ABP: a low-cost, energy-efficient clustering algorithm for relatively static and quasi-static MANETs

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Abstract: Clustering techniques have been proposed to construct hierarchies of nodes inside Mobile Ad Hoc Networks (MANETs) thereby increasing their scalability and manageability and reducing the amount of maintained routing information. Herein, we introduce a distributed clustering algorithm that uses both location and energy metrics for cluster formation. Our proposed solution addresses cluster stability, manageability and energy efficiency issues. Unlike existing active clustering methods, our algorithm relieves the network from the unnecessary burden of control messages broadcasting, especially for relatively static and quasi-static network topologies. The efficiency, scalability and competence of our algorithm against alternative approaches have been demonstrated through simulation results.

Keywords: mobile ad hoc network; MANETs; clustering; scalability; stability; manageability; energy efficiency.

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1 Introduction

Mobile Ad Hoc Networks (MANETs) represent complex distributed systems that comprise wireless mobile nodes that can freely and dynamically self-organise into arbitrary and temporary 'ad hoc' network topologies, allowing people and devices to seamlessly internetwork in areas with no pre-existing communication infrastructure (Chlamtac et al., 2003). Wireless communication and the lack of centralised administration pose numerous challenges in MANET environments (Perkins, 2001). Node mobility results in frequent failure and activation of links, causing a routing algorithm reaction to topology changes and hence increasing network control traffic (Hong et al., 2002). Ensuring effective routing and QoS support while considering the relevant bandwidth and power constraints remains a great challenge. Given that MANETs may comprise a large number of MNs, a hierarchical structure will scale better (Li and Gerla, 1997).

Hence, one promising approach to address routing problems in MANET environments is to build hierarchies among the nodes, such that the network topology can be abstracted. This process is commonly referred to as clustering and the substructures that are collapsed in higher levels are called clusters (Yu and Chong, 2005). Cluster-based routing is an interesting solution to address nodes heterogeneity, and to limit the amount of routing information that propagates inside the network. The grouping of the network nodes into a number of overlapping clusters enables the aggregation of the routing information, and consequently increases the routing algorithms scalability. Specifically, clustering makes possible a hierarchical routing in which paths are recorded between clusters (instead of between nodes); this increases the routes lifetime, thus decreasing the amount of routing control overhead (Belding-Royer, 2003).

The concept of clustering in MANETs is not new; many algorithms that consider different metrics and focus on diverse objectives have been proposed (Chlamtac et al., 2003; Yu and Chong, 2005). However, most existing algorithms fail to guarantee stable cluster formations. More importantly, they are based on periodic broadcasting of control messages resulting in increased consumption of network traffic and Mobile Hosts (MHs) energy.

In this paper, we introduce a distributed algorithm, the Adaptive Broadcast Period (ABP) algorithm, for efficient and scalable clustering of MANETs that corrects the two aforementioned weaknesses. The main contributions of ABP algorithm are: fast completion of clustering procedure, where both location and battery power metrics are taken into account; derived clusters are sufficiently stable, while cluster scale is effectively controlled so as not to grow beyond certain limits; minimisation of control traffic volume, especially in relatively static MANET environments. The initial ideas behind our proposed algorithm have been presented in Gavalas et al. (2006).

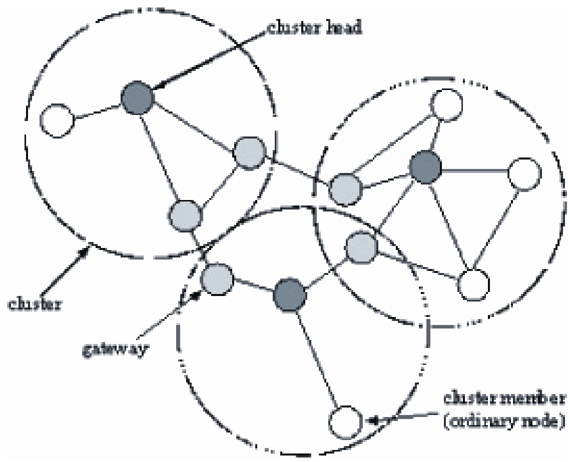
It should be stressed that ABP clustering algorithm mainly suits relatively static and quasi-static MANETs. In such environments, ABP not only considers both energy and location metrics for cluster formation, but also adjusts the control traffic required for cluster maintenance according to the average measured node mobility.

