.
2. Data item whose total correlation is highest with selected items is chosen next. All data items are chosen similarly.
3. In the end, original data items kept by mobile host M_i obtain highest priority. Other data items' priorities are in the same order as their selection order in rule 2.

Data replication strategies extended for considering data item correlations are as following [9];

- *C-SAF (Correlated – Static Access Frequency):* Each mobile node calculates data priority value of data items. Every node allocates replicas according to data priorities instead of access frequencies. As communication among neighboring nodes is not required for this method, the communication overhead is low. Nonetheless, similar to SAF method replica duplications are available if neighboring nodes have similar access patterns.

- *C-DAFN (Correlated – Dynamic Access Frequency Neighborhood):* At the beginning of the replica allocation period, mobile hosts send their access frequency information to other nodes. Thus, mobile hosts are aware of their connected nodes. Firstly, every mobile host determines the replicas to be allocated via C-SAF methodology. Then in order to eliminate replica duplications, mobile nodes start elimination process in breadth-first order from the node having lowest identifier. A node replaces a replica when neighboring node holds original copy of that data item. Moreover, if replica duplication exists, then the mobile host whose original data items have lower correlation with that data item removes that data item. A new data item is allocated from the data priority list. Depending on the initial messaging, the traffic overhead of C-DAFN is higher than C-SAF method. However, C-DAFN is able to eliminate replica duplications among neighboring nodes therefore total number of data items replicated is increased. As the number of replicated data items increases, overall data availability is improved.

- *C-DCG (Correlated – Dynamic Connectivity based Grouping): G*rouping strategy of mobile hosts in the overall network is the same as DCG method. Briefly, every mobile node broadcasts its data access frequencies. Each set of connected mobile nodes are controlled by a leader node. Mobile hosts are grouped as *biconnected components* by leader node. Replica allocation strategy is executed over all mobile nodes of a group. First of all, original data items within the group are sorted by decreasing total access frequencies. Total access frequency is the summation of all access frequencies of all mobile hosts of the group. Next, priorities of data items are evaluated for all group members. Data correlation of two data items D_j and D_k for a group G is calculated as following:

$$\sum_{M_i \in G} p_{i-jk} \tag{1}$$

Correlation value of two data items in a group is the summation of all data correlation values of all members. According to those data correlation values, priorities of data items are calculated in similar way as mentioned previously. After data priorities are determined, data item replicas are allocated in priority orders. Each data item is allocated at the mobile host whose original data items have the strongest correlation. This study proves that C-DCG method results in the highest data accessibility compared to the other methods because more data items are replicated all over the group. Moreover, it has been demonstrated that data correlation based replica allocation is more successful in reducing data misses. C-DCG method also applies information sharing of access frequencies across all connected hosts. This gives rise to higher traffic overhead than C-SAF and C-DAFN methods.

2.3.2.2 Group Mobility Awareness

DCG and C-DCG methods have the purpose of forming stable mobility groups so that mobile hosts involved in the group are not disconnected easily. Therefore replicating over all the mobile nodes in the group provides a larger cache capacity. Total cache capacity is used to replicate more number of data items. Consequently, data access requirements of mobile hosts are probably satisfied unless mobile hosts of the group are disconnected. Furthermore, C-DCG improves data accessibility by regarding data correlations. Its strength comes from improving data availability when a mobile host requests a data item and its correlated item is also accessible within the group. Hara argues that stable groups are formed by grouping mobile nodes as *biconnected components*. Biconnected components of a connected graph are not disconnected even if one of the nodes in the component disappears.

There are some other studies in the literature that stress on stability of groups. One study ([10]) is about the effect of group mobility on data replication in ad hoc networks. Although Hara aims to form stable groups in DCG methodologies, mobility patterns of mobile nodes are not considered. A static network topology based grouping is applied. Different from Hara's studies, the work ([10]) suggests an improvement in group stability by taking care of group mobility. Details of the approach in [10] are described in this section.

Mobility based System Model [10]:

Main idea of this study ([10]) is to explore mobile nodes' mobility in order to obtain large and stable groups, named as mobility groups. Group mobility exploration is based on Reference Point Group Mobility (RPGM) [13] model depending on the phenomenon that mobile nodes would like to move in similar way. As described in section 2.2, mobile nodes follow a reference node in RPGM. In addition this work ([10]) assumes that reference node and other mobile nodes follow waypoint mobility model [11]. Figure 2 demonstrates typical motion behavior in RPGM model. Light colored node represents reference node, whereas dark colored node is the mobile node M_i. Positions of mobile node M_i and its reference node at times T(k-1) and T(k) are shown.

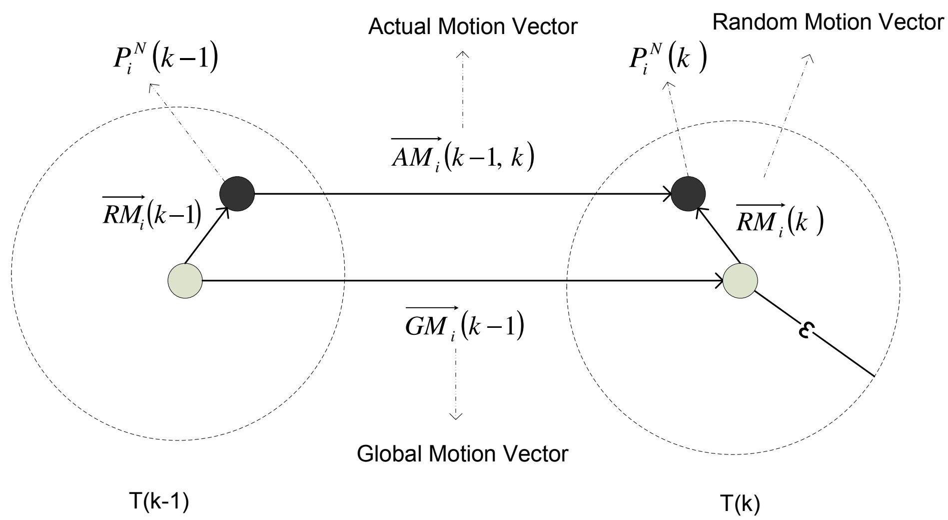


Figure 2 – RPGM Motion Behavior (Adopted from [10])

In addition due to waypoint mobility, mobile nodes are in either *pause* or *motion* period at a time. Each time slot is of length δ. Mobile nodes have varying speeds within [v_{min}, v_{max}] limits. Before explaining details of study [10], some preliminary concepts are described.

Global Motion Vector: Motion vector of the reference mobile node within a single time slot δ is called global motion vector and represented by $\overrightarrow{GM_i(k)}$ for time T(k). If positions of mobile node M_i and its reference node are $P_i^N(k)$ and $P_i^R(k)$ respectively, then

$$P_i^R(k+1) = P_i^R(k) + \overrightarrow{GM}_i(k) \tag{2}$$

and in motion periods

$$v_{\min} \times \delta \leq \left|\overrightarrow{GM}_i(k)\right| \leq v_{\max} \times \delta \tag{3}$$

hold.

Random Motion Vector: Vector pointing from position of the reference node to the position of the mobile node is random motion vector. In RPGM mobile nodes do not leave the circular movement area of the reference node as shown in Figure 2. ε stands for radius of the circle centered at reference node's position. Similar to equations 2 and 3 following equations hold;

$$P_i^N(k+1) = P_i^R(k+1) + \overrightarrow{RM}_i(k+1) \tag{4}$$

and

$$0 \leq \left|\overrightarrow{RM_i(k)}\right| \leq \varepsilon \tag{5}$$

Actual Motion Vector: Actual motion vector is the vector pointing from the position of a mobile node M_i at time T(x) to the position at time T(y) and is symbolized as $\overrightarrow{AM}_i(x, y)$. As each mobile node remains within the circular ε region during motion periods, following relations are ensured. Those relations are used in upcoming parts of the mobility based grouping.

$$\left|\overrightarrow{AM}_i(k-1, k)\right| \geq \left|\overrightarrow{GM}_i(k-1)\right| - 2\varepsilon \tag{6}$$

$$\left| \overrightarrow{AM_i}(k-1, k) \right| \leq \left| \overrightarrow{GM_i}(k-1) \right| + 2\varepsilon \quad \textbf{(7)}$$

Allocation Unit Construction in Mobile Environment [10]:

Most important phase of the proposed strategy is allocation unit construction. Mobile nodes are divided into allocation units so that data items are replicated over all nodes of the allocation unit. Allocation units are determined by the mobility patterns. This part explains allocation unit construction approach of [10]. Mobile nodes are assumed to obey Reference Point Group Mobility (RPGM) and waypoint motion models.

Accordingly, mobile nodes are grouped with respect to motion behavior similarities. A three step clustering strategy is applied. Clustering is based on mobility information of mobile nodes, thus each mobile node keeps a position list history. Position list is composed of information units keeping timestamp and position pairs. Only position changes are stored in the list. Namely, if node's latest position in the list equals to the current position then current position is discarded. Moreover, position list has limited size, thus when list size is exceeded, entry having smallest timestamp is deleted from the list and new entry is inserted. Position list is used for keeping mobility history of nodes. Clustering algorithm of [10] benefits from this position list.

This work puts forward a three step clustering algorithm which is based on group mobility. Firstly, due to RPGM mobile nodes are in either motion or pause period at a time slot. Mobile nodes that follow the same reference node are likely to have same pause and motion periods. As a result, mobile nodes are clustered by their pause and motion period similarities. However, as pause and motion periods are derived from position lists, limited list capacity together with long pause or motion periods may cause faulty groupings. Hence, after first step of pause and motion period clustering mobile nodes are clustered by their motion angle and length similarities with respect to reference node. The logic behind this clustering strategy is built on two lemmas.

These two lemmas and their proofs are described because our mobility aware clustering phase is also derived from the approach in [10].

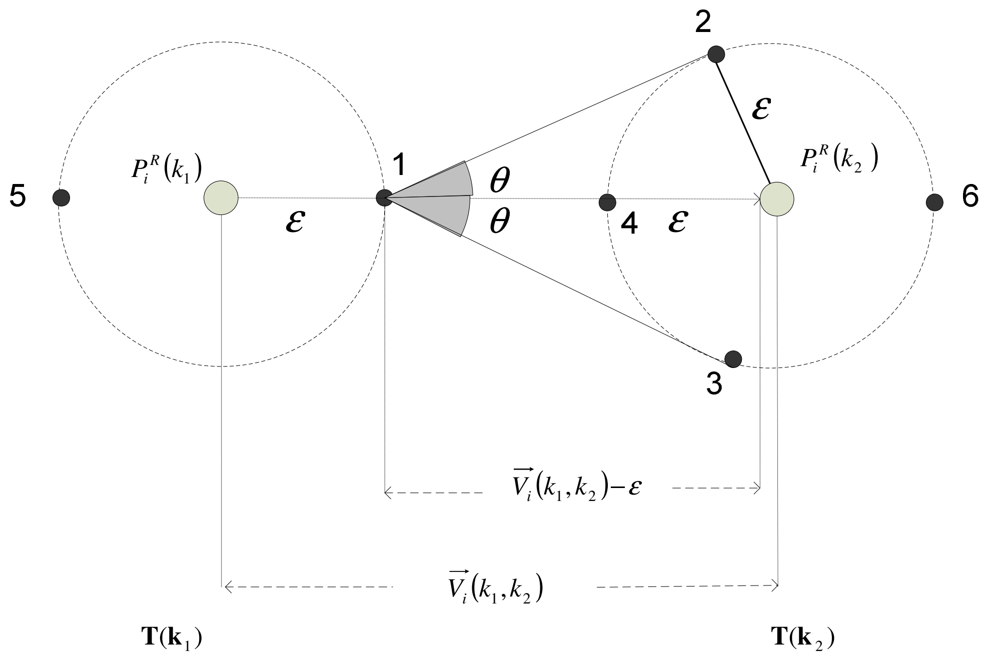


Figure 3 – Movement Scenarios for RPGM (Adopted from [10])

Lemma 1. Let $\vec{V_i}(k_1, k_2)$ be the global motion vector of M_i from time $T(k_1)$ to $T(k_2)$ keeping the relation

$$\vec{V_i}(k_1, k_2) = (k_2 - k_1) \times \overrightarrow{GM}_i(k_1) \tag{8}$$

This lemma states an angular limitation for mobile nodes and their reference nodes. The maximum angular difference between actual motion vector $\overrightarrow{AM}_i(k_1, k_2)$ of M_i and $\vec{V_i}(k_1, k_2)$ is declared as;

$$\theta = \left| \sin^{-1}\left(\frac{\varepsilon}{(\mathrm{k}_2 - \mathrm{k}_1) \times \mathrm{v}_{\min} \times \ \delta - \varepsilon} \right) \right| \tag{9}$$

$v_{\min}$, δ and ε represent minimum velocity of mobile nodes, time slot length and maximum random vector length respectively. Graphical demonstration of the relation is given in Figure 3.

Proof. According to the Figure 3, angle between actual motion vector and global motion vector of M_i is maximal when the mobile node moves from position 1 to position 2 or 3. Sinus of the maximum angle θ is

$$\sin(\theta) \leq \frac{\varepsilon}{\left|\overrightarrow{\mathrm{V_i}}(\mathrm{k_1}, \mathrm{k_2})\right| - \varepsilon} \qquad \textbf{(10)}$$

After substituting equation 8 in equation 10;

$$\sin(\theta) \leq \frac{\varepsilon}{(\mathrm{k_2} - \mathrm{k_1}) \times \left|\overrightarrow{\mathrm{GM_i}}(\mathrm{k_1})\right| - \varepsilon} \qquad \textbf{(11)}$$

In order to maximize right hand side of the equation, denominator is minimized by replacing global motion vector's length with its minimum value from equation 3. In the end, proposed relation of lemma 1 is obtained.

$$\sin(\theta) \leq \frac{\varepsilon}{(k_2 - k_1) \times v_{\min} \times \delta - \varepsilon} \qquad \textbf{(12)}$$

$$0 \leq \theta \leq \left| \sin^{-1}\left(\frac{\varepsilon}{(k_2 - k_1) \times v_{\min} \times \delta - \varepsilon}\right) \right| \qquad \textbf{(13)}$$

□

Lemma 2. This lemma asserts a length limitation for actual motion vector of the mobile node M_i and its reference node. The maximum length difference between actual motion vector $\overrightarrow{AM_i}(k_1, k_2)$ of M_i and $\overrightarrow{V_i}(k_1, k_2)$ is declared as 2ε.

Proof. Length of actual motion vector is maximal when mobile node M_i moves from position 5 to position 6 in Figure 3. By using equation 7,

$$\underbrace{\left|\overrightarrow{AM}_i(k_1,k_2)\right|}_{\left|\vec{V}_i(k_1,k_2)\right|+2\varepsilon} - \left|\vec{V}_i(k_1,k_2)\right| \le \left|\vec{V}_i(k_1,k_2)\right| + 2\varepsilon - \left|\vec{V}_i(k_1,k_2)\right| \qquad \textbf{(14)}$$

$$\left|\overrightarrow{AM}_i(k_1,k_2)\right| - \left|\vec{V}_i(k_1,k_2)\right| \le 2\varepsilon \qquad \textbf{(15)}$$

In addition, length of actual motion vector is minimal when mobile node M_i moves from position 1 to position 4. By using equation 6,

$$\underbrace{\left|\overrightarrow{AM}_i(k_1,k_2)\right|}_{\left|\vec{V}_i(k_1,k_2)\right|-2\varepsilon} - \left|\vec{V}_i(k_1,k_2)\right| \ge \left|\vec{V}_i(k_1,k_2)\right| - 2\varepsilon - \left|\vec{V}_i(k_1,k_2)\right| \qquad \textbf{(16)}$$

$$\left|\overrightarrow{AM}_i(k_1,k_2)\right| - \left|\vec{V}_i(k_1,k_2)\right| \ge -2\varepsilon \qquad \textbf{(17)}$$

Therefore, the following holds;

$$0 \le \left|\,\left|\overrightarrow{AM}_i(k_1,k_2)\right| - \left|\vec{V}_i(k_1,k_2)\right|\,\right| \le 2\varepsilon \qquad \textbf{(18)}$$

□

Two heuristics are developed to estimate motion vector of the reference node namely, global motion vector. This work states two heuristics as following;

> ***Heuristic 1:*** *In a mobility group, an actual motion vector is close to the global motion vector if it has the maximal number of neighbors in angle with maximal difference* θ.
>
> ***Heuristic 2:*** *In a mobility group, an actual motion vector is close to the global motion vector if it has the maximal number of neighbors in length with maximal difference* 2ε.

Mobile nodes are grouped in three steps. First step is already mentioned to be grouping by pause and motion period similarities. Secondly, mobile nodes are grouped by angular similarities. Value of the maximum difference angle θ is calculated from Lemma 1 whereas value of ε is an algorithm parameter. Each mobile node's number of angular neighbors is evaluated and the node having maximum number of neighbors is accepted to form a separate group together with its neighbors. This procedure is repeated until all mobile nodes are investigated. Thirdly, after grouping by angle differences, each mobility group is examined once more considering the length differences. Each mobile node's number of neighbors with a maximal difference 2ε is obtained and mobile node having maximum number of neighbors in length is also separated as a different group together with its neighbors. That procedure is also repeated until all mobile nodes are investigated.

2.4 Discussion

Our problem domain focuses on mobility of nodes in groups. Therefore a group mobility model is adopted in this study as well. Furthermore, target application scenario of our thesis work accepts that mobile nodes come together to complete a common mission in groups for example, in a battlefield. Each group follows a leader node that is responsible for completion of subpart of the mission. Thus, Reference Point Group Mobility Model (RPGM) [12] is adopted, where each mobile node has random waypoint mobility model. Group members are interested in similar data items that are related to the sub-mission. Hence, data interests of mobile nodes are alike if they belong to the same sub-mission group.

In addition, our data replication process for MANETs is executed at regular periods by a manager mobile node. The process should be executed at a center which has knowledge about the overall network. Therefore a leader node is elected just before data replication process commences. As the execution is periodic, there is no need to ensure leader's stability. Therefore mobile node having Lowest-ID among all connected nodes is elected as a leader. This simple extrema-finding leader election algorithm is preferred as a result of no stability constraints and lower messaging overhead compared to other leader election algorithms.

To the best of our knowledge, there does not exist a data replication methodology for mobile ad hoc networks that performs both mobility aware and data interest based clustering together with profile dependent (data correlation, remaining energy and memory aware) replica allocation. Contributions of the thesis work are explored in the remaining chapters.

CHAPTER 3

MOBILITY and POWER AWARE DATA INTEREST BASED DATA REPLICATION

3.1 Problem Definition

This study is mainly related to improving data accessibility in mission critical applications performed by collaborating mobile users. Mobile users having a common mission are accepted to move in a predetermined region. A mission can be divided into sub-missions and mobile users are divided into separate groups to complete some part of mission. A rescue operation in a battlefield or an environmental exploration task is few of the example applications. Each mobility group has a mobile leader. The members of the group follow that leader in terms of mobility pattern. Mobile users within the same group are likely to move closer and have similar mobility patterns.

Each group is determined according to the sub-mission based criteria where group members' information requirements are also common. Mobile nodes that come together to complete a sub-mission have similar data interest patterns. Mobile devices having different specifications are able to collect different types of data such as graphical information and sense information about environmental conditions obtained from sensors attached to them. Mobile users are owners of some type of data. Mobile users can access data items hold by other nodes originally. As mobility groups may become disconnected due to their mission based movements, data that is shared across different groups should be replicated appropriately. Hence, data replication is primary matter of our problem domain.