The remainder of the paper is organised as follows: Section 2 provides an overview of clustering concepts and algorithms. Section 3 describes the details of our ABP algorithm and Section 4 discusses simulation results. Finally, Section 5 concludes the paper and draws directions for future work.

2 Clustering in mobile ad hoc networks

In clustering procedure, a representative of each subdomain (cluster) is 'elected' as a *Cluster Head* (CH) and a node which serves as intermediate for inter-cluster communication is called *gateway*. Remaining members are called *ordinary nodes*. The boundaries of a cluster are defined by the transmission area of its CH. With an underlying cluster structure, non-ordinary nodes play the role of dominant forwarding nodes, as shown in Figure 1.

Figure 1 CHs, gateways and ordinary nodes in MANETs clustering



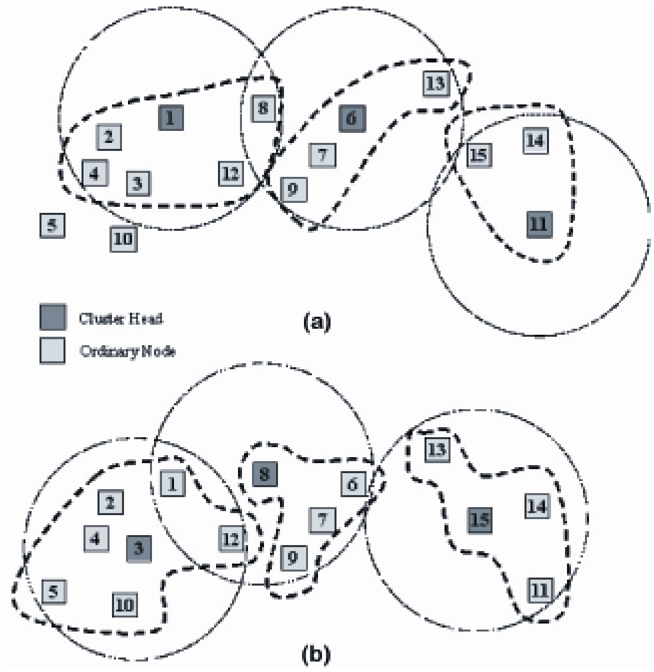
By replacing the nodes with clusters, existing routing protocols can be directly applied to the network. Only gateways and CHs participate in the propagation of routing control/update messages. In dense networks this significantly reduces the routing overhead, thus solving scalability problems for routing algorithms in large MANETs. Several dynamic clustering strategies based on these ideas have been proposed in the literature (e.g. Basagni, 1999; McDonald and

Znati, 1999; Chatterjee et al., 2002; Yi et al., 2003; Li et al., 2004; Sivavakeesar et al., 2004; Gavalas et al., 2006). These strategies mainly differ in the criteria used to organise and maintain the cluster.

Cluster architectures do not necessarily include a CH in every cluster. CHs hold routing and topology information, relaxing ordinary MHs from such requirement; however, they represent network bottleneck points (Chlamtac et al., 2003). In clusters without CHs, every MH has to store and exchange more topology information, yet, that eliminates the bottleneck of CHs. Yi et al. identified two approaches for cluster formation, *active* clustering and *passive* clustering (Yi et al., 2003). In active clustering, MHs cooperate to elect CHs by periodically exchanging information, regardless of data transmission. On the other hand, passive clustering suspends clustering procedure until data traffic commences (Yi et al., 2001). It exploits ongoing traffic to propagate 'cluster-related information' (e.g. the state of a node in a cluster, the IP address of the node) and collects neighbour information through promiscuous packet receptions.

Passive clustering eliminates major control overhead of active clustering, still, it implies larger setup latency which might be important for time critical applications; this latency is experienced whenever data traffic exchange commences. On the other hand, in active clustering scheme, the MANET is flooded by control messages, even while data traffic is not exchanged thereby consuming valuable bandwidth and battery power resources.

Figure 2 LID vs. HD algorithms clustering



Recently Multi-Point Relays (MPRs) have been proposed to reduce the number of gateways in active clustering. MPR hosts are selected to forward broadcast messages during the flooding process (Qayyum et al., 2001). This technique substantially reduces the message overhead as compared to a typical flooding mechanism, where every node retransmits a message when it receives its first copy. Using MPRs, the Optimized Link State Routing (OLSR) protocol can provide optimal routes, and at the same time minimise the volume of signalling traffic in the network (Clausen and Jacquet, 2003). An efficient clustering method should be able to partition a MANET quickly with little control overhead. Due to the dynamic nature of MANETs, optimal cluster formations are not easy to build. To this end, two distributed clustering algorithms have been proposed: Lowest ID (LID) algorithm (Yi et al., 2003) and Highest Degree (HD) algorithm (Yi et al., 2003). Both of them belong to active clustering scheme.