Rescue operation case reveals the notion of a correlation among data items. In other words, both graphical views and sense data (temperature, darkness level etc.) of a particular region may be related and accessed simultaneously by mobile users.

In conclusion, this thesis work inspires from the problem domain where a mission critical task is accomplished by a number of groups of mobile users. Mobile users are assumed to own different types of mobile devices which are different in data collection specifications but similar in low power and limited memory capacity constraints. Data owned by mobile users may be required by all MANET participators and a series of data items are accessed at a single time due to correlation. Main purpose of the work is to replicate data items appropriately so that data accessibility is improved. Problem domain specific considerations of the proposed data replication strategy are explained in the remaining parts.

3.2 System Model and Architecture

Our system model assumes a mobile ad hoc network at which data items are shared among different mobile users. Each participant of the ad hoc network is named as a *mobile node* throughout this paper. Mobile nodes that show similar mobility patterns form a *mobility group*. Group of mobile nodes may become disconnected due to different mobility patterns therefore it is crucial to replicate the data items hold in other groups' nodes.

In order to improve data accessibility all over the network, data items should be replicated properly. Similar to previous studies in the literature, data items are replicated by using collaboration of mobile nodes. Namely, mobile nodes are clustered into stable groups and data item replication is conducted on the composition of the caches of the group members. However, the point is to form groups that are as stable as possible. A mobility group is more stable if the group is not disconnected easily. Mobile nodes may be disconnected when they fall distant so that they are not within the communication range of each other anymore. Thus, some mobile nodes may become unreachable and data items kept by that unreachable node become inaccessible. Consequently, this study suggests mobility aware and data interest based clustering strategy in order to obtain more stable mobility groups. This step of our replication strategy is called as the *clustering phase*.

After clustering phase is completed, data items are replicated within each mobility group. Replicas of data items are allocated on caches of all mobility group members. Data item replicas are inserted to the most appropriate mobile node. Appropriateness is evaluated by taking care of both *user profile*s and *device profile*s. Data access frequency, data correlation, remaining power and remaining memory constraints are considered. This process is named as *replica allocation phase*.

The process is managed by a mobile node that becomes leader of connected nodes at the beginning of replica allocation procedure. Consequently, a leader node is elected at the initial step of the process so that leader node can hear most of the mobile nodes and conduct the clustering and replica allocation phases of the process. Thus, *leader election phase* is the first step of our data replication approach.

The rationale behind the proposed approach is to replicate data items across different mobility groups so that data accessibility for the overall network is increased. Suggested mobility aware and data interest based clustering strategy aims to form stable mobility groups, unlikely to be disconnected. Replica allocation phase involves data interest and data correlation with power awareness.

3.2.1 Assumptions

Our approach adopts a set of assumptions given as follows:

- Each mobile node has a unique name demonstrated by a numerical value. Mobile nodes are represented by the letter M subscripted by its identifier such as M_i where $1 \leq i \leq S$ and S is total number of mobile nodes.

- Each mobile node owns a data item originally. Data items are assumed to be read-only and are not updated.

- Each data item has a unique numerical identifier. Data items are represented by the letter D subscripted by its identifier such as D_k where $0 \le k \le P$ and P is the total number of data items.

- Each mobile node has a limited cache capacity (C), excluding the original data item. Data item replicas are hold at this cache memory spaces.

- Mobile nodes obey RPGM group mobility model and random waypoint mobility behavior. Reasons for accepting these models are explained in section 2.4.

- Each mobile node is responsible for logging data access and mobility information. These information help in constructing device and user profiles.

- Each mobile node has a *Main Data Interest Item* which is used to form data access patterns. Mobility groups are determined according to sub-mission divisions. Each sub-mission has a data interest item related to the sub-mission. Thus, members of a mobility group have a common sub-mission and a common data interest item.

- Each mobile node accesses a series of data items in a single data access session. Data items within the same access session are surely correlated.

- Data replication process is executed at predetermined periods, called as relocation period and demonstrated by *T*.

3.2.2 Preliminaries

The thesis work issues an application level approach for data replication in MANETs. Before depicting features of the suggested methodology, some preliminary concepts that support input data for our approach are provided in this section. Firstly, data access generation method of our application is described.

Secondly, suggested strategy uses a set of historical data kept by each mobile node's application. This historical knowledge is stored by logging required data regularly in data access logs and mobility logs. Thus, log management is also outlined. Lastly, since our approach utilizes user and device profiles, meaning and contents of profiles are explained.

3.2.2.1 Data Access Management

Mobile users tend to access a series of data items at a time, assuming that a single data item access is not as realistic as real world applications. Some data items are surely related to each other and become useful when they are explored together. Moreover, as the problem definition section implies, in case the mobile nodes are grouped by sub-missions, a set of data items is much more associated to that sub-mission. Nonetheless, mobile nodes have a main data interest item which is critical for the sub-mission.

In order to simulate mobile users' data access patterns, a randomized data access generator is implemented. Unlike previous studies [8, 9], mobile users' access frequencies is not predetermined and static. Data access frequency to each data item is determined at runtime. According to the main data interest item, each mobile user's data access pattern is generated by *normal distribution function*. Normal distribution function has user's main data interest item as mean value μ whereas standard deviation σ is an algorithmic constant. Figure 4 shows data access frequency results from a simulation run where the main data interest item (μ) is 15 and standard deviation value (σ) is 0,8.

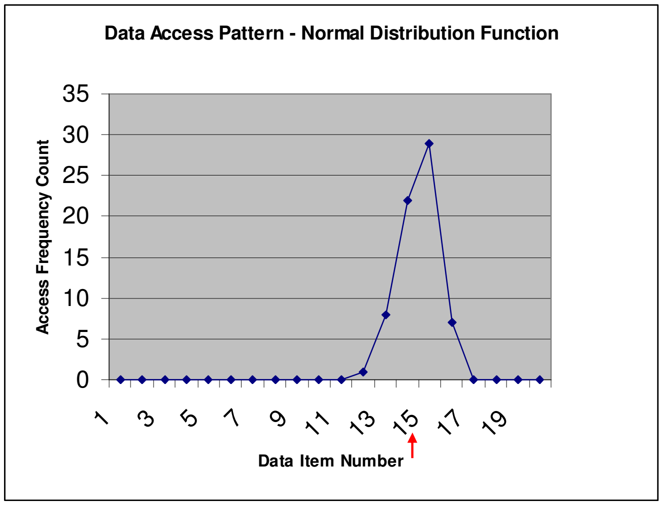


Figure 4 – Data Access Pattern

A series of data items are accessed at predetermined periods. Each data item in the series is obtained from the normal distribution function. Thus, data items in the access range are automatically correlated. From Figure 4, it can be derived that data items D_{17}, D_{16}, D_{15}, D_{14}, and D_{13} are correlated.

3.2.2.2 Log Management

Clustering and replica allocation phases of the proposed data replication strategy require some historical information about mobile nodes. Mobility aware and data interest based clustering strategy addresses mobility logging and data access logging. Replica allocation methodology further needs access frequency and data correlation values. Consequently mobility and data access behaviors of mobile nodes are logged. Periodic logging provides required historical information for our suggested algorithm. Log management is divided into two main categories. Data access and mobility information are logged and managed separately at each mobile node.

3.2.2.2.1 Data Access Information Logging

Clustering phase is data interest based where mobile nodes are grouped with respect to the data interest similarities after mobility pattern similarities. Data interest similarity is extracted from data access frequency patterns of mobile nodes. In addition, replica allocation method determines proper replica holders by taking care of access frequencies and data correlations.

Each mobile node has the responsibility of logging data access requests. Each data access request is a series of a set of data items. Data access requests are kept in a data access list having limited size. In case list size is exceeded, the oldest data access series is removed from the list. Data access frequencies of data items are also stored in another list. At each access request, data access count for the corresponding data item is incremented by one. By this way, a limited history on data accesses and a complete history on data access frequencies are obtained. Limit of the data access list is an algorithmic constant and set as 10. A sample data access log for mobile node 17 is shown in Figure 5. M_{17} has data item D_3 as the main data interest item. Each data access includes the original data item hold by the mobile node. This attitude is based on the fact that original data items are always in the cache and cannot be replaced.

```
*************  Printing Data Access Log of NodeID 17********************
[ 17 4 3 1 3 ]---------------------------------
[ 17 3 1 3 1 ]---------------------------------
[ 17 5 1 ]-------------------------------------
[ 17 3 3 ]-------------------------------------
[ 17 2 ]---------------------------------------
[ 17 1 1 ]-------------------------------------
[ 17 1 ]---------------------------------------
[ 17 3 3 3 1 ]---------------------------------
[ 17 5 3 1 1 ]---------------------------------
[ 17 3 ]---------------------------------------
************************************************************************
************  Printing Data Access Freq List of NodeID 17***************
Data Item No: 3 Access Count: 20
Data Item No: 1 Access Count: 18
Data Item No: 4 Access Count: 8
Data Item No: 2 Access Count: 6
Data Item No: 5 Access Count: 3
Data Item No: 6 Access Count: 0
Data Item No: 7 Access Count: 0
Data Item No: 8 Access Count: 0
Data Item No: 9 Access Count: 0
Data Item No: 10 Access Count: 0
Data Item No: 11 Access Count: 0
Data Item No: 12 Access Count: 0
Data Item No: 13 Access Count: 0
Data Item No: 14 Access Count: 0
Data Item No: 15 Access Count: 0
Data Item No: 16 Access Count: 0
Data Item No: 17 Access Count: 0
Data Item No: 18 Access Count: 0
Data Item No: 19 Access Count: 0
Data Item No: 20 Access Count: 0
************************************************************************
```

Figure 5 – Sample Data Access Log for Mobile Node 17

3.2.2.2.2 Mobility Information Logging

Mobile nodes are clustered into groups with respect to their mobility pattern similarities. Mobility pattern similarities are obtained from motion histories. Hence, mobile nodes are responsible for logging their positions at every log period (1 second). Log period is named as *position log time-slot length* and represented by δ. Positions are kept in a position list. Position list is managed like the strategy described in [10].

Similar to data access logs, mobility logs has a limit too. Limit of the position list is an algorithmic constant and set as 10. A sample position log for mobile node 17 is shown in Figure 6. As it can be seen in Figure 6, at every position log time-slot (1 second) position of the mobile node 17 is inserted into the position list. Mobile node M_{17} changes its location at each time-slot, thus a new entry exists per second. If the mobile node remained at the same location, then that position would not be put into the list [10].

```
****************  Printing Positon Log of NodeID 17 ***********
TimeStamp:  291
Location:   X Coord: 617.027 Y Coord: 435.122

TimeStamp:  292
Location:   X Coord: 617.29 Y Coord: 435.478

TimeStamp:  293
Location:   X Coord: 617.577 Y Coord: 435.863

TimeStamp:  294
Location:   X Coord: 618.036 Y Coord: 436.481

TimeStamp:  295
Location:   X Coord: 618.264 Y Coord: 436.788

TimeStamp:  296
Location:   X Coord: 618.541 Y Coord: 437.162

TimeStamp:  297
Location:   X Coord: 618.819 Y Coord: 437.539

TimeStamp:  298
Location:   X Coord: 619.152 Y Coord: 437.988

TimeStamp:  299
Location:   X Coord: 619.614 Y Coord: 438.611

TimeStamp:  300
Location:   X Coord: 620.048 Y Coord: 439.194

**************************************************************
```

Figure 6 – Sample Position Log

3.2.2.3 Profile Management

Profile is a collection of information that reflects status of the point of interest. Interest point can be any identity depending on the issue. Status is the information that target application is related to. In our case, mobile nodes are the point of interest. Mobile node is composed of several aspects related to user and mobile device. Our application domain interests in only user and device profiles. Contents of both profiles are explained in following sections.

3.2.2.3.1 User Profile

Data access and mobility related information is user specific. This information is periodically logged as it is described in previous log management section. Those logs together form user profile (Figure 7). User profile mirrors user related preferences regarding data item accesses and motions.

Each user profile includes two types of user dependent information. These are;

- **Data Interest Information:** Data access logs are explored to form data interest profile of users. Data interest profile has following items;

    - Identifier of the owner mobile node
    - Identifier of the data item kept as original by the mobile node
    - Data correlation values for every data item pair extracted from data access logs
    - Data access frequency values extracted from data access logs

- **Mobility Information:** Position logs are explored to form mobility profile of users. Mobility pattern similarity is obtained from the following user profile contents;

    - Identifier of the owner mobile node
    - Start time stamp of latest pause period extracted from position logs
    - End time stamp of latest pause period extracted from position logs
    - Start time stamp of latest motion period extracted from position logs
    - End time stamp of latest motion period extracted from position logs
    - Actual motion vector of mobile node (Definition of actual motion vector is provided in section 2.3.2.2)

<table>
<tr><th colspan="6">USER PROFILE PACKET</th></tr>
<tr><td colspan="6">Mobility Information</td></tr>
<tr><td rowspan="2">Node ID</td><td colspan="2">Pause Period</td><td colspan="2">Motion Period</td><td>Actual Motion Vector</td></tr>
<tr><td>t^{P}_{start}</td><td>t^{P}_{stop}</td><td>t^{M}_{start}</td><td>t^{M}_{stop}</td><td>$\overrightarrow{AM}(t^{M}_{start}, t^{M}_{stop})$</td></tr>
<tr><td colspan="6">Data Interest Information</td></tr>
<tr><td rowspan="2">Node ID</td><td rowspan="2">Original Data Item ID</td><td colspan="3">Data Correlation Matrix</td><td>Access Frequency List</td></tr>
<tr><td colspan="3">$DC = \{c_{ij} : i = 1 \rightarrow P, j = 1 \rightarrow P\}$</td><td>$AF = \{f_i : i = 1 \rightarrow P\}$</td></tr>
</table>

Figure 7 – User Profile Packet (Mobility & Data Interest Information)

3.2.2.3.2 Device Profile

In replica allocation phase remaining power of each mobile node is considered. Since remaining energy is a property of the mobile device, it is kept in device profile including following items;

- Identifier of the owner mobile node
- Remaining energy of the mobile device in percentages

3.2.3 Data Replication Process

Our *Mo*bility and *Po*wer *Aw*are *D*ata *I*nterest *B*ased *D*ata *R*eplication (MoPoAwDIB-DR) process is realized in three main phases. Figure 8 demonstrates the flowchart of the overall process. As it can be seen from Figure 8, the process is initiated by electing leader nodes that conduct remaining phases of the process. The procedure is managed by a centralized node so it is able to evaluate overall network for replication. After leader election phase is completed, the procedures applied on member nodes and leader nodes are executed in parallel. Leader node is the one that is responsible for starting the data replication process. Other nodes are in awaiting state until process is initiated (left and right sides of the flowchart). Nodes that are not leader wait for information request messages from their leader node. Other requests are discarded because a node should take place in a single data replication process simultaneously. Information requests triggered by leader node are shown on left hand side of the chart whereas reaction path at member nodes is given on right hand side of Figure 8.

Leader node collects required historical mobility and data access information. After all prerequisites are collected at leader node, it applies the data replication process beginning with clustering phase and then continuing by replica allocation phase. When replica allocation decisions are made, results of the process are sent to member nodes. Results of data replication process include suggested cache contents for each mobile node. After that time, mobile nodes have the responsibility to replicate suggested data items into their caches. Therefore each mobile node requests the data items that do not exist in its cache from other nodes.

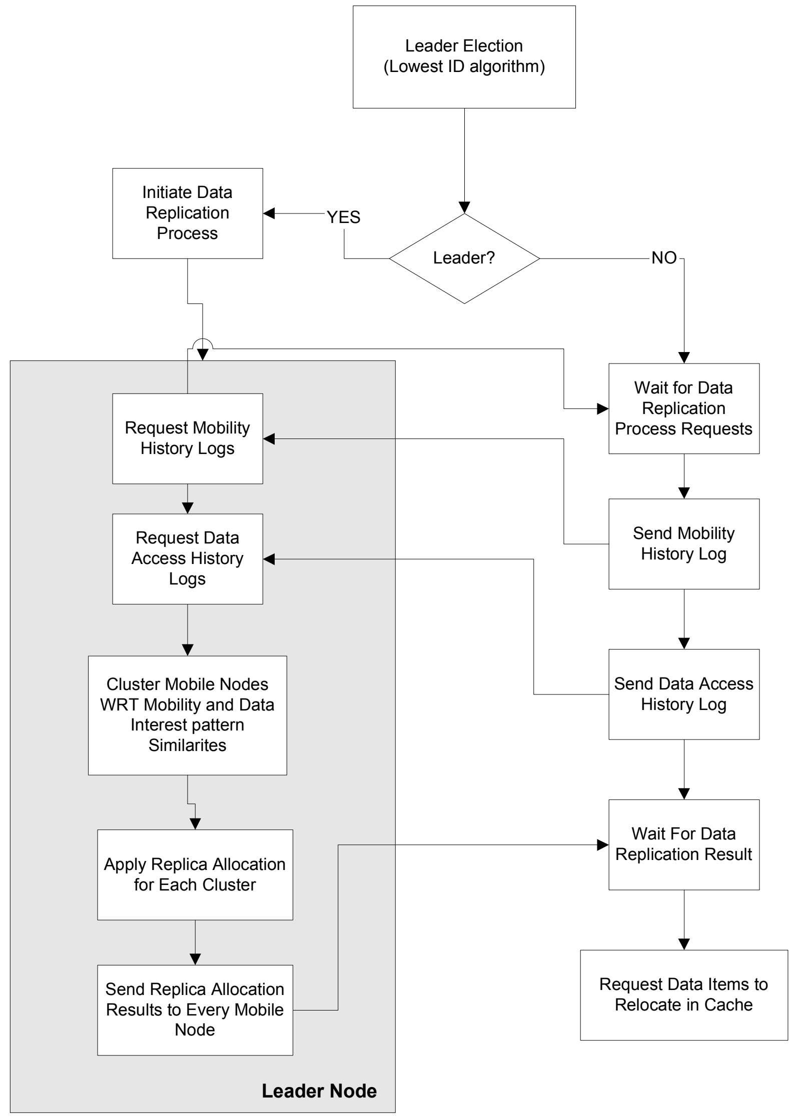


Figure 8 – Flow Chart Diagram for MoPoAwDIB-DR

3.2.3.1 Leader Election Phase

Data replication process is executed on a controller node since an overall conditional evaluation is required. Therefore, the process begins with determination of the leader node.

A leader election protocol is applied at this phase. Leader election phase is triggered at each period of data replication process (relocation period). Our process does not force that elected leader should be stable since periodic execution mechanism is adopted. Our approach takes a snapshot of the network state and executes accordingly. Hence a simple extrema-finding leader election protocol, Lowest-ID is applied.

Initially every node sends hello_messages to each other. By this way nodes are informed about other nodes which are within their communication range. Before exchanging hello_messages, nodes are in Not_Leader_Elected state and identifier of the leader is set as their own identifier. When a node receives a hello_message, it compares current value of leader id by the received messages' owner id. If sender node has an id smaller than current leader id, then leader id is set to message owner id. This control is repeated for every received message. When all hello_messages are exchanged each node evaluates value of current leader id. When leader id is equal to id of the node itself, that node announces its leadership to all other nodes. Nodes receiving leadership advertisement message accepts the leadership of the node having smallest id.

After leader is elected, that leader node is responsible for managing remaining phases, clustering and replica allocation, of the process.

3.2.3.2 Clustering Phase

After leader election phase is completed, leader nodes conduct rest of the data replication process. Replicating data over a group of mobile nodes reveals the effectiveness of mobile node collaboration. Mobile node collaboration level is defined after network is divided into clusters. Clustering phase is the key step in this strategy because data replication is performed on composition of caches of all cluster members. Mobile nodes are clustered so that resultant mobility groups are less likely to be disconnected in the near future. Data items that are replicated over members of the group remain accessible and so data accessibility is improved.