In LID algorithm, each node is assigned a unique ID. Periodically, nodes broadcast the list of nodes located within their transmission range (including themselves) through a 'Hello' control message. The LID node in a neighbourhood is then elected as the CH; nodes which can 'hear' two or more CHs become gateways, while remaining MHs are considered as ordinary nodes. In HD algorithm, the HD node in a neighbourhood, i.e. the node with the largest number of neighbours is elected as CH. Figure 2 compares LID vs. HD algorithm approaches.

LID method is a quick clustering method, as it only takes two 'Hello' message periods to decide upon cluster structure and also provides a more stable cluster formation than HD. In contrast, HD needs three 'Hello' message periods to establish a clustered architecture (Li et al., 2004). In HD method, losing contact of a single node (due to MH movement), may cause failure of the current CH to be reelected; also CHs may fail to provide sufficient quality of service to their members as their member list expands. On the other hand, HD method can get fewer clusters than LID, which is more advantageous in large-scale network environments.

In current clustering schemes, stability and cluster size are very important parameters; however, reducing the number of clusters does not necessarily result in more efficient architectures. A CH may end up dominating so many MHs that its computational, bandwidth and battery resources will rapidly exhaust. Therefore, effective control of cluster size is another crucial factor.

Summarising, both LID and HD algorithms use exclusively location information to form clusters and elect CHs. In a more recent approach, Li et al. proposed Vote-based Clustering (VC) algorithm, where CH elections are based not purely on location but also on the battery power level of MHs (Li et al., 2004). In particular, MHs with high degree (large number of neighbours) and sufficient battery power are elected as CHs. However, simulations have shown that the combination of position and power information in clustering procedure results in frequent CH changes, i.e. overall cluster structure instability (Li et al., 2004). In a MANET that uses cluster-based services, network performance metrics such as throughput, delay and effective management are tightly coupled with the frequency of cluster reorganisation. Therefore, stable cluster formation is essential for better management and QoS support.

In addition, LID, HD and VC algorithms share a common design characteristic which derives from their active clustering origin. Cluster formation is based on the periodic broadcast of 'Hello' signalling messages. In cases where MHs are relatively static (e.g. in collaborative computing, on-the-fly conferencing, etc.), periodic 'storms' of control messages only occur to confirm that cluster structure established in previous periods should remain unchanged. These unnecessary message broadcasts not only consume network bandwidth, but valuable battery power as well.

A different clustering strategy is proposed in McDonald and Znati (1999), Sivavakeesar et al. (2004), where the cluster stability objective is addressed by identifying groups of MHs which exhibit similar mobility pattern; such groups of nodes are included into the same cluster, given that they are within transmission range of each other. These strategies partition the network into clusters that provide some guarantees on the path stability with respect to nodes mobility: the nodes belonging to the same cluster are expected to be reachable along paths internal to the cluster for a period of time t, with a probability $\geq \alpha$ (hence, they are called (α–t) cluster methods). However, these clustering schemes typically make the non-realistic assumption that mobility information is provided by a GPS card with sufficient accuracy, mounted on every mobile node. In addition, they are not adequate for MANET environments where MHs show no group mobility behaviour. As described in Section 3, our proposed clustering algorithm does not consider mobility as a metric for cluster formation, yet, CHs monitor the mobility behaviour of their attached cluster members to adapt the local 'Hello' Broadcast Period (BP) accordingly.

Finally, Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol has been proposed in Heinzelman et al. (2000). LEACH is a clustering-based protocol that utilises randomised rotation of local cluster base stations (CHs) to evenly distribute the energy load among the sensors in the network. LEACH has been proposed for Wireless Microsensor Networks, wherein nodes mobility is not an issue, hence, LEACH is not directly related to this work.

3 The adaptive broadcast period algorithm

Our ABP algorithm aspires to correct the inefficiencies of existing active clustering algorithms (LID, HD and VC). Emphasis is given on following three directions:

- A quick method for cluster formation is needed; required speed though should not be achieved at the expense of instable cluster configurations. To meet this objective, we modify VC algorithm to avoid frequent CH 'reelections'.
- Cluster sizes should be controlled to derive neither too large nor too small clusters.
- Control messages BP should be dynamically adapted to avoid unnecessary message exchanges, when the mobility pattern of MHs is such that network topology is relatively static.