In our approach mobile nodes are clustered with respect to both mobility pattern and data interest pattern similarities. Details of mobility aware clustering and data interest based clustering are explained in following sub-sections.

3.2.3.2.1 Mobility Aware Clustering

Mobility aware clustering phase extracts historical mobility behavior of mobile nodes. Mobile nodes showing similar historical mobility patterns are accepted to be likely to conserve mobility pattern similarities. At the time of relocation period (*T*), every mobile node sends mobility information to the leader node. Mobility information (Figure 7) is formed by using position logs (Figure 6). Each position list entry is examined to find latest pause and motion periods. After latest pause and motion periods are detected, actual motion vector for latest motion period is calculated by the following formula;

$$\overrightarrow{AM}_i(t^M_{start}, t^M_{stop}) = \left\langle \left(X_{P_i^N(t^M_{stop})} - X_{P_i^N(t^M_{start})}\right), \left(Y_{P_i^N(t^M_{stop})} - Y_{P_i^N(t^M_{start})}\right) \right\rangle \qquad \textbf{(19)}$$

Then, $\overrightarrow{AM}_i(t^M_{start}, t^M_{stop})$ is converted into polar coordinates because mobility aware clustering compares angle and distance values of mobile nodes. Figure 9 demonstrates the mobility information part of user profile of M_{17} converted from position logs shown in Figure 6. In Figure 6, it is observed that the mobile node moves in every log period (1 second) and therefore there not exist pause period. Values of pause period timestamps are set to "-1". As the node moves in every time-slot δ, its motion period begins with the first entry's timestamp in the position log, and ends with latest entry's timestamp. Position of M_{17} at latest motion start and stop timestamps are $P_i^N(t^M_{start}) = \langle 617.027, 435.122 \rangle$ and $P_i^N(t^M_{stop}) = \langle 620.048, 439.194 \rangle$ respectively. Then actual motion vector from equation 19 is

$$\overrightarrow{AM}_i(t^M_{start}, t^M_{stop}) = \left\langle (620.048 - 617.027), (439.194 - 435.122) \right\rangle$$

After actual motion vector is converted into polar coordinates, the vector shown in Figure 9 is obtained.

```
************** Mobility Info Data of Node: 17 *****************
   Node ID: 17
   iTimestampPauseStart: -1
   iTimestampPauseEnd: -1
   iTimestampMotionStart: 291
   iTimestampMotionEnd: 300
   ActualMotionVector: RadianAngle: 0.932496 Length: 5.07014
***************************************************************
```

Figure 9 – Node 17 – User Profile, Mobility Information Section

When leader node starts clustering phase, all received mobility information messages are used as input to mobility aware clustering process. From lemma 1 and heuristic 1 of Huang's study explained in section 2.3.2.2, maximum angular difference θ per mobile node is calculated by equation 13. In addition, from lemma 2 and heuristic 2 of Huang's study (section 2.3.2.2) mobile nodes are clustered by length difference just after angular clustering. Value of maximum random vector length ε is an algorithmic constant and set to 2 meters. Other system parameters for clustering phase are shown in Table 1.

Table 1 – System Parameters for Clustering Phase

Parameter Symbol	Parameter Description	Value
ε	Maximum Random Vector Length	2 meters
$v_{\min}$	Minimum Velocity for Mobile Nodes	5 meter / sec
δ	Motion Time-Slot Length	1 second
DIT	Data Interest Threshold	0,70 (70 %)

Mobility aware clustering algorithm is derived from Huang's work [10]. Details of the procedure is referenced to section 2.3.2.2, thus same specifications are not repeated in this part. Data flow diagram of the procedure applied at leader node is given in Figure 10.

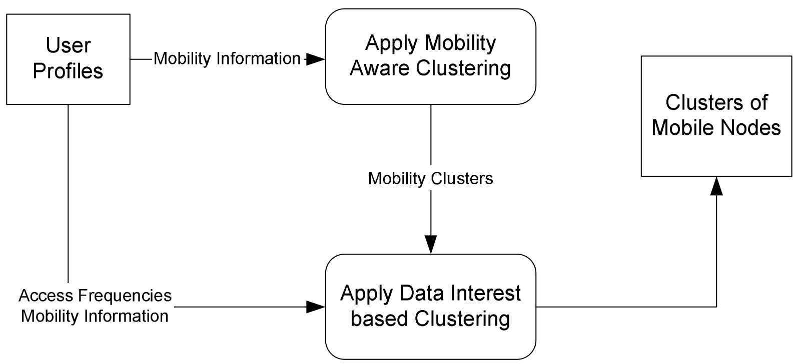


Figure 10 – Clustering Phase – Data Flow Diagram

3.2.3.2.2 Data Interest Based Clustering

Main objective of data interest based clustering is to further investigate resultant mobility aware clusters whether all members have similar data interest patterns or not. Mobile nodes having similar data interest patterns are clustered into separate groups. Mobile nodes' data access frequency values for each data item helps in determining data interest similarities.

Two mobile nodes have same data interest pattern if the number of data items, that commonly take place in both of the nodes' most frequently accessed items list, is above a threshold value. The threshold value (*DataInterestThreshold, DIT*) is declared as a system parameter and represents similarity percentage (Table 1). In order to detect commonly accessed data items, the entire access list is not examined.

Instead, 25% of the data access list (obtained from user profiles) is explored. Data interest based clustering algorithm conducted at leader node is given in Figure 11.

Symbolic Notation:

DIC : Set of data interest clusters

MC: Set of mobility clusters, in user profile information format

C_i : Single cluster in MC

DIN: Data interest neighbors, set of mobile nodes

N_i: Mobile node i

AFL : Access frequency list of mobile node i

d_x: *Data item x*

Procedure DataInterestBasedClustering(*MC*)

```
DIC ← Ø
for each cluster Ci in MC
    for each node Ni in Ci
        DINi ← Ø
        AFLi ← Access frequency list of Ni derived from MC
        for each node Nj in Ci
            AFLj ← Access frequency list of Nj derived from MC
            AccessFreqDiff ← ReturnAccessFreqSimDiff(AFLi, AFLj)
            if(AccessFreqDiff ≥ DataInterestThreshold)
            then insert Nj into DINi
        Remove members of DINi  from Ci
        Insert DINi  into DIC
return DIC
```

Procedure ReturnAccessFreqSimDiff(AFL$_i$, AFL$_j$)

```
#ofItemsToCompare  ← sizeof AFLi / 4
#ofSameItems ← 0
for each item dx ∈ AFLi / 4
    if(dx ∈ AFLj / 4 )
    then increase #ofSameItems
AccessFreqSimilarityDiff ← #ofSameItems / #ofItemsToCompare
return AccessFreqSimilarityDiff
```

Figure 11 – Data Interest Based Clustering Algorithm

Hara in C-DCG method [9] groups mobile nodes as *Biconnected Components* where mobility patterns are discarded. Although there are mobility aware clustering studies in the literature [10], our approach differs in considering both mobility and data interest patterns. Mobility pattern similarity does not guarantee that the group is not disconnected. Different sub-mission groups are merged into one single group when they move together for a period of time. Our approach differentiates sub-mission groups by using data interest patterns. Hence, our approach results in better group estimations.

Different clustering approaches are implemented on network simulator (ns-2). Graphical user interface of ns-2 is called as network animator (*nam*). Figure 12 gives mobility patterns of mobile nodes from time $t = 0\ sec$ to time $t = 900\ sec$. Although mobile nodes belonging to different groups move close for a period of time, they may move to different directions after a point in time. Groups 1, 2, 3 and groups 4, 5, 6 have similar mobility histories for a period of time as it can be observed in Figure 12. Relocation period is set to $T = 200\ sec$ for this simulation run.

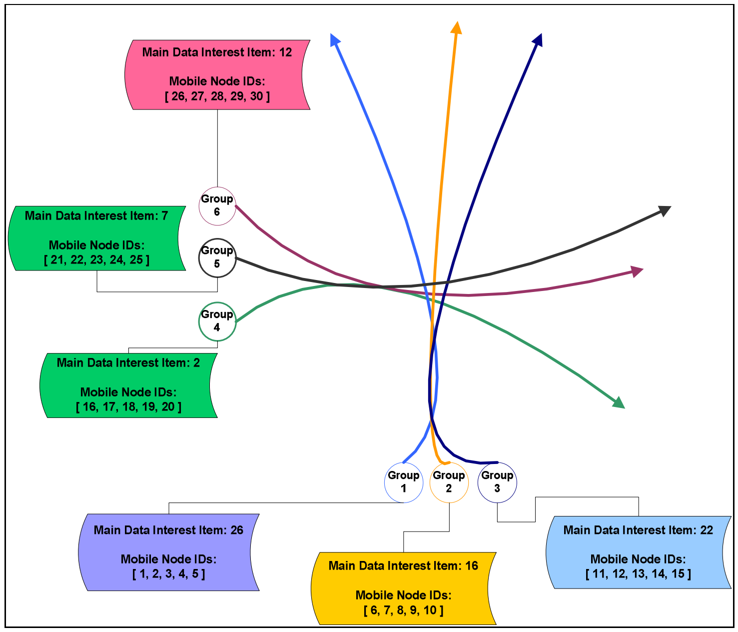
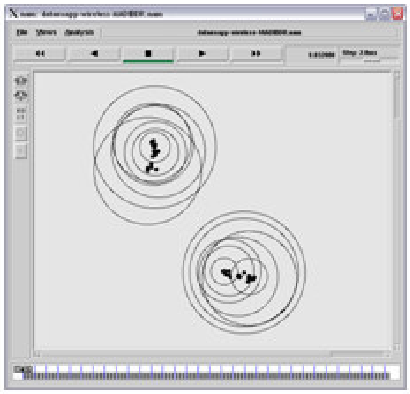
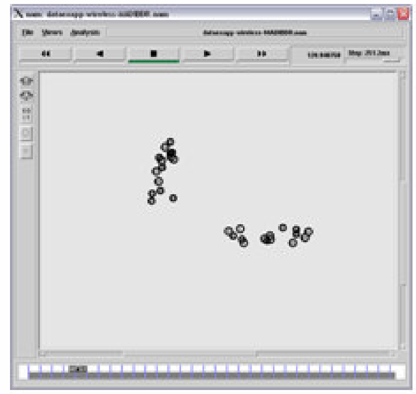


Figure 12 – Mobility Patterns of 6 Mission Critical Groups

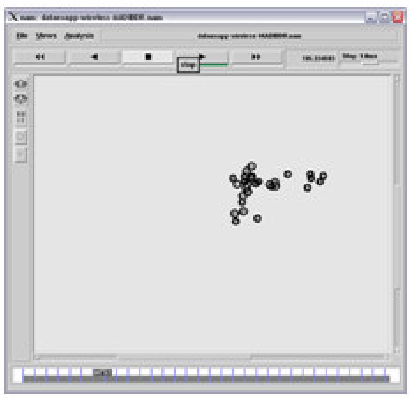
Figures 13, 14, 15 are *nam* screenshots for the same simulation scenario but for different clustering strategies. Figure 13 includes the screenshots of the simulation until replica allocation period (T = *200 sec*).



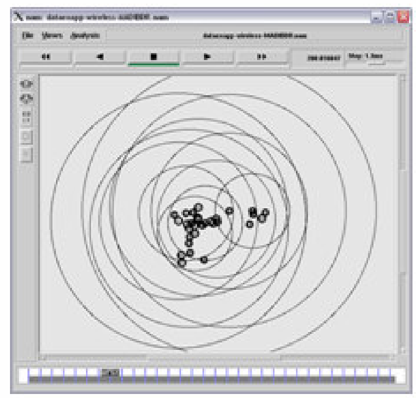
(a) At t = *0,03* sec



(b) At t = *120,94* sec



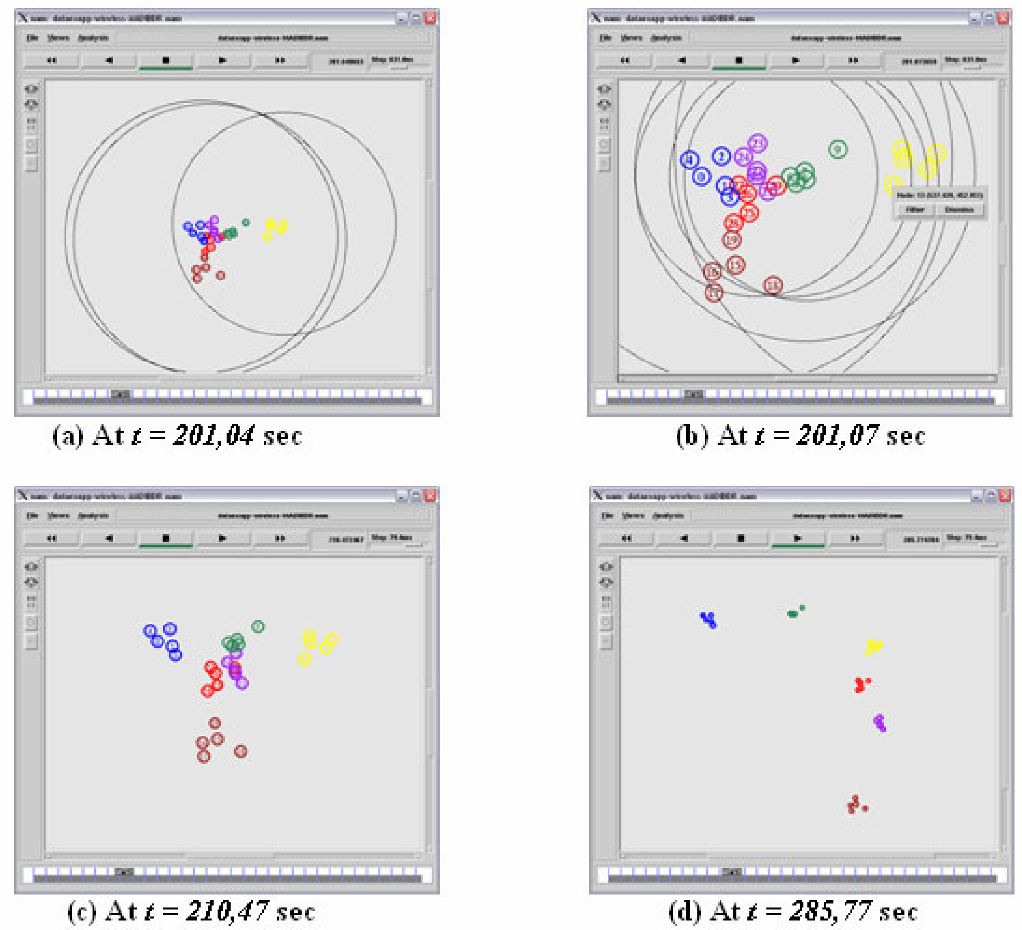
(c) At t = *195,33* sec



(d) At t = *200,01* sec

Figure 13 –Screenshots until Relocation Period = 200 sec

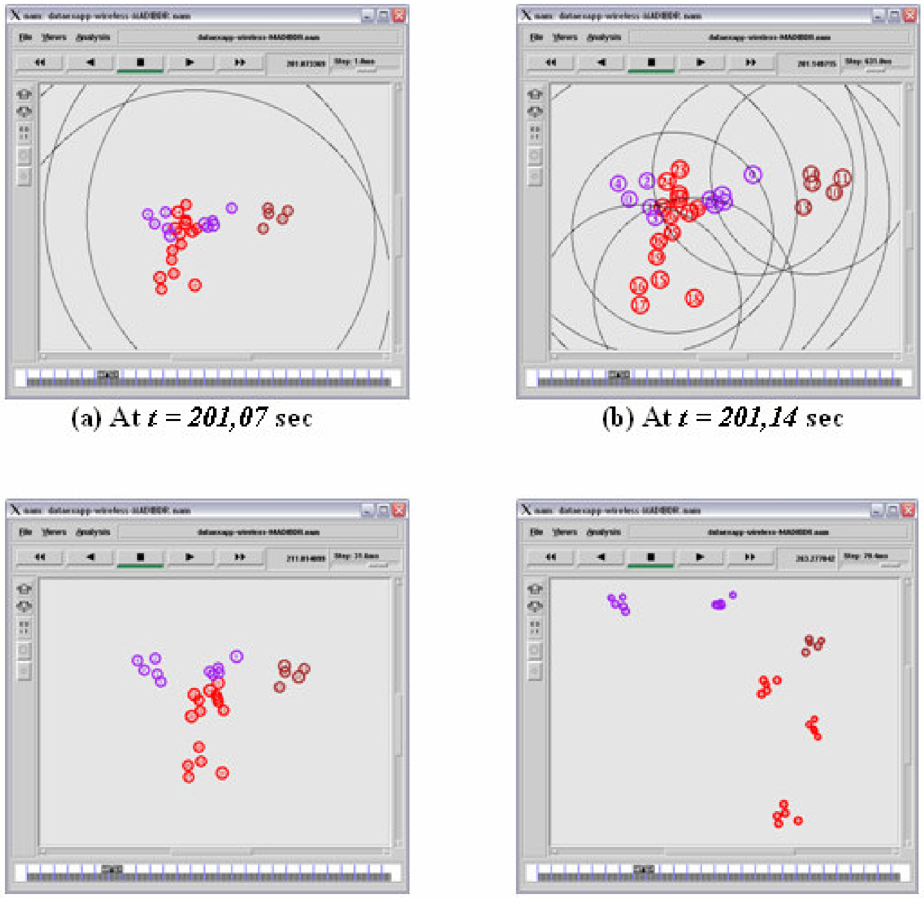
At time t = *200* sec data replication process is triggered. Figure 13 (d) shows the messaging among mobile nodes due to mobility and user profile information exchanges.



(a) At $t = 201,04$ sec
(b) At $t = 201,07$ sec
(c) At $t = 210,47$ sec
(d) At $t = 285,77$ sec

Figure 14 – Screenshots for Mobility Aware and Data Interest based Clustering

Figure 14 (a-d) shows clusters of mobile nodes in different colors. Our mobility aware and data interest based clustering strategy suggested in this thesis work results in 6 different clusters as expected. After a period of time sub-mission critical groups are separated from each other as shown in Figure 14(d).



(a) At t = *201,07* sec (b) At t = *201,14* sec

(c) At t = *211,01* sec (d) At t = *263,27* sec

Figure 15 – Screenshots for Mobility Aware Clustering

Figure 15 (a-d) shows results of the clustering approach where mobile nodes are grouped by only mobility pattern similarities but data interest patterns are not considered. From Figure 15(a, b), it can be seen that mobile nodes are clustered into 3 mobility groups. Mobile nodes moving together all take place in the same group. Thus it is obvious that sole mobility aware clustering misses possible disconnections due to different sub-missions that can be observed in Figure 15(d).