The methodology chosen to achieve the three aforementioned objectives is detailed in the following sections.

3.1 Cluster formation

Similarly to VC and unlike LID and HD protocols, both position and battery power metrics are considered in CH election. However, emphasis has been given to prevent frequent CH changes and prolong the average lifetime of CH serving time and cluster membership, therefore, meeting the requirement for steadier cluster formations.

3.1.1 Network model

A MANET can be divided into several overlapped clusters. A cluster comprises of a subset of nodes that communicate via their assigned CH. The network is modelled as an undirected graph G (V, E), where V denotes the set of all MHs (*vertices*) in the MANET and E denotes the set of links or *edges* (i, j), where $i, j \in V$. Each link signifies that two MHs are within the transmission range of each other. Let S_i be the set of MHs that can be reached by node i. We assume every link is bidirectional so that link (i, j) exists if and only if $j \in S_i$.

Each MH has a unique identifier (MH_ID), which is a positive integer. MHs also hold information about the identity of their assigned CH (CH_ID). CHs are easily identified by their identical MH_ID and CH_ID values.

Control information is communicated through 'Hello' messages, transmitted on the common wireless channel. Every MH acquires information from incoming 'Hello' message sent by its neighbours. We assume that only when two MHs lie within mutual transmission range, they can communicate directly with each other, i.e. a bidirectional link exists. Another attribute of MHs is their battery power level (remaining battery time), which is a positive integer, $0 \leq b \leq 100$; it is noted that startup battery levels may vary among nodes. We assume linear decrease of b over time; naturally, battery energy of CHs exhausts faster than ordinary MHs as they serve a number of MHs, forwarding messages on their behalf. In particular, the power b_t of ordinary nodes at time t is evaluated according to equation (1):

$$b_t = \left\lceil \frac{N_1 \cdot b_i}{t} \right\rceil \tag{1}$$

where b_i is the initial node's power and N_1 a normalisation factor. Similarly, the power b_t of CHs at time t is evaluated according to equation (2):

$$b_t = \left\lceil \frac{N_2 \cdot b_{i,CH}}{n \cdot t_{CH}} \right\rceil \tag{2}$$

where $b_{i,CH}$ is the node's power at the time that took over the CH responsibility, n is the mean number of cluster members over CH service time t_{CH} and N_2 a normalisation factor.

3.1.2 Clustering algorithm

Our clustering algorithm considers both location and power information to partition a MANET into separate clusters. In this context, we introduce the concept of 'Cluster Head Competence' (CHC), which represents the competence of an MH to undertake the role of a CH.

The format of a typical 'Hello' message is shown in Figure 3. Each 'Hello' message includes identifications of its sender (MH_ID) and sender's assigned CH (CH_ID). CHC represents a weighted sum of sender's degree (number of neighbours) and its battery power level. Finally, the 'Option' message field is used for cluster size management purposes (see Subsection 3.2), and BP field is used to adapt the BP within a particular cluster (see Subsection 3.3).

Figure 3 'Hello' packet format

MH_ID	*CH_ID*	*CHC*	*Option*	*BP*
8 bit	8 bit	8 bit	4 bit	8 bit

CHC values are calculated according to the following equation:

$$CHC = (c_1 \times d + c_2 \times b) - p \quad (3)$$

where:

- c_1, c_2: weighted coefficients of MH degree and battery availability, respectively ($0 \le c_1, c_2 \le 1$, $c_1 + c_2 = 1$)
- d: number of neighbours (degree of MH)
- b: remaining battery lifetime (percentage of remaining over full battery power)
- p: 'handover' penalty coefficient (explained in the following subsection).

The algorithm's execution involves the following steps:

1 Each MH sends a 'Hello' message randomly during a 'Hello' cycle. If an MH has just joined the MANET, it sets CH_ID value equal to a negative number. That signifies an MH is not a member of any cluster and has no knowledge of whether it is within transmission radius of another MH.

2 Each MH counts how many 'Hello' messages it received during a 'Hello' period, and considers that number as its own degree (d).

3 Each MH broadcasts another 'Hello' message, setting CHC field equal to the value calculated from equation (3).

4 Recording received 'Hello' messages during two 'Hello' cycles, each MH identifies the sender with highest CHC value and thereafter considers it as its CH.

In the next 'Hello' cycle, CH_ID value will be set to elected CH's ID value. In the case of two or more MHs having the same lowest CHC value, the one with the LID is 'elected' as CH. Following the aforementioned algorithm steps, clustering procedure is completed within two 'Hello' cycles.

ABP execution steps are illustrated in Figure 4. Table 1 presents how CHC values are calculated, where the coefficients of equation (3) are set to $c_1 = 0.4$ and $c_2 = 0.6$.

Figure 4 Illustration of ABP execution: (a) original placement of mobile nodes on the plane (dashed circles indicate nodes transmission range) and (b) cluster formation based on ABP clustering (CHC values calculation is based on the figures provided in Table 1) (see online version for colours)

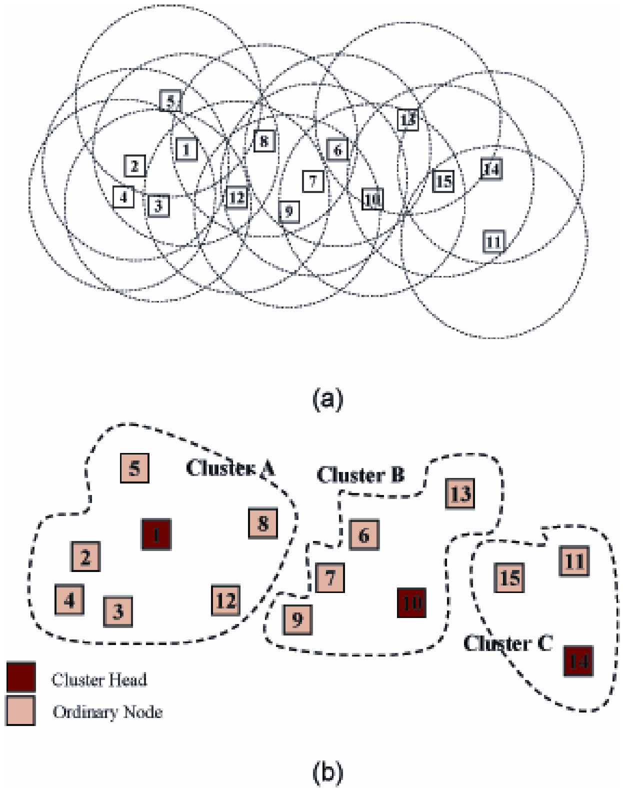


Table 1 Calculation of CHC values in ABP (where, $c_1 = 0.4$, $c_2 = 0.6$ and $p = 1$), based on equation (3)

MH_ID	*d*	*b*	CHC
1	6	4	3, 8
2	4	5	3, 6
3	4	3	2, 4
4	3	4	2, 6
5	2	2	1
6	5	4	3, 4
7	5	2	2, 2
8	5	1	1, 6
9	5	4	3, 4
10	5	5	4
11	2	4	2, 2
12	5	2	2, 2
13	3	4	2, 6
14	2	7	4
15	4	2	1, 8

3.1.3 Securing cluster stability

Notably, our clustering algorithm extends the ideas of HD approach so as to include the battery energy metric in CH election process (when setting $c_1 = 1$, $c_2 = 0$ and $p = 0$ in equation (3), the two algorithms coincide). This similarity implies that our proposed algorithm runs the risk of providing instable cluster formations (cluster instability has been identified as the main weakness of HD algorithm (Li et al., 2004)), i.e. clusters are sensitive to hosts mobility.

According to the preceding description of our algorithm steps, CH reelection occurs when an ordinary MH claims higher CHC value compared to the current CH. For instance, that is likely to happen when: (1) a cluster member relocates away of its cluster perimeter, (2) a new MH moves within a cluster boundary, (3) the current CH presents slightly lower power level than an ordinary MH. Such re-election could trigger a global cluster reconfiguration process and massive transfers of routing data among elected CHs.

To correct this inefficiency, we introduce a penalty coefficient p in the calculation of CHC value, as shown in equation (3). The value of p is set to an integer value ($p > 0$) for ordinary MHs, while $p = 0$ for CHs. Assigning an appropriate value to p, we prevent MHs with slightly higher degree or lower battery power to that of current CHs to take up the role of CH, thereby avoiding unnecessary handovers. In other words, CH re-elections occur only in the event of major modifications of MANET topology structure (e.g. current CHs' degree has significantly decreased) or in cases where CHs future engagement on packet forwarding activity will soon cause their battery exhaustion.