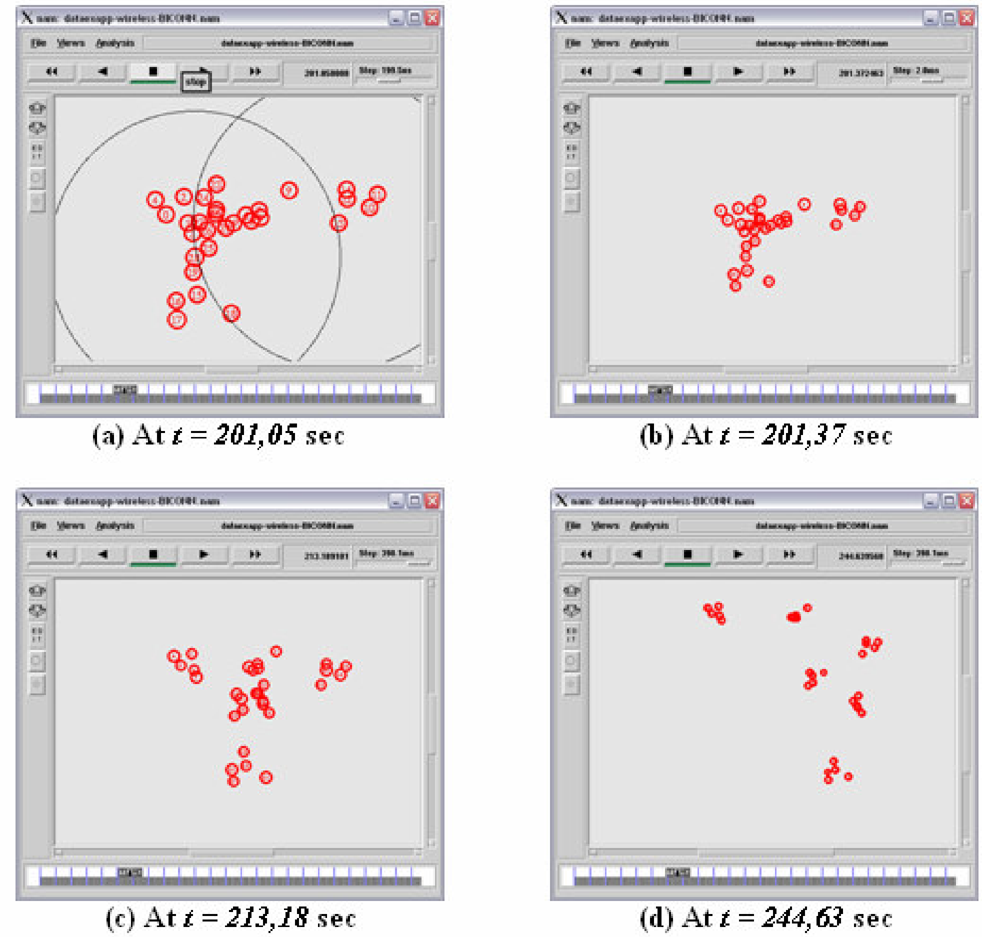


Figure 16 – Screenshots for Biconnected Components based Clustering

Lastly, Figure 16 (a-d) includes screenshots of the clustering approach where mobile nodes are grouped as *Biconnected Components*. Since at the time of relocation period $T = 200$ sec mobile nodes are so close to each other (see Figure 13), all mobile nodes form a single biconnected component. Figure 16 (a) shows that all mobile nodes are colored in red, in other words all of them are in the same cluster.

Those demonstrations prove the advantage of mobility aware clustering over biconnected components based clustering and also improvement of data interest aware clustering over sole mobility aware clustering. The main performance metric of the study, data accessibility, is investigated in performance evaluation chapter.

3.2.3.3 Replica Allocation Phase

Data replication procedure continues with replica allocation phase after mobile nodes are clustered into groups by the leader node. Data items are replicated within each cluster so that items that are correlated and frequently accessed are highly available. Aim is to estimate data access requests proactively as a consequence of correlation. When correlation among two items is high then, mobile node accessing one of the data items have the probability to request the other data item too. Therefore, correlated data items should together be available on the network. Our replica allocation phase is a proactive strategy based on both user and device profiles. The strategy is user profile dependent because access frequencies and data correlations are regarded. Moreover it is based on device profiles since remaining energy and remaining cache size of mobile nodes are considered.

Leader node obtains all required process inputs from user profiles and device profiles Data flow diagram of replica allocation phase is shown in Figure 17. Proposed replica allocation methodology is applied for each cluster and the methodology results in cache content suggestions for members of clusters.

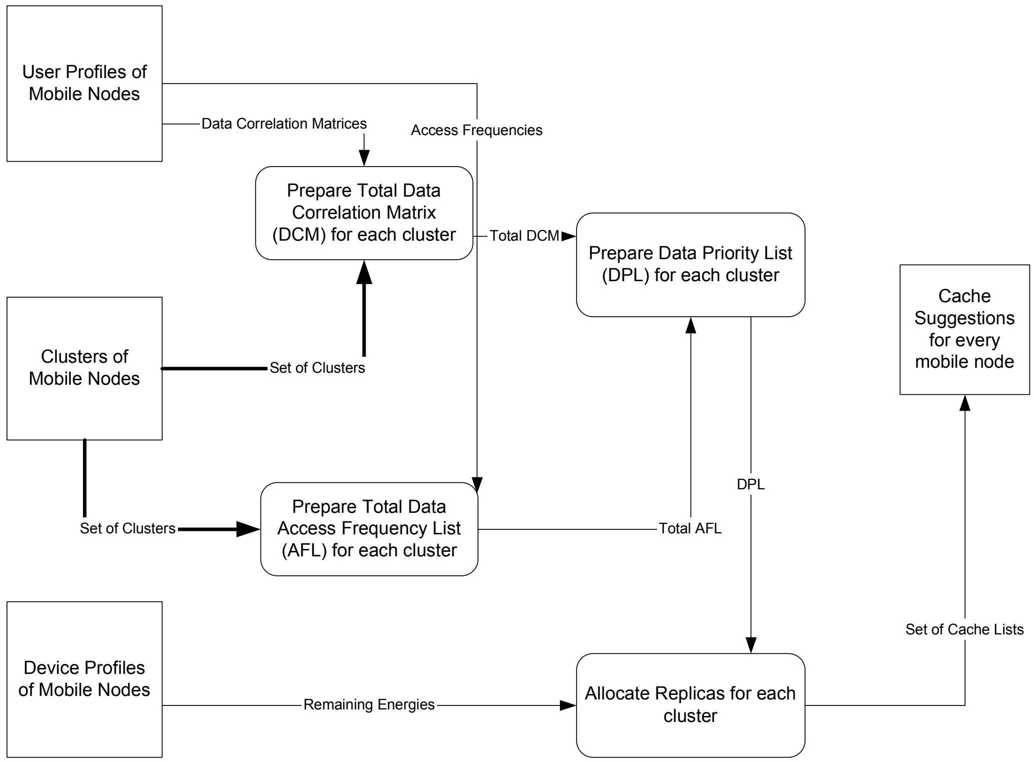


Figure 17 – Replication Allocation Phase – Data Flow Diagram

Replica allocation phase commences with ordering all data items according to a priority value. Data items are replicated in the order of data priority list. Definition of data priority and data priority list formation is inherited from [9] as described in section 2.3.2.1. Total data correlation values and total access frequencies are input for preparing data priority lists (*DPL*). The notion of correlation among data items is given below.

Data Correlation Value: Data items that are accessed in a single data access series are assumed to be correlated. Data correlation values are calculated for every data item pair D_j, D_k on each mobile node M_i by using equation 20.

$$p_{i-jk} = \frac{Number\ of\ times\ D_j\ and\ D_k\ accessed\ at\ same\ time}{Total\ number\ of\ data\ accesses} \quad (i = 1 \ldots S,\ j,k = 1 \ldots P) \tag{20}$$

For instance; sample data access log given in Figure 5 is signed on Figure 18 to demonstrate calculation of correlation values for data items D_1 and D_3. Accordingly;

$$p_{17-1,3} = \frac{4}{10} = 40\ \%$$

Since data items 1 and 3 exist in 4 data access series in a total of 10 data access series logs, the correlation is 40 %.

```
    *************  Printing Data Access Log of NodeID 17*******
 1  [ 17 4 3 1 3 ]--------------------------------- 1
 2  [ 17 3 1 3 1 ]--------------------------------- 2
 3  [ 17 5 1 ]-------------------------------------
 4  [ 17 3 3 ]-------------------------------------
 5  [ 17 2 ]---------------------------------------
 6  [ 17 1 1 ]-------------------------------------
 7  [ 17 1 ]---------------------------------------
 8  [ 17 3 3 3 1 ]--------------------------------- 3
 9  [ 17 5 3 1 1 ]--------------------------------- 4
 10 [ 17 3 ]---------------------------------------
    ***********************************************************
```

Figure 18 – Sample Data Access Log for Data Correlations of Items 3 and 1

The example shows calculation of a data correlation value at a single node. When nodes are grouped into clusters, data correlation of two data items is calculated as the summation of all data correlation values of all group members. Calculated group data correlation values are utilized in both obtaining *DPL* of the group and evaluation of replica holders. The basic principle behind replica allocation phase is to find the most appropriate holder for each data item. Each data item is assigned a weight named as *Data Replication Value* and represented by DRV_{ij}.

Data Replication Value: DRV_{ij} is defined for each data item D_i and mobile node M_j pair. Data items have data replication values as a combination of user and device profiles. Equation 21 is the formula established for calculating Data Replication Value.

$$\begin{aligned} DRV_{ij} = \quad & Weight_1 \otimes \text{RemainingEnergy}_i \oplus \\ & Weight_2 \otimes \text{RemainingCacheSize}_i \oplus \\ & Weight_3 \otimes \text{Data Correlation Value with Original Data Item}_{ij} \end{aligned} \tag{21}$$

First and second parameters of equation 21 are device profile sourced whereas last parameter is user profile sourced. Last parameter is the data correlation value of data item D_i with the original data item hold by mobile node M_j. DRV_{ij} value of a data item D_i at a mobile node M_j involves only correlation with the original data item because it cannot be guaranteed that mobile nodes will be able to reach the data items in caching suggestions or not. Remaining energy parameter aims to give less chance to the replica holder candidate unless it has high energy. It results from the fact that less remaining energy means higher probability to disconnect from the network. Remaining memory parameter provides a load balancing on mobile nodes. Data access request from other nodes causes replica holders to consume energy for replying data requests. Thus, replacing frequently accessed items on separate holders is also energy saving. Weights of each parameter are algorithmic constants and their values are listed in Table 2.

Table 2 – Weight Parameter Configuration

Weight Parameter	Value
Mobile Node Remaining Energy Weight ($Weight_1$)	0.3
Mobile Node Remaining Cache Size Weight ($Weight_2$)	0.1
Data Correlation Value Weight ($Weight_3$)	0.6

A heuristic approach is adopted in replica allocation phase. Data Replication Value constitutes decision point of the heuristic. Heuristic aims to decide on the replica holder node for a data item. The heuristic is as following;

Heuristic: Replicate a data item D_i at mobile node M_j which has maximum Data Replication Value (DRV_{ij}) among other mobile node candidates and whose cache is not full and does not already include D_i.

Application of replica allocation algorithm as a combination of data correlations, data access frequencies and data replication values is introduced in pseudo code format at Figure 19.

Symbolic Notation:

CS : Set of clusters

C_i : Single cluster in CS

DPL_i: Data priority list of C_i

AFL_i : Access frequency list of C_i (total access frequencies)

DCM_i: Data correlation matrix of C_i (total data correlation values)

DRV_{ij} : Data replication value of data item I at mobile node j

ChS : Set of caches

ODL_i: Original data items list

M_j: Mobile node

d_x: Data item x

Procedure ReplicaAllocation(*CS*)

```
for each cluster Ci in CS
     ODLi ← Find all original data items list for Ci
     AFLi ← Find total access frequency values for Ci
     DCMi ← Find total data correlation values for Ci
     DPLi ← FormDataPriorityList(AFLi, DCMi, ODLi )
     ChS  ← AllocateReplicas(DPLi)
return ChS
```

Procedure AllocateReplicas(DPL_i, C_i)

```
ChS ← Ø
(for each data item di in DPLi) && (All Caches is not FULL)
     Calculate DRV of di for every mobile node in Ci
```

```
        Choose node Mj (having maximum DRV ) && (Cache of Mj is not FULL)
        ChS ← Insert di into cache of Mj
    return ChS
```

<u>Procedure FormDataPriorityList (AFL$_i$, *DCM$_i$*, *ODL$_i$*)</u>

```
    DPLi ← ∅
    DPLi ← Insert org. data items in decreasing total access freq. values
    Remove original data items from AFLi
    Among ⌊n / x⌋ of AFLi find two mostly correlated data items
    Insert these two data items into DPLi
    while(AFLi is not EMPTY)
        ds ← FindStronglyCorrelatedDataItem(AFLi, DPLi, DCMi,)
        DPLi ← Insert ds into data priority list
        Remove ds from AFLi
    return DPLi
```

<u>Procedure FindStronglyCorrelatedDataItem(AFL$_i$, *DPL$_i$* , *DCM$_i$*)</u>

```
      for each data item di ∈ AFLi
          Find total data correlation value among di and all items in DPLi
      return data item ds having maximum total data correlation value
```

Figure 19 – Data Replication Algorithm

Replica allocation strategy that we urge outputs device state sensitive caching suggestions. Advantages of the proposed replica allocation phase become apparent when energy related disconnections occur. In this part replica allocation differences between the proposed strategy (MoPoAwDIB-DR) and existing strategies are explored. Different from our power aware replica allocation strategy, existing studies do not consider remaining energy. Instead they only use data correlation values and access frequencies. Existing approach is named as MobAwCorrDCG.

A simulation scenario having mobility patterns is shown in Figure 20. Each group consists of 5 mobile nodes and not all nodes have same initial energies. Two of the five nodes in each group have lower initial energies than others. Therefore they become unreachable after some time in the simulation. Relocation period for that simulation run is set to 200 seconds (T = *200* sec).

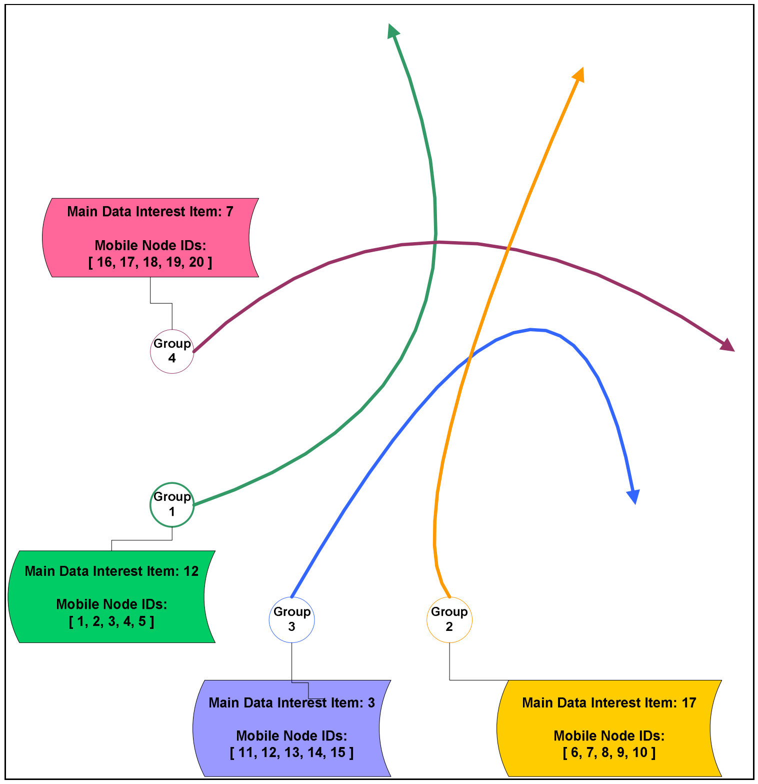
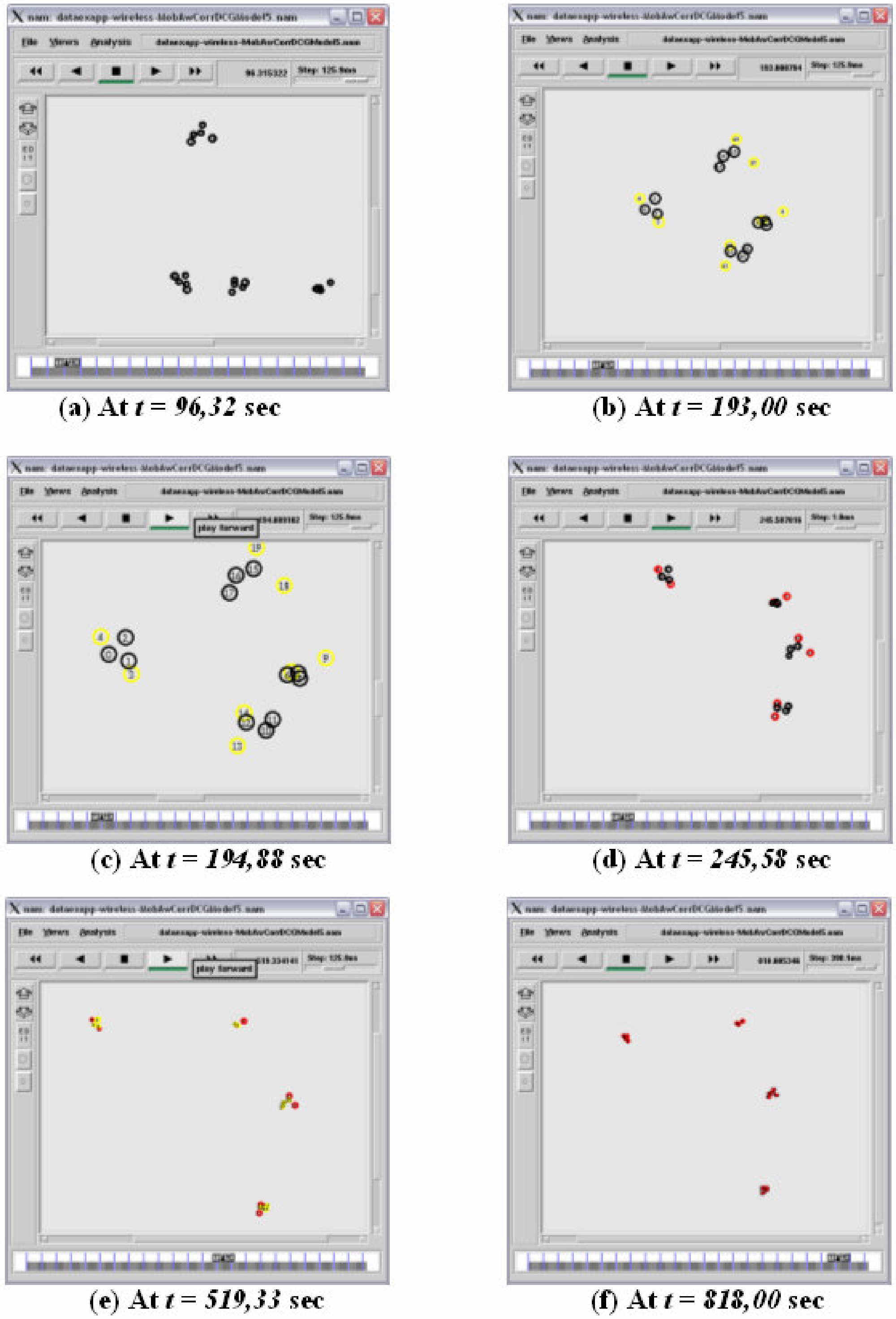


Figure 20 – Mobility Patterns of 4 Mission Critical Groups

Mobile nodes' energy levels are represented by different colors in *nam (network animator)* graphical user interface. No clustering based coloring is applied for that simulation run. Thus, colorings shown in screenshots are consequences of energy levels. Nodes colored in yellow demonstrate that energy level is critically low and nodes colored in red are disconnected since they have used up all of their energies. Figure 21 involves screenshots for that simulation run. Before relocation period at $t = 194$ sec two mobile nodes in each group are colored in yellow (Figure 21- b, c), namely they have less amount of remaining energy. After data replication process is completed at $t = 245$ sec (Figure 21-d) these nodes are disconnected from the network as they are colored in red. Thus, data items hold by those nodes are not available anymore. At $t = 519$ sec other mobile nodes also lacks energy (Figure 21-e), and at $t = 818$ sec all mobile nodes consume their batteries (Figure 21-f).



(a) At $t = 96,32$ sec

(b) At $t = 193,00$ sec

(c) At $t = 194,88$ sec

(d) At $t = 245,58$ sec

(e) At $t = 519,33$ sec

(f) At $t = 818,00$ sec

Figure 21 – Screenshots for Mobile Nodes Having Different Initial Energies

In this case study, replica allocation results for two different approaches are compared for the cluster containing mobile nodes 6, 7, 8, 9, 10. Remaining energy levels and cache states at the time of relocation period ($T = 200$ sec) are given in Figure 22. Nodes M_9 and M_{10} have 34% of their total energy whereas other nodes have 80% of their energy at the time of relocation period. Initially all mobile nodes' caches include only the original data items.

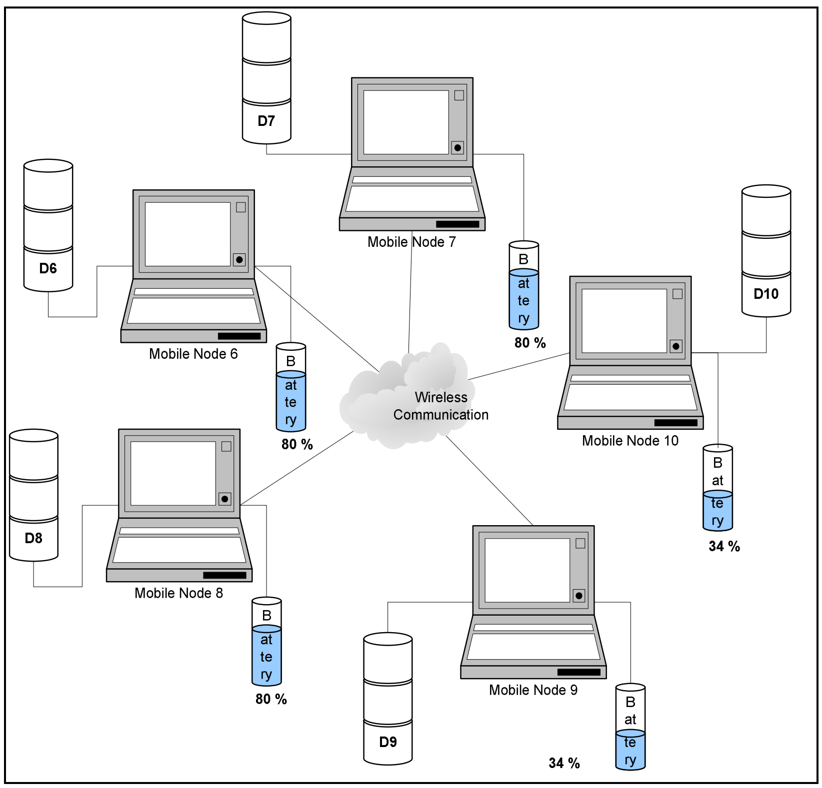


Figure 22 – Energy and Cache States of Nodes M_6, M_7, M_8, M_9, M_{10}

Figure 23 presents total data correlation matrices and data priority lists obtained at relocation time for two different approaches. As it can be seen from Figure 23, first 5 data items in data priority lists, gray colored, are the data items which are kept as original within the group. Data items in *DPL*s are ordered by the algorithm given in Figure 19. Data item orderings and correlation values are not the same but relatively alike for these two strategies because data access frequencies are determined by normal distribution function and generated dynamically. In addition, Figure 23 shows summation of all data correlation values of all nodes in the group. Columns and rows of the total data correlation matrix represent identifiers of data items. The cells that have highest correlation values are shaded in gray color.

Total Data Correlation Values for MoPoAwDIB-DR

Data	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0	0	0	0	0	0.17	0	0	0.17	0	0	0	0.17	0	0	0	0.17	0.17	0.17	0.17
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0.17	0	0	0	0	0	0	0	0	0	0.17	0	0.17	0.17	0.33	0.33	0.33	0	0.17	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0.17	0.17	0.33	0.67	0.5	0.17	0
8	0	0	0	0	0	0	0	0	0	0.17	0	0	0	0.17	0.33	0.33	0.33	0.17	0.33	0
9	0.17	0	0	0	0	0	0	0	0	0	0	0.17	0	0	0	0.33	0.5	0.67	0.33	0.33
10	0	0	0	0	0	0	0	0.17	0	0	0	0	0	0.33	0.17	0.5	0.33	0.5	0.17	0
11	0	0	0	0	0	0.17	0	0	0	0	0	0	0	0.17	0	0	0.17	0	0	0
12	0	0	0	0	0	0	0	0	0.17	0	0	0	0	0	0	0	0.17	0.17	0	0
13	0.17	0	0	0	0	0.17	0.33	0	0	0	0	0	0	0	0	0.17	0.33	0.17	0	0
14	0	0	0	0	0	0.17	0.17	0.17	0	0.33	0.17	0	0	0	0.17	0.5	0.67	0.17	0	0
15	0	0	0	0	0	0.33	0.17	0.33	0	0.17	0	0	0	0.17	0	0.17	0.17	0.17	0	0
16	0	0	0	0	0	0.33	0.33	0.33	0.33	0.5	0	0	0.17	0.5	0.17	0	0.83	0.33	0.33	0.17
17	0.17	0	0	0	0	0.33	0.67	0.33	0.5	0.33	0.17	0.17	0.33	0.67	0.17	0.83	0	0.67	0.33	0
18	0.17	0	0	0	0	0	0.5	0.17	0.67	0.5	0	0.17	0.17	0.17	0.17	0.33	0.67	0	0.33	0.17
19	0.17	0	0	0	0	0.17	0.17	0.33	0.33	0.17	0	0	0	0	0	0.33	0.33	0.33	0	0.17
20	0.17	0	0	0	0	0	0	0	0.33	0	0	0	0	0	0	0.17	0	0.17	0.17	0

Data Priority List for MoPoAwDIB-DR

10	6	7	8	9	17	16	18	19	14	15	13	1	20	11	12

Total Data Correlation Values for MobAwCorrDCG

Data	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0	0	0	0	0	0	0.17	0	0	0	0	0	0.17	0	0	0.17	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0.17	0.17	0.5	0.5	0.5	0.17	0	0.17
7	0.17	0	0	0	0	0	0	0	0	0	0	0.17	0.17	0	0.33	0.17	0.17	0.17	0	0.17
8	0	0	0	0	0	0	0	0	0	0	0.17	0	0	0.67	0.17	0.5	0.33	0.33	0.17	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0.33	0.5	0.5	0.33	0.33	0.33	0
10	0	0	0	0	0	0	0	0	0	0	0.17	0	0	0	0.5	0.67	0.5	0.67	0.17	0.17
11	0	0	0	0	0	0	0	0.17	0	0.17	0	0	0	0.17	0	0	0	0.17	0	0.17
12	0	0	0	0	0	0	0.17	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0.17	0	0	0	0	0.17	0.17	0	0.33	0	0	0	0	0.17	0.17	0.33	0	0.33	0	0
14	0	0	0	0	0	0.17	0	0.67	0.33	0	0.17	0	0.17	0	0.17	0.5	0.5	0.67	0.33	0
15	0	0	0	0	0	0.5	0.33	0.17	0.5	0.5	0	0	0.17	0.17	0	0.83	0.83	0.17	0.33	0.17
16	0.17	0	0	0	0	0.5	0.17	0.5	0.5	0.67	0	0	0.33	0.5	0.83	0	1	0.83	0.17	0.17
17	0	0	0	0	0	0.5	0.17	0.33	0.33	0.5	0	0	0	0.5	0.83	1	0	0.33	0.33	0.17
18	0	0	0	0	0	0.17	0.17	0.33	0.33	0.67	0.17	0	0.33	0.67	0.17	0.83	0.33	0	0.17	0.33
19	0	0	0	0	0	0	0	0.17	0.33	0.17	0	0	0	0.33	0.33	0.17	0.33	0.17	0	0
20	0	0	0	0	0	0.17	0.17	0	0	0.17	0.17	0	0	0	0.17	0.17	0.17	0.33	0	0

Data Priority List for MobAwCorrDCG

6	7	8	9	10	16	17	15	18	14	19	13	20	11	1	12

Figure 23 – Total Data Correlation Matrices and Data Priority Lists

Figures 24 and 25 designate cache states of mobile nodes after data replication is completed. Figure 24 shows results for our approach whereas Figure 25 includes caching proposals of the approach regarding only data correlation and access frequency values. Mobile nodes M_9 and M_{10} have lower energy levels at relocation time. Hence, it is possible to compare cache suggestions for M_{10}. Our approach does not cache most frequently data items D_{16} and D_{18} (see *DPL* of MoPoAwDIB-DR in Figure 23) at M_{10} even if the correlation among the original data item kept by M_{10} and data items D_{16} and D_{18} is the highest. The cells signed in blue color represent correlation values among those data items which are the highest of other data items (see Figure 23). Nonetheless as the other approach only regards data correlation values it prefers M_{10} for holding replicas of D_{16} and D_{18} (see Figure 25).

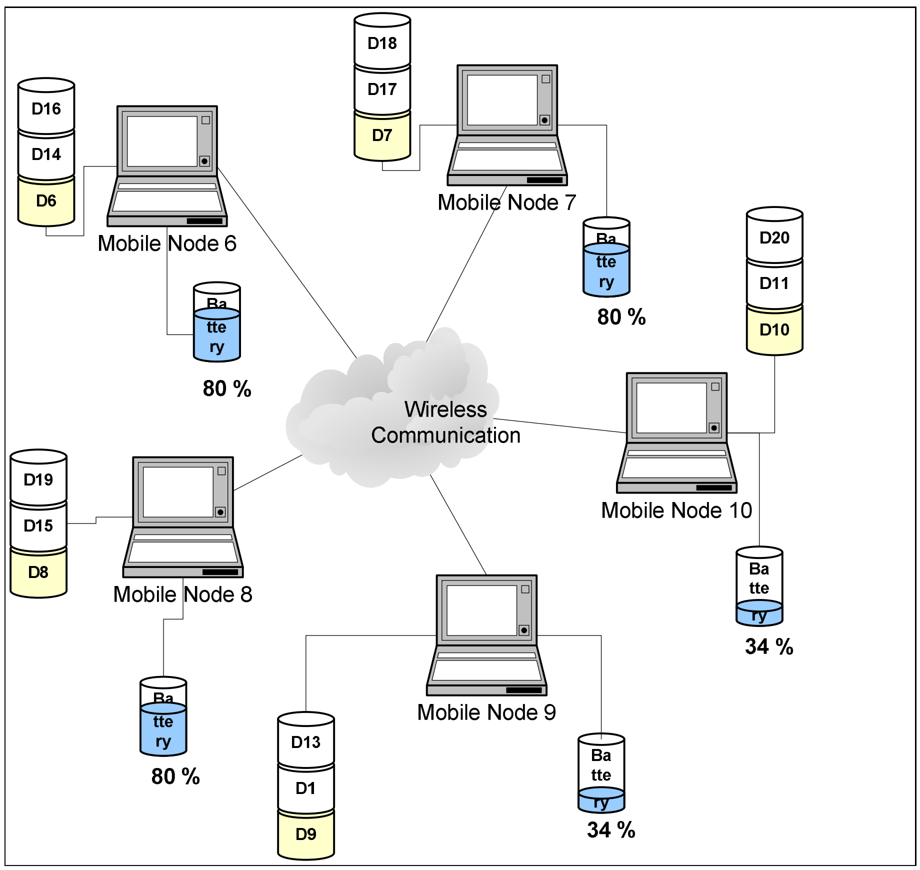


Figure 24 – Replica Allocation Results for MoPoAwDIB-DR

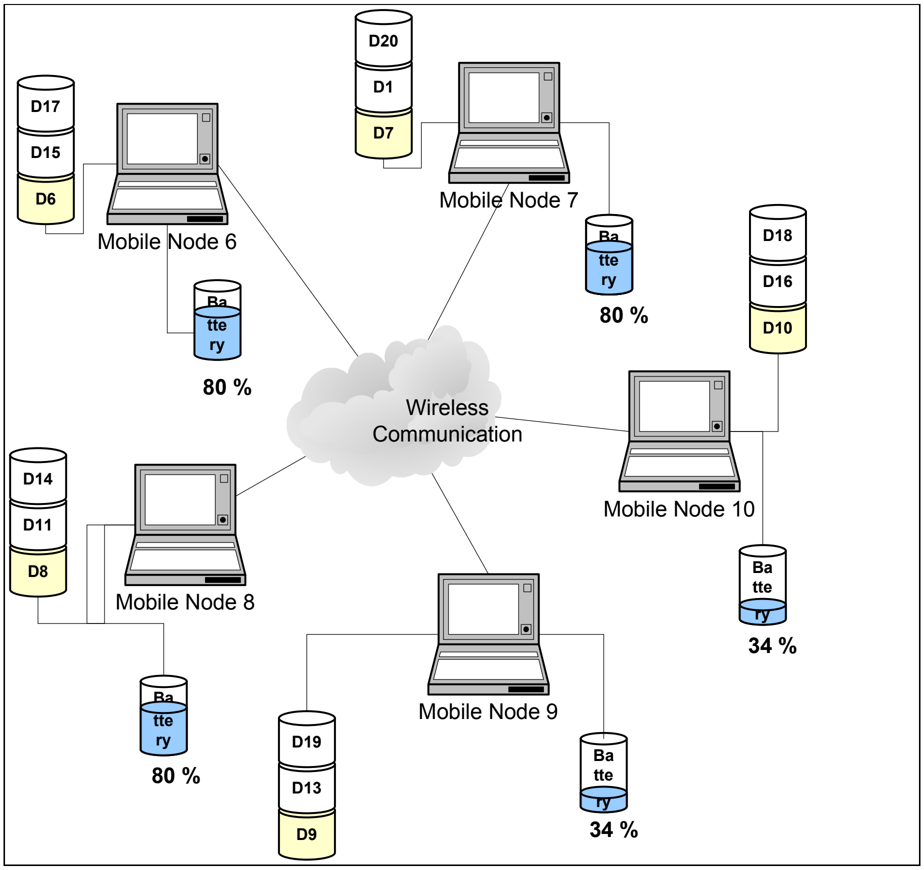


Figure 25 – Replica Allocation Results for Data Correlation based Approach

3.3 Simulation Environment

Our proposed data replication approach is an application level procedure. Application level implementation is developed on a simulation environment. This section describes the reasons for choosing ns-2 (Network Simulator-2) as our simulation environment. Then, a brief explanation of ns-2 simulation environment is provided. Lastly, extensions developed on ns-2 for developing our data replication process are explained.

3.3.1 Choosing Network Simulator

Simulation environment for this thesis study is selected after comparison of a group of commonly used simulators. Figure 26 demonstrates percentages of network simulator usages for wireless mobile ad hoc network studies in the literature.

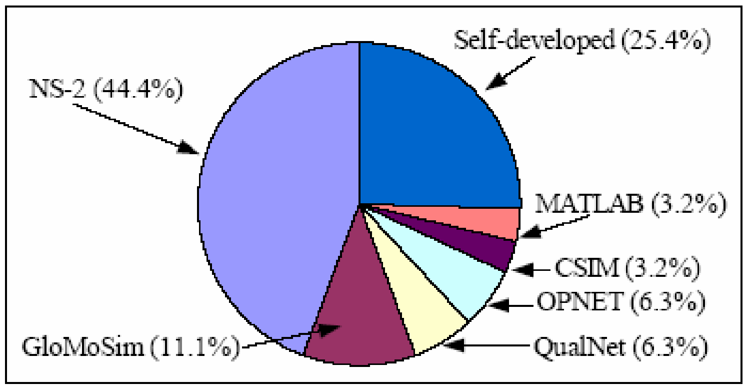


Figure 26 – Usage Percentages of Network Simulators (Adopted from [39])

As it can be seen in Figure 26, ns-2 is the most commonly used network simulator with a percentage of 44.4 % [39]. GloMoSim and self-developed simulators follow ns-2. In our study developing a network simulator would be time-consuming and out of scope of the work.

Among network simulator alternatives, ns-2 becomes a much more preferable choice. Ns-2 has a wide range of sample codes and documentation. It is developed for Linux – UNIX operating systems, but it also supports Windows OS by the help of Cygwin. As ns-2 is open-source, it provides developer to enhance main properties of the simulator for application specific needs. There is also a free, open-source simulation visualization tool developed for ns-2 called *NAM* (Network AniMator). Unlike ns-2, GloMoSim and OPNET are not open-source; therefore there is no chance to extend their properties due to application specific needs. As a result we have preferred ns-2 (version 2.29) as our network simulator environment and developed our application level data replication process on Ubuntu-LiNUX operating system.

3.3.2 Ns-2 Simulation Environment

Ns-2 is an object-oriented, discrete event network simulator [22, 23]. Ns-2 is developed by using both C++ and OTcl (Object – Oriented version of Tool Command Language) at UC Berkeley. C++ implementation of ns-2 provides performance improvements for the simulation, and Otcl provides writing simulation scripts easily. Ns-2 integrates C++ and Otcl implemented classes by constructing a linkage between pure Otcl objects and pure C++ objects. The implementation architecture of ns-2 is shown in Figure 27.

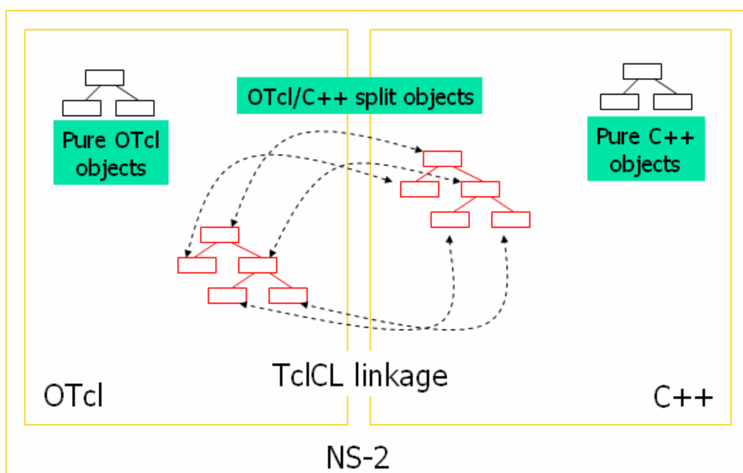


Figure 27 – ns-2 Implementation Architecture (Adopted from [23])

In ns-2 every operation is declared as an event and time increments when an event is raised. Event firing is managed by a scheduler. Therefore, ns-2 is named as a discrete event simulator [22, 24].

Ns-2 includes simulation of a set of protocols for different network levels (routing protocols, transport protocols, MAC layer protocols, link layer protocols…etc.). In order to simulate a network scenario in ns-2, topology of the network should be structured. Network participators forming the topology are represented by *node*s. Every defined node becomes a part of the network topology. Packet exchanges among connected nodes are controlled at endpoints called *agents*. Agents are endpoints attached to nodes and are responsible for network-layer packet construction and consumption. At the top most level, application specific implementations exist. *Applications* are attached to agents. Packets received by agents are forwarded to applications.

3.3.3 Using ns-2

Hierarchical implementation structure (node-agent-application) of ns-2 described in previous section helps in developers to extend ns-2 easily for their own protocol implementations. As our thesis work is about an application level data replication mechanism on mobile ad hoc networks, mobile ad hoc network specific implementations of ns-2 are used as they exist in the ns-2 library. However, application level and agent level extensions are developed. Extensions applied on ns-2 are shown in Figure 28.

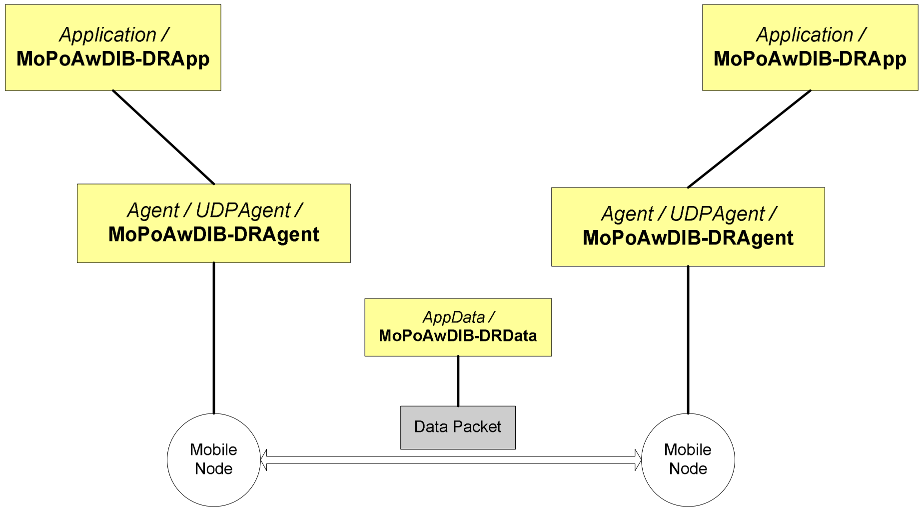


Figure 28 – ns-2 Extension for MoPoAwDIB-DR Implementation

Mobile ad hoc networking in ns-2 is simulated by using an already existing enhancement on n*ode* implementation called m*obile node*. Therefore our simulation extension is based on mobile nodes. Each member in the network topology is represented by a mobile node instance.

Ns-2 involves some commonly used protocols in its library. As it is open source, it is possible to generate target specific additions within the original source code. Ns-2 includes AppData, UDPAgent, and Application classes in its library. AppData is a generic data packet for carrying application dependent information. Moreover, UDPAgent has the properties of a UDP protocol as an agent. Application is a generic class that is responsible for handling application level message exchanges. In our thesis study, UDPAgent and Application implementations are extended to achieve simulation of the suggested data replication methodology; MoPoAwDIB-DR. MoPoAwDIB-DRAgent inherits from UDPAgent. MoPoAwDIB-DRAgent is responsible for encoding and decoding the application specific MoPoAwDIB-DRData and forwarding that data packet to the application level. At application level MoPoAwDIB-DRApp is developed. It inherits from ns-2's built-in Application class.

Our proposed data replication process (MoPoAwDIB-DR) is completely implemented as an application level protocol including further operational extensions. Figure 28 does not demonstrate full implementation details for the thesis work, it only figures out data, application and agent level extensions appended to ns-2.

3.4 Performance Issue

3.4.1 Performance Metrics

Main objective of the thesis work is to urge a novel data replication strategy for MANETs. In order to compare existing studies in the literature with our approach following metrics are used;

Data Accessibility: Data accessibility metric measures the effect of data replication process so that data items' availability in the overall network is observed. Data availability is the primary consideration of data replication approaches. Data accessibility is the ratio of number of successful data access requests to total data access requests by each mobile user. As a result of data correlation, in our study it has been accepted that if one of the data items in a single data access series is unreachable then all data item requests in the set are not successful. Data items are useless when their correlated items are unreachable. Data accessibility metric can be formulized as following;

$$Data\ Accessibility = \frac{Number\ of\ Successful\ Access\ Requests}{Number\ of\ Total\ Access\ Requests} \qquad \mathbf{(22)}$$

Cache Hit Ratio: Another metric is cache hit ratio of each mobile node. Cache hit ratio represents the proportion of successful data access requests in local cache. This metric is important in the sense that data items are locally available or not. Data items that are not found in cache are requested from other mobile nodes in the network and thus increasing messaging namely traffic overhead. Cache hit ratio can be formulized as following;

$$Cache\ Hit\ Ratio = \frac{Number\ of\ \ Access\ Requests\ Hit\ on\ Cache}{Number\ of\ Total\ Access\ Request} \qquad \textbf{(23)}$$

Traffic: Traffic is defined as summation of the traffic for message exchanges during data replication process and the traffic produced for data access requests. By this way, it is possible to compare messaging overhead of different data replication strategies. Traffic is measured in units of bytes.

3.4.2 Advantages of MoPoAwDIB-DR

Mobility and Power Aware Data Interest Based Data Replication (MoPoAwDIB-DR) process differs from existing data replication procedures in many ways.

Mobility aware and data interest based clustering brings the advantage of better group estimations. As our target application domain contains mobile ad hoc mission groups that come together to complete a common task, it is crucial to foresee possible disconnections due to mission based different movement directions. Data interest similarity based grouping eliminates faulty clustering of mobility groups that are moving together for a period of time but having different missions. Mission differences would probably result in mobility pattern divergences. Sole mobility aware clustering is unable to estimate real mobility groups but both mobility aware and data interest based clustering outperforms other methods in better group estimations.

Replicating data item on the mobile node candidate having more free cache space provides a balance on the number of replicas carried by each mobile node. There would not be such a node carrying all most frequently accessed items all together and thus unexpected disconnections of mobile nodes, other than energy related, would not affect data availability severely. In addition power aware replica allocation helps in better disconnection estimations. Mobile node that is poor in energy is a weaker replica holder candidate and therefore data items having high priorities are not replicated on those weak candidates. Consequently, possible disconnections of those mobile nodes do not decrease data availability as severely as other methodologies not considering power constraints.

Following performance evaluation chapter compares our MoPoAwDIB-DR strategy to other existing methodologies with respect to data availability, cache hit ratio and traffic metrics.

CHAPTER 4

PERFORMANCE EVALUATION

This chapter compares the proposed data replication strategy to other approaches and evaluates the results in terms of performance metrics. A set of comparison models is implemented in order to observe the performance improvements of our strategy. First part of the chapter describes comparison models and specifies properties of each. Later, results of models with respect to data accessibility and cache hit ratio metrics are demonstrated and evaluated. Furthermore, advantages of our methodology specific features, namely data interest aware clustering and power aware replica allocation, are investigated. Finally, the effect of different relocation periods on data accessibility and traffic is explained.

4.1 Comparison Models

Comparison models are implemented in order to prove the performance improvements of the proposed data replication strategy (MoPoAwDIB-DR) in terms of data accessibility, cache hit ratio and traffic. Comparison models are derived from the studies in the literature mentioned at related works chapter. Each model has different approaches in clustering and data replication phases. Comparison models are similar to our approach in the way that data replication is completed in two phases; clustering and replica allocation, but differ in the applied procedures.

Table 3 demonstrates the features supported by models. Explanations of the comparison models are given below.

Table 3 – Comparison Models

Model Name	Clustering Phase			Replica Allocation Phase			
	Mobility Aware	Data Interest Aware	Biconnected Components	Access Frequency	Data Correlation	Power Aware	Memory Aware
MoPoAwDIB-DR	✓	✓		✓	✓	✓	✓
MoPoAwDIB-DR-NonDataInterestAw	✓			✓	✓	✓	✓
MobAwCorrDCG	✓	✓		✓	✓		
BICONN			✓	✓	✓	✓	✓
CorrDCG			✓	✓	✓		

MoPoAwDIB-DR (Mobility and Power Aware Data Interest Based – Data Replication): It is the base model that our thesis work suggests. It performs mobility aware and data interest based clustering and then uses access frequency, data correlation, remaining energy and remaining memory criteria for replica allocation phase.

MoPoAwDIB-DR-NonDataInterestAware: This model is the same as the originally proposed MoPoAwDIB-DR model expect for the clustering strategy. This model performs only mobility aware clustering, whereas original MoPoAwDIB-DR model uses both mobility and data interest pattern similarities for clustering of mobile nodes. Therefore mobile nodes having similar movement patterns but different data interest values are likely to be grouped separately in original MoPoAwDIB-DR model. As our target application domain is composed of mission critical groups that are likely to move together and have similar data interest patterns, MoPoAwDIB-DR is expected to form much more stable mobility groups.

MobAwCorrDCG (Mobility Aware Correlated Dynamic Connectivity Grouping): This model is originated from one of the related works existing in the literature. Hara's study [9] emphasizes C-DCG method as the best replica allocation method according to data accessibility. C-DCG uses Biconnected Components for clustering and takes care of access frequency and data correlation for replica allocation. However, that comparison model uses our clustering strategy (Mobility and Data Interest Aware) and uses Hara's replica allocation strategy. By this way, it is expected to reveal the advantage of remaining energy and memory capacity awareness of our suggested method compared to existing replica allocation method.

BICONN (BiConnected Components): This model uses the same replica allocation phase as our thesis work MoPoAwDIB-DR. Unlike MoPoAwDIB-DR, it groups mobile nodes with respect to Biconnected Components algorithm. As studies in the literature [8, 9] use Biconnected Components for clustering, it is aimed to prove the fact that suggested novel data replication strategy performs better because of mobility and data interest aware clustering (MoPoAwDIB-DR).

CorrDCG (Correlated Dynamic Connectivity Grouping): This model is inherited from Hara's study [9]. It applies Biconnected Components for clustering of mobile nodes and uses access frequency and data correlation in order to find appropriate replica allocation candidates within each group. The model is implemented in order to compare the improvements that come with power and memory awareness features of replica allocation.

4.2 Data Accessibility

This section proves the performance improvement achieved by data replication strategy of this thesis work, MoPoAwDIB-DR. Two simulation scenarios at different relocation periods are performed. First simulation scenario has relocation period as 300 seconds and second scenario has it as 200 seconds. Data accessibility performance of our strategy MoPoAwDIB-DR is compared with the performance of models BICONN, CorrDCG, and MoPoAwDIB-DR-NonDataInterestAware. Model BICONN is used to show the importance of mobility and data interest aware clustering over Biconnected Components based clustering. CorrDCG is a variation of BICONN excluding power and memory aware replica allocation. NonDataInterestAware version of our MoPoAwDIB-DR model lacks data interest aware clustering only. These two simulation scenarios would not be able to reveal the effects of power aware replica allocation and data interest aware clustering.

Effects of these features are explored in other simulation scenarios (Section 4.4 and 4.5).

4.2.1 Simulation Environment and Parameters

Two simulation scenarios are executed for exploring advantage of the proposed data replication strategy over other models. Table 4 demonstrates algorithmic parameters and environmental properties of the first and second simulation scenarios.

Table 4 – System Parameters of Simulation Scenarios

Parameter	Simulation Scenario 1	Simulation Scenario 2
Environment Area Size	1000 x 1000	1000 x 1000
Number of Mobile Nodes	20 (5 mobile nodes per group)	20 (5 mobile nodes per group)
Number of Mobility Groups	4	4
Number of Data Items	20	20
Relocation Period	**300 sec**	**200 sec**
Total Simulation Time	900 sec	900 sec
Radio Communication Range	250 meters	250 meters

Except relocation period values, all other simulation parameters are identical for two scenarios. Mobility behaviors and data interest patterns of mobile nodes are given in Figures 29 and 30. Figures consist of mobility patterns for each mobility group which is shown by arrows. Colored boxes attached to mobility groups include value of the main data interest item for each mobility group and identifiers of mobile nodes that belong to the group.

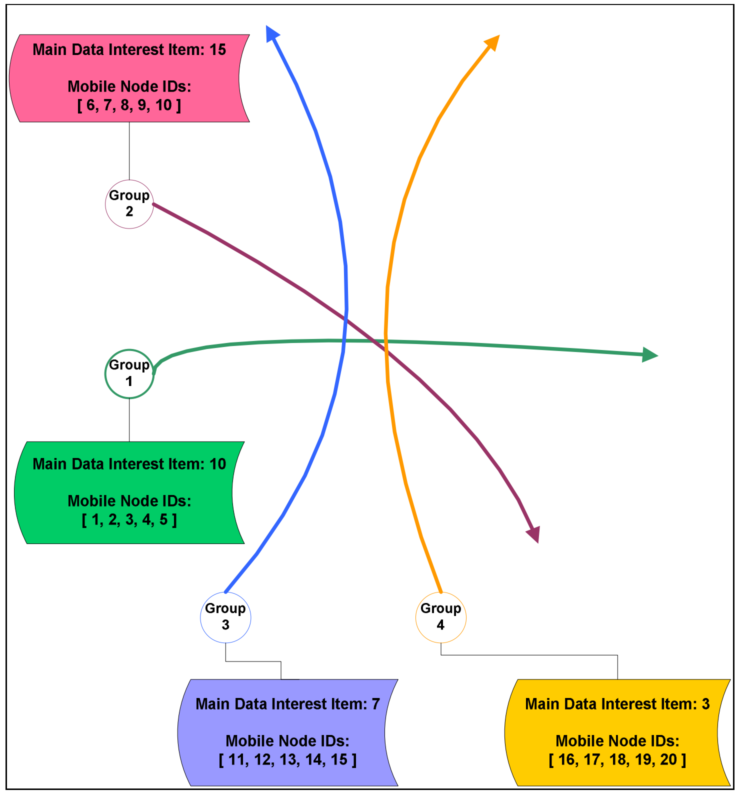


Figure 29 – Mobility Scenario of First Simulation

Figure 29 illustrates mobility patterns and groups of the first simulation scenario having relocation period as 300 seconds. Mobility groups 1 and 2 move from west-to-east direction whereas groups 3 and 4 move from south-to-north direction. Group 1, 2, 3, 4 have main data interest items as D_{10}, D_{15}, D_7, D_3 respectively. Members of group 1 are M_1, M_2, M_3, M_4, M_5; group 2 are M_6, M_7, M_8, M_9, M_{10}; group 3 are M_{11}, M_{12}, M_{13}, M_{14}, M_{15}; group 4 are M_{16}, M_{17}, M_{18}, M_{19}, M_{20}.

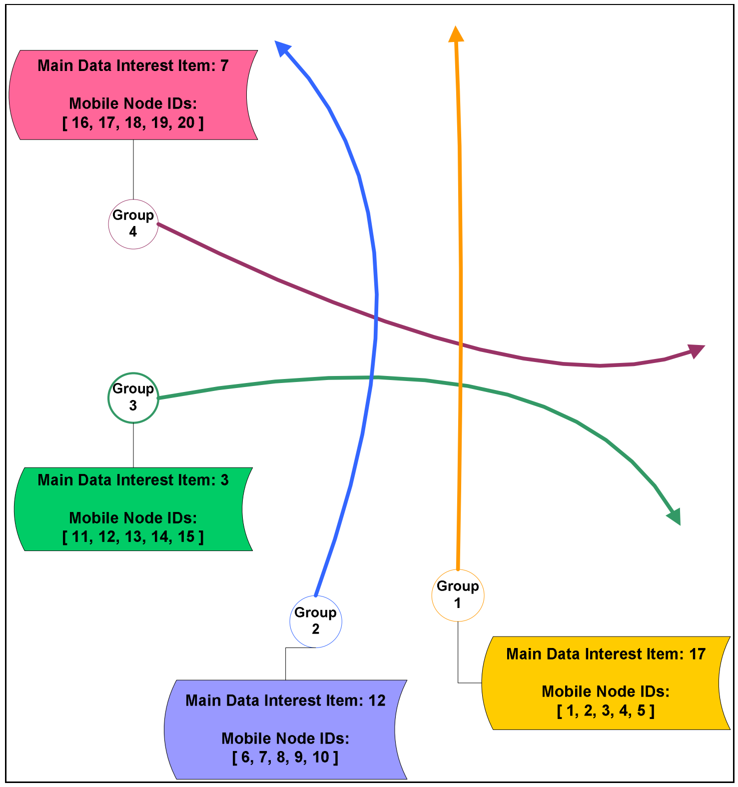


Figure 30 – Mobility Scenario of Second Simulation

Figure 30 illustrates mobility patterns and groups of the second simulation scenario having relocation period as 200 seconds. Mobility groups 3 and 4 move from west-to-east direction whereas groups 1 and 2 move from south-to-north direction. Group 1, 2, 3, 4 have main data interest items as D_{17}, D_{12}, D_3, D_7 respectively. Members of group 1 are M_1, M_2, M_3, M_4, M_5; group 2 are M_6, M_7, M_8, M_9, M_{10}; group 3 are M_{11}, M_{12}, M_{13}, M_{14}, M_{15}; group 4 are M_{16}, M_{17}, M_{18}, M_{19}, M_{20}.

4.2.2 Experimental Results

Mobility groups start their motion apart from each other; therefore data accessibility due to main data interest items is low for each mobile node at the beginning. As mobile nodes come closer, they enter radio communication range of each other so data accessibility increases. At times t = 300 sec and t = 200 sec data replication procedure runs and replicas are allocated for each mobile node by leader node(s). After replicas are allocated, the accessibility suddenly increases for mobility aware and data interest based model MoPoAwDIB-DR (Figures 31, 32). However, the models that group mobile nodes as Biconnected Components, BICONN and CorrDCG represent decrements in data accessibility. This results from the fact that Biconnected Components strategy is not able to find stable mobility groups. Mobility aware clustering methods are more successful in finding the mobile nodes that tend to move closer and not to disconnect from each other. Therefore, mobility aware models form more stable groups and allocating replicas within group results in better data accessibility percentages. Both Figure 31 and Figure 32 show average data accessibility percentages. After relocation period mobile nodes continue moving to different directions. Thus, from figures we can see that data accessibility of BICONN and CorrDCG decreases with time whereas MoPoAwDIB-DR and MoPoAwDIB-DR-NonDataInterestAware have increasing data accessibility percentages throughout the simulation.

Advantage of data interest aware clustering cannot be proved for these simulation runs because mobility patterns of groups are not similar to each other. Following simulations show importance of data interest aware clustering effectively (Section 4.4).

In conclusion, graphical representations (Figure 31, 32) clearly demonstrate that our model outperforms other strategies in terms of data accessibility.

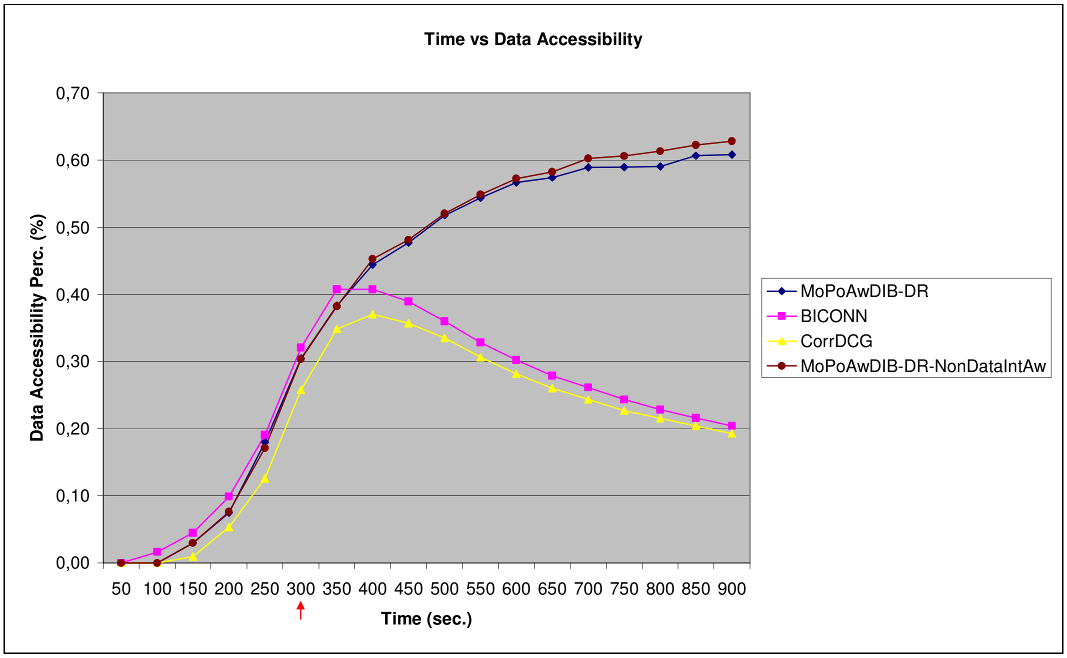


Figure 31– Data Accessibility, Relocation Period = 300 sec

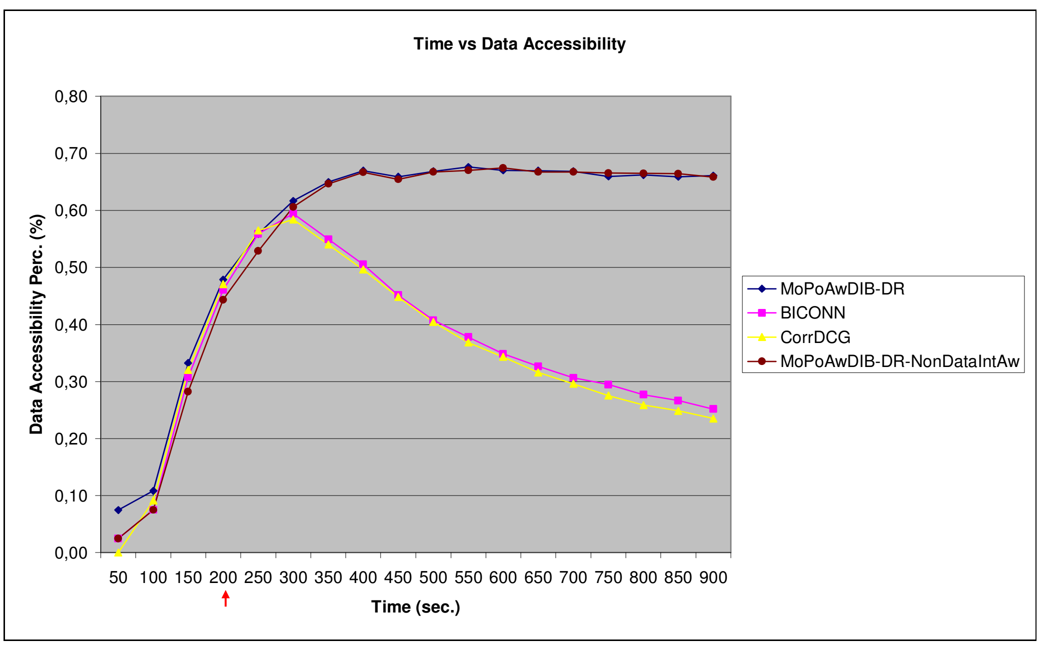


Figure 32 – Data Accessibility, Relocation Period = 200 sec

4.3 Cache Hit Ratio

Cache hit ratio performance metric is investigated for the same simulation runs given in previous data accessibility section. Average cache hit ratios are recorded for mobile nodes through total simulation time.

4.3.1 Simulation Environment and Parameters

Same simulation scenarios are applied as the data accessibility evaluation section. Therefore, Table 4 including algorithmic parameters and simulation environment properties is also valid for cache hit ratio case. Similarly, mobility scenarios of mobile nodes and group main data interest items can be seen in Figures 29, 30.

4.3.2 Experimental Results

Figures 33 and 34 show average cache hit ratio percentages of mobile nodes that access a series of data items regularly. Until data replication periods at t = 300 sec, and t = 200 sec average cache hit ratios of mobiles are nearly similar because initial caches only include the data items that are originally kept. Then, each access to the original data item is a cache hit only. The impact of replica allocation procedure after t = 300 sec and t = 200 sec becomes obvious on cache hit ratios. Data items are allocated within caches of mobile nodes for each group.

Cache hit ratios of mobiles nodes that apply mobility aware clustering methodology is higher than the mobile nodes applying Biconnected Components strategy. As our data replication model, MoPoAwDIB-DR is based on remaining energy and remaining memory parameters for replicating data, the model may prefer different candidates for replica allocation. For instance, for a data item D_i model CorrDCG always prefers the mobile node having higher data correlation value with that item, but our MoPoAwDIB-DR may prefer another non-optimal candidate in terms of data correlation since that mobile node has less remaining energy or remaining cache size. This attitude explains the minor variances in cache hit ratio of MoPoAwDIB-DR and MoPoAwDIB-DR-NonDataInterestAware after replica allocation is completed.

As can be seen models BICONN and CorrDCG has lower cache hit ratios than models MoPoAwDIB-DR and MoPoAwDIB-DR-NonDataInterestAware. This represents the advantages of mobility and data interest awareness over Biconnected Components strategy in clustering phase.

Initial energies of mobile nodes are the same and enough for completion of the simulation. As a result, effect of power awareness for replica allocation cannot be proved by these graphical representations. In order to figure out the advantage of power awareness other suitable simulation results are provided at following section (Section 4.5).

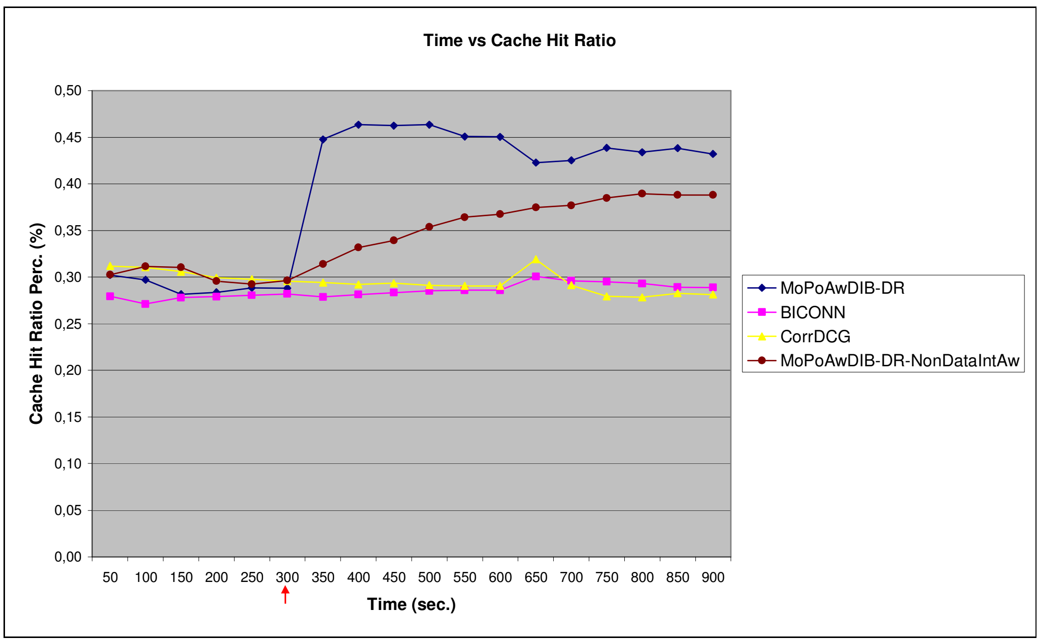


Figure 33 – Cache Hit Ratio, Relocation Period = 300 sec

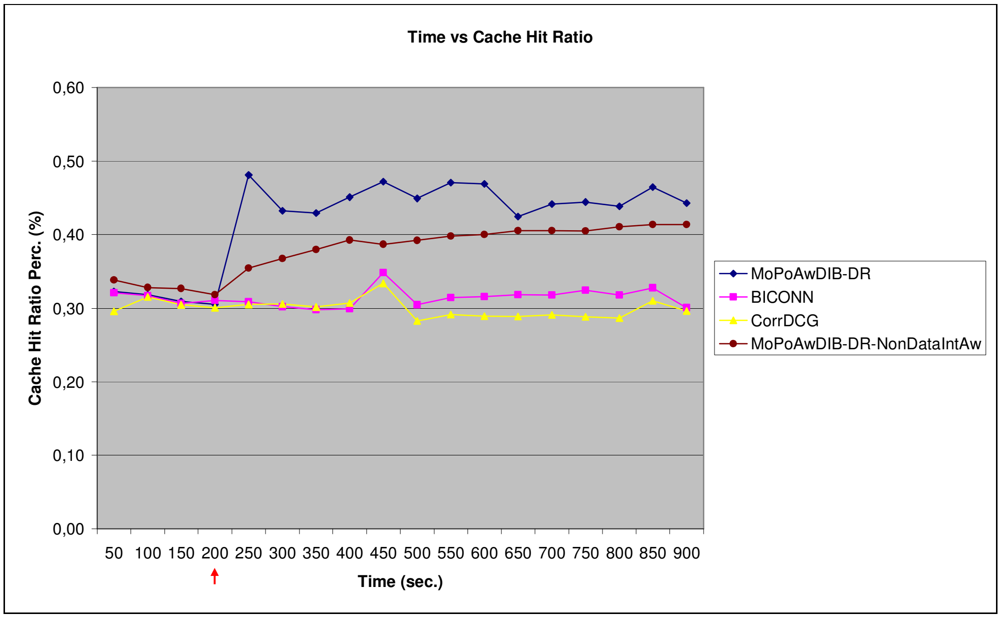


Figure 34 – Cache Hit Ratio, Relocation Period = 200 sec

4.4 Importance of Data Interest Aware Clustering

The importance of data interest based clustering arouses when mobile nodes belonging to different sub-missions move closer for a period of time. When data replication algorithm is run, the mobility aware clustering is expected to unify different sub-mission groups in a single cluster due to mobility pattern similarity. However, our model MoPoAwDIB-DR aims to estimate grouping both on mobility and data interest patterns correctly. Therefore, MoPoAwDIB-DR model would form more stable groups that are less likely to be disconnected because of different sub-missions. To illustrate this fact, a simulation scenario is prepared. Results of the simulation run are investigated on data accessibility and cache hit ratio metrics.

4.4.1 Simulation Environment and Parameters

Table 5 shows environmental and algorithmic parameters of the simulation scenario. There are 6 mobility groups including 5 mobile nodes each. Relocation period for that simulation is 200 seconds.

Table 5 – System Parameters for Simulation Scenario

Parameter	Simulation Scenario for Data Interest Aware Clustering
Environment Area Size	1000 x 1000
Number of Mobile Nodes	30 (5 mobile nodes per group)
Number of Mobility Groups	6
Number of Data Items	30
Relocation Period	200 sec
Total Simulation Time	900 sec
Radio Communication Range	250 meters

Figure 35 draws mobility patterns of the simulation scenario. Mobility groups 4, 5 and 6 start movement at the same point and they move all together from west-to-east direction for a period. Later they continue on different directions. Likewise groups 1, 2 and 3 have similar motion paths later then, they divert. Groups 1, 2, 3, 4, 5, 6 have main data interest items as D_{26}, D_{16}, D_{22}, D_2, D_7, D_{12} respectively. Members of group 1 are M_1, M_2, M_3, M_4, M_5; group 2 are M_6, M_7, M_8, M_9, M_{10}; group 3 are M_{11}, M_{12}, M_{13}, M_{14}, M_{15}; group 4 are M_{16}, M_{17}, M_{18}, M_{19}, M_{20}; group 5 are M_{21}, M_{22}, M_{23}, M_{24}, M_{25}; group 6 are M_{26}, M_{27}, M_{28}, M_{29}, M_{30}.

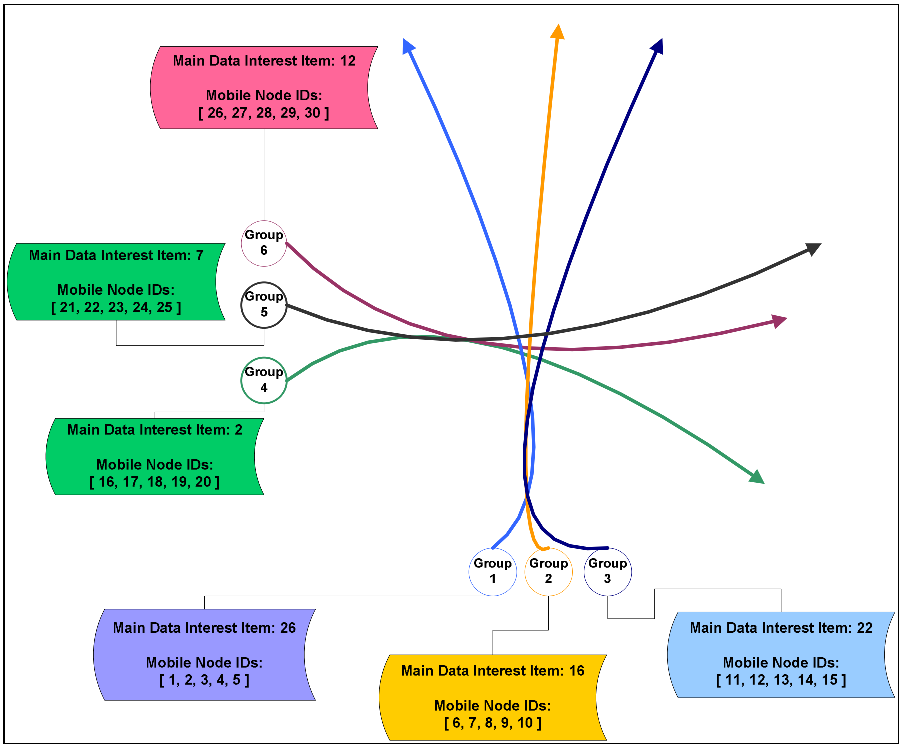


Figure 35 – Mobility Scenario for Data Interest Aware Clustering

4.4.2 Experimental Results

Figure 36 shows average data accessibility of mobile nodes. Unlike the results given in data accessibility section, that result explains improvement provided by data interest aware clustering. As can be seen in Figure 36, data accessibility of our model MoPoAwDIB-DR is higher than the model MoPoAwDIB-DR-NonDataInterestAware. After relocation period t = 200 sec both mobility aware clustering models (MoPoAwDIB-DR, MoPoAwDIB-DR-NonDataInterestAware) have increasing data accessibilities in contrast to Biconnected Components based clustering models (BICONN, CorrDCG). Nonetheless, our data interest based clustering model MoPoAwDIB-DR obtains higher data accessibility rates compared to NonDataInterestAware model.

Consequently, it is possible to say that Figure 36 proves that data interest aware clustering is successful in differentiating sub-missions groups even though they have similar mobility patterns.

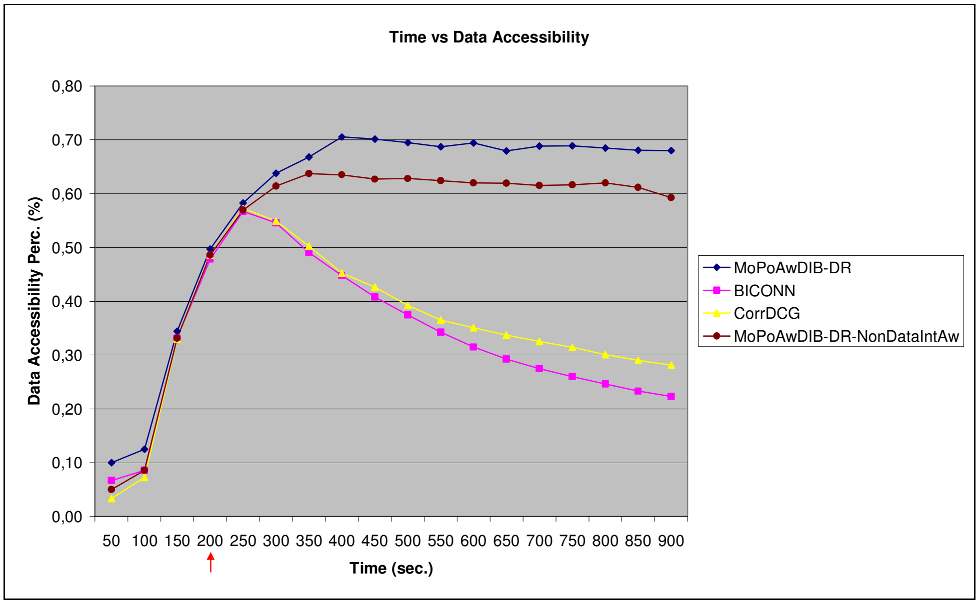


Figure 36 – Data Accessibility for Data Interest Awareness Scenario

Figure 37 illustrates results of the other performance metric, cache hit ratio. Cache hit ratios for all models are nearly equal until the replica allocation period since caches only include original data items. After data is replicated cache hit ratios increase. It can be derived from Figure 37 that as time increases, cache hit ratio of MoPoAwDIB-DR model reaches higher cache hit ratios compared to MoPoAwDIB-DR-NonDataInterestAware model because data interest aware clustering clusters mobile nodes correctly and ends with better caching alternatives. In addition other models BICONN and CorrDCG output a single biconnected component since all mobile nodes are so close to each other.

Hence, effects of data interest aware clustering on cache hit ratio can also be observed. Our model results in better cache hit ratios while other comparison models fall behind its ratios.

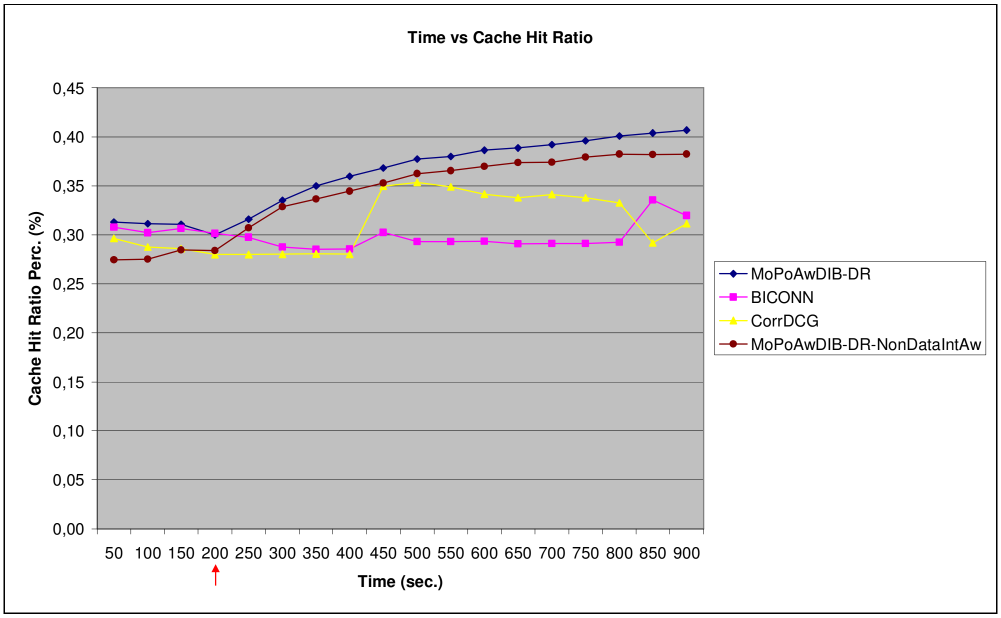


Figure 37 – Cache Hit Ratio for Data Interest Awareness Scenario

4.5 Importance of Power Aware Replica Allocation

Allocating replicas on mobile nodes is power aware in our MoPoAwDIB-DR approach. Mobile nodes having lower remaining energies are weak replica holder candidates even though they have higher data correlation values. Mobile nodes having lower remaining energy are more likely to be disconnected from the group due to energy consumption. Hence, data items that are accessed frequently are not replicated on mobile nodes which are poor in energy.

In order to prove the importance of power aware replica allocation, we have observed data accessibility percentages for different models. Models MobAwCorrDCG and CorrDCG are the same as MoPoAwDIB-DR and BICONN at clustering phase respectively but allocate replicas by using only data correlation and data access frequencies.

4.5.1 Simulation Environment and Parameters

Table 6 involves system parameters used in the simulation run. 4 mobility groups exist and each one is composed of 5 mobile nodes. Relocation period is set to 200 seconds.

Table 6 – System Parameters for Simulation Scenario

Parameter	Simulation Scenario for Data Interest Aware Clustering
Environment Area Size	1000 x 1000
Number of Mobile Nodes	20 (5 mobile nodes per group)
Number of Mobility Groups	4
Number of Data Items	20
Relocation Period	200 sec
Total Simulation Time	900 sec
Radio Communication Range	250 meters

Figure 38 shows mobility patterns of mobile nodes from time $t = 0$ *sec*. to time $t =$ *900 sec*. In this simulation not all mobile nodes have the same initial energies. Two mobile nodes in every group have less initial energy than other members of the group. At time $t = 300$ *sec*, mobile nodes having lower initial energies disconnect from the network since they have consumed all their energies. Groups 1, 2, 3, 4 have main data interest items as D_{12}, D_{17}, D_3, D_7 respectively. Members of group 1 are M_1, M_2, M_3, M_4, M_5; group 2 are M_6, M_7, M_8, M_9, M_{10}; group 3 are M_{11}, M_{12}, M_{13}, M_{14}, M_{15}; group 4 are M_{16}, M_{17}, M_{18}, M_{19}, M_{20}.

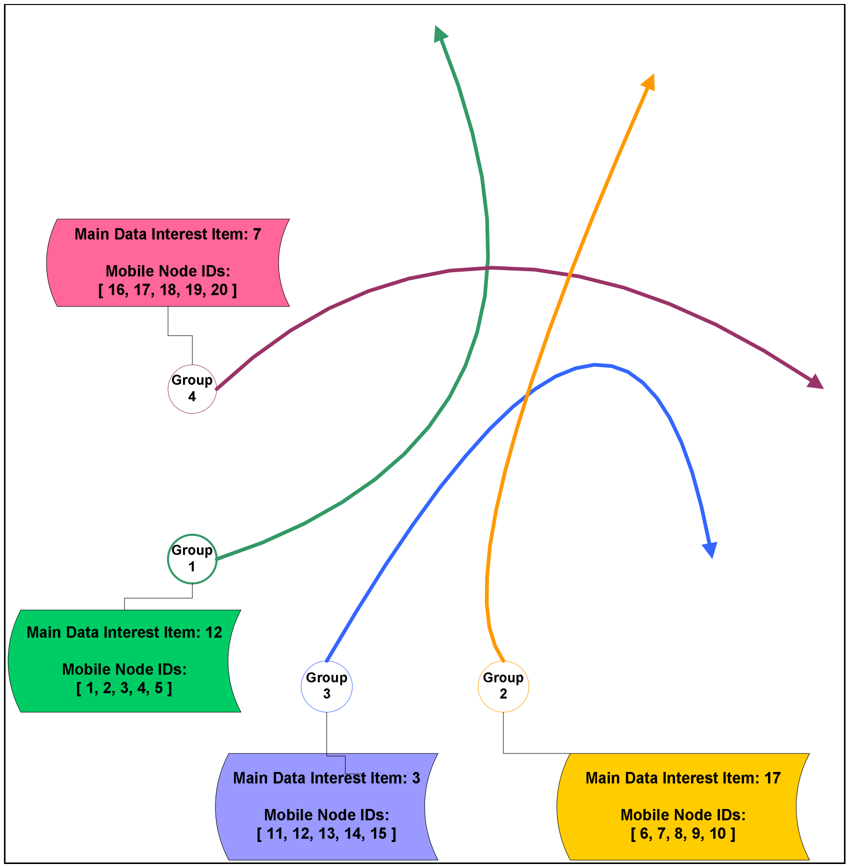


Figure 38 – Mobility Scenario for Power Aware Replica Allocation

4.5.2 Experimental Results

In the light of given information it is possible to comment on the graphical demonstration of data accessibility percentages shown in Figure 39. From Figure 39, after time $t = 200\ sec$, when data replication is completed, data accessibility increases sharply for each model. After time $t = 300\ sec$, a decrement in data accessibility is observed for mobile nodes because two mobile nodes are disconnected from each mobility group. Therefore data items that are allocated on those mobile nodes become inaccessible. For model MobAwCorrDCG data accessibility decreases as time increments. Unlike MobAwCorrDCG, our strategy MoPoAwDIB-DR is more successful in keeping data accessibility rate despite of the mobile nodes disconnected due to power consumption. Models BICONN and CorrDCG are same in clustering strategy but different in replica allocation method. BICONN applies the same replica allocation phase as our strategy, while CorrDCG is not power aware. Although both models reveal decreasing data accessibility, BICONN is able to keep data accessibility at higher rates.

To sum up, overall simulation results show that after some of the mobile nodes are disconnected due to lack of energy; power aware replica allocation (MoPoAwDIB-DR, BICONN) gives higher data accessibility in contrast to the models not considering remaining energy (MobAwCorrDCG, CorrDCG).

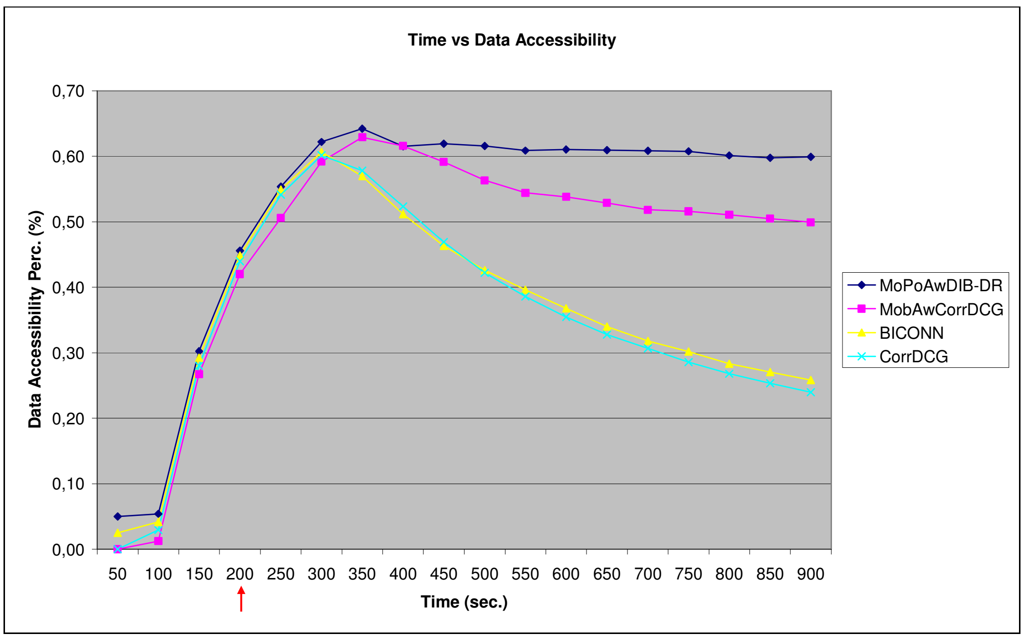


Figure 39 – Data Accessibility for Power Aware Replica Allocation Scenario

4.6 Effects of Relocation Period

Relocation period determines how frequent data replication process is executed. This frequency forms a cost trade off between messaging overhead and group disconnection recovery. As relocation periods are frequent then grouping estimations are refreshed regularly so disconnections are detected early. Nonetheless, this frequency brings about more message exchanges as the process requires. This section explores the effects of different relocation period values on data accessibility performance metric. In addition cost analysis for relocation period is obtained by investigating total traffic produced.

4.6.1 Simulation Environment and Parameters

Table 7 gives environmental and algorithmic parameters for the simulation scenario applied to compare the effect of value of relocation period. Relocation periods are set as 200, 300, 400, 500, 600 seconds.

Table 7 – System Parameters for Relocation Period Comparison Scenario

Parameter	Simulation Scenario for Relocation Period Comparison
Environment Area Size	1000 x 1000
Number of Mobile Nodes	20 (5 mobile nodes per group)
Number of Mobility Groups	4
Number of Data Items	20
Total Simulation Time	900 sec
Radio Communication Range	250 meters

Figure 40 shows movement directions of mobility groups. Each mobility group initiates from different directions of the simulation area and they do not move towards a defined direction instead they move around. Groups 1, 2, 3, 4 have main data interest items as D_8, D_{13}, D_{18}, D_{32} respectively. Members of group 1 are M_1, M_2, M_3, M_4, M_5; group 2 are M_6, M_7, M_8, M_9, M_{10}; group 3 are M_{11}, M_{12}, M_{13}, M_{14}, M_{15}; group 4 are M_{16}, M_{17}, M_{18}, M_{19}, M_{20}.

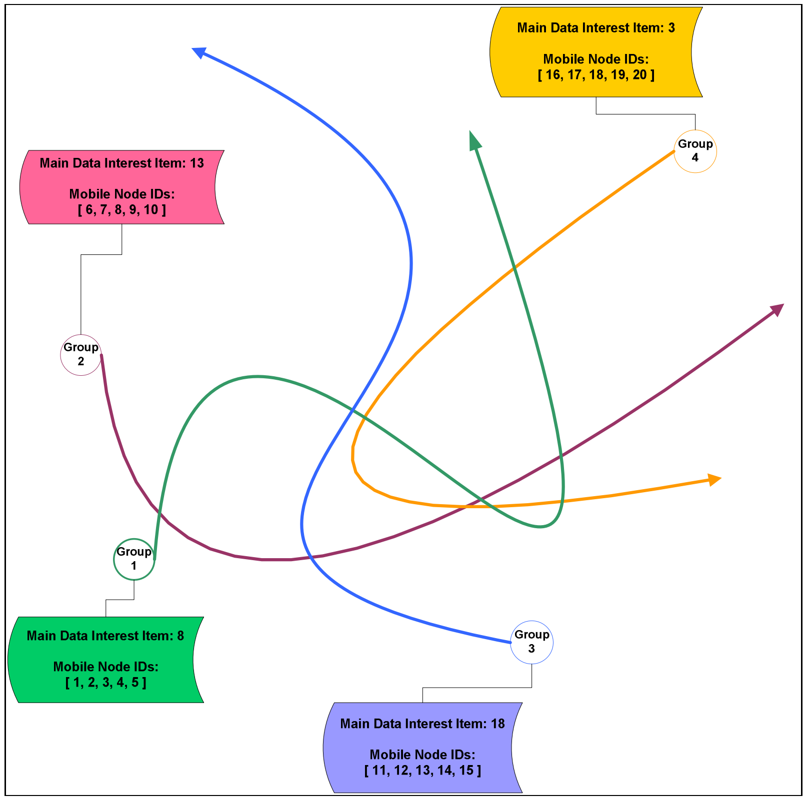


Figure 40 – Mobility Scenario for Relocation Period Comparison Scenario

4.6.2 Experimental Results

Figure 41 demonstrates the effect of relocation period on accessibility measure. Data replication strategies that cluster nodes with respect to mobility patterns result in a regular decrease in data accessibility. Mobility aware data replication procedures degrade in accessibility as replica allocation period is increased. Connectivity state of all mobile nodes within the network changes frequently and unexpectedly due to both mobility and environmental specifications in MANETs. Therefore, the more frequently data replication is performed, the more stable clusters are formed and the earlier connectivity changes are detected. Unlike mobility aware data replication schemes, data replication processes obeying biconnected component formation for clustering show irregular behaviors. Biconnected Component method is weak in detecting actual mobility groups that tend to move together. Consequently, data accessibility may increase or decrease significantly whether replica allocation execution produces different biconnected components for separate mobility groups or not. The increase in accessibility at relocation period of 400 seconds comes out from the state that mobility groups are apart enough to take place in different biconnected components.

Hence, greater relocation periods prevent adaptation to new connectivity situations and cause lower data accessibilities. Mobility aware data replication models obey this deduction since they estimate mobility pattern of mobile nodes better than biconnected component based models.

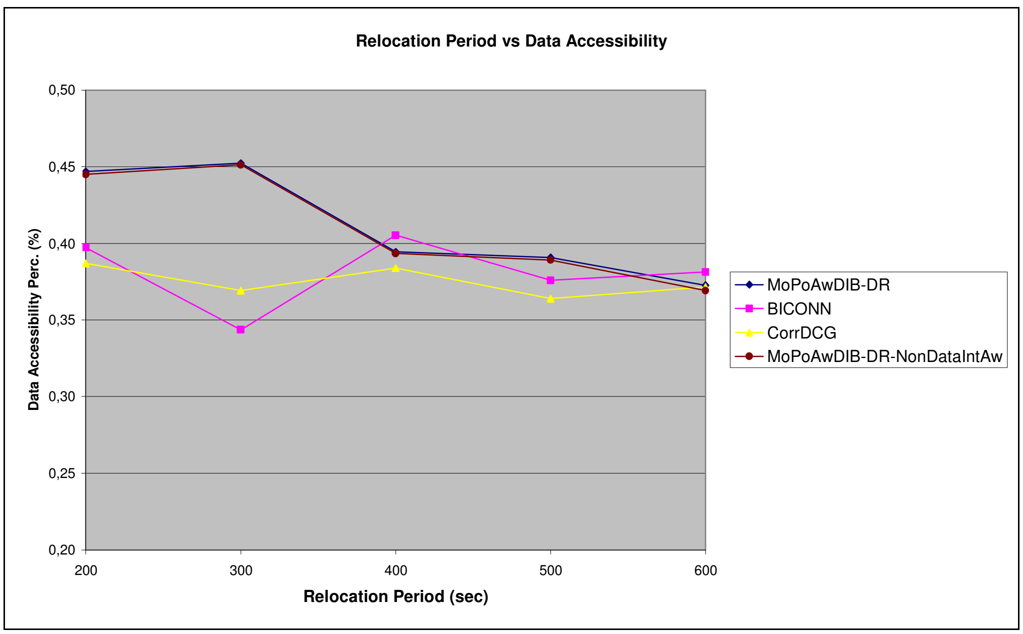


Figure 41 – Data Accessibility for Different Relocation Periods

In this simulation experiment traffic is measured in units of bytes. Traffic is defined as addition of the traffic for message exchanges in data replication process and the traffic produced for data access requests. By this way, it is possible to compare messaging overhead of different data replication strategies. Figure 42 illustrates that whenever replica allocation is renewed often, namely at lower relocation periods, traffic overhead of all methodologies goes up. It should be noticed that total traffic produced by mobility aware models is usually lower compared to the models using biconnected components for clustering. Therefore, if replicas are allocated at proper mobile nodes, the traffic overhead of data access requests decreases. Thus, biconnected component methods cannot avoid the traffic overhead of data access requests.

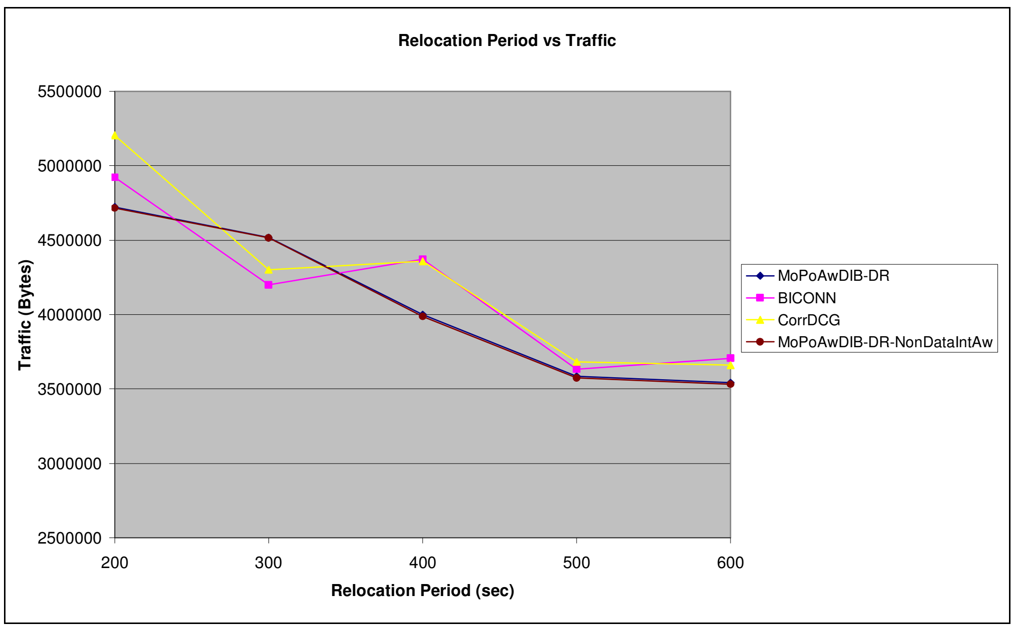


Figure 42 – Traffic for Different Relocation Periods

CHAPTER 5

CONCLUSION AND FUTURE WORK

This thesis study presents a mobility and power aware data interest based data replication (MoPoAwDIB-DR) strategy for mobile ad hoc networks in wireless environment. Proposed data replication process is composed of three phases in the order of leader election phase, clustering phase and replica allocation phase. Data replication process utilizes both user profiles and device profiles of mobile nodes.

In clustering phase, the mobile nodes which show similar mobility pattern and data interest pattern, are grouped into the same cluster. In replica allocation phase, the algorithm determines which data item to replicate on which mobile node. This decision is based on not only data access frequency and data correlation values but also remaining energy and memory capacities of mobile nodes. The notions of motion pattern and data interests in terms of data access frequency and data correlation address the user profiles. On the other hand, remaining energy and memory address the device profiles.

In spite of existing studies in the literature on data replication for MANETs, our approach achieves better data accessibility for mission critical mobility groups. In this work, mobile nodes are clustered by data interest pattern similarity, after mobility pattern similarity clustering so that stronger stable clusters are formed. Different sub-mission groups moving closer for a period of time can be distinguished by data interest based clustering. Furthermore, our replica allocation strategy is power aware replica, where mobile nodes having less amount of remaining energy are not preferred as replica holder. By this method, disconnections of the mobile nodes that have low energy are tolerated.

A simulation dependent performance evaluation is conducted by using ns-2 simulation environment. Our suggested model (MoPoAwDIB-DR) is explored and compared using data accessibility; cache hit ratio and traffic metrics. In addition, special simulation scenarios are performed in order to prove the importance of the main contributions; data interest aware clustering and power aware replica allocation. It has been proved that our approach outperforms all of the existing methodologies with respect to these performance metrics. The simulation results also reveal the improvement obtained in data accessibility.

As a future work, the shortcoming of periodic execution mechanism of the data replication process can be explored. For example, data replication procedure can be triggered dynamically after an initial clustering phase. This invocation can result from the changes in network topology. By this way, clustering phase would not be repeated periodically; instead only replica allocation suggestions are updated. This requires a continuous position advertisement, which may require the investigation of the messaging overhead versus data accessibility costs.

Another future work is about examining the importance of stability of the leader node. As the data replication process is executed by the elected leader node, it is crucial to guarantee that the process is completed. Thus an alternative leader election protocol considering energy capacities of candidates can be investigated instead of Lowest-ID protocol.

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