It should be stressed that the inclusion of the 'handover' penalty coefficient p is not a fundamental solution to the problem of cluster instability. The issue of optimal selection of p values needs to be further investigated; this issue is discussed in Section 4, which presents the simulation results.

3.2 Cluster size management

The objective of clustering algorithms is to partition the network into several clusters. Optimal cluster size is dictated by the trade-off between spatial reuse of the channel (which drives towards small clusters) and delay minimisation (which drives towards large clusters) (Li and Gerla, 1997). In addition, large clusters lead to rapid exhaustion of CH battery power, while CHs represent network bottleneck points. On the other hand, small cluster sizes lead to formation of multiple clusters, implying growth of routing information and also network topology which is difficult to manage.

To address the issue of efficient cluster size management, we propose an adaptive cluster load balance method. The 'Option' field of 'Hello' packet (see Figure 3) is used for that purpose. CHs set the value of 'Option' field equal to the number of their dominated MHs. In contrast, ordinary MHs reset the 'Option' field value to 0. The number of MHs dominated by a single CH is not allowed to exceed a specified threshold T. The value of 'Option' field is of importance for MHs currently not belonging to any cluster or not being dominated by the CH that issued the 'Hello' message. In such cases, if 'Option' value equals T, MHs cannot request membership to the CH that broadcasted the 'Hello' message. As a result, potential CH bottlenecks are prevented and cluster sizes are moderated.

In addition, the above-described cluster size management method guarantees balanced load among various clusters. Resource consumption and data traffic is fairly distributed among network clusters, and does not burden certain clusters against others.

3.3 Dynamically adaptive control messages broadcast period

A principal consideration of our ABP algorithm is to reduce the number of control messages circulated within the MANET. Minimisation of message broadcasts ensures bandwidth savings and conserves computational resources and battery power not only on elected CHs but on ordinary nodes also.

The idea behind controlling the volume of broadcast messages is based on the realistic hypothesis that ad hoc networks are not always highly mobile. This is usually the case in MANETs facilitating communication of mobile users in convention centres, conferences or electronic classrooms. Existing active clustering algorithms involve periodic broadcast of 'Hello' messages to sense potential topological differences between two successive 'Hello' periods. When considering relatively static MANET topologies though, such modifications seldom occur. Namely, bandwidth and power resources are consumed only to verify that existing clustering configurations are still valid.

ABP algorithm corrects this clear inefficiency by dynamically adjusting 'Hello' BP. In particular, BP duration depends on the current mobility pattern of MHs. For highly mobile MHs, BP is shortened, i.e. message broadcasts are frequent enough to maintain consistent and accurate topology information. However, when Mobility Rate (MR) is low (i.e. MHs position on the plane does not considerably change over time relatively to their neighbours position), BP is lengthened, relaxing the MANET from unnecessary control message storms.

Yet, it is essential to guarantee that all individual cluster members share the same BP value. Should permission to request adaptation of BP is granted to all MHs, that will soon lead to serious BP synchronisation problem: MHs are likely to receive simultaneous BP adaptation requests from different MHs. As a result, members of the same cluster will adjust their BP to different time spans, which will severely affect the validity of CH 'election' process described above. Hence, in ABP algorithm, only CHs are entitled to issue BP adaptation requests to their dominated MHs. In case of node migration to a neighbouring cluster, its new CH informs the node about the BP of the local cluster.

Most existing methods for estimating nodes MR pose the requirement for GPS card with sufficient accuracy mounted on every mobile node. We propose an alternative, novel method for measuring MR which relaxes mobile nodes from such requirement.

Each CH v measures its neighbourhood MR through contrasting the topology information it obtains during successive BPs. CHs maintain a short 'Topology History Table' (THT); THT rows comprise vectors representing the IDs of neighbouring nodes, where each THT row refers to different BP. Calculated MR value actually represents the mean 'vector distance' among vectors recorded by v during the latest n BPs (where n is a small integer in order to minimise memory requirement):

$$MR_t = (1/n)\sum_{i=0}^{n-1}(n-i)\left|\overline{THT_{t-iBP} - THT_{t-(i+1)BP}}\right| \quad (4)$$

where t denotes the current time. The factor $(n - i)$ signifies that more recent mobility activity weights more in the calculation of MR_t compared to past node mobility.

Figure 5 Neighbouring nodes of node with ID = 1 during four successive BPs (see online version for colours)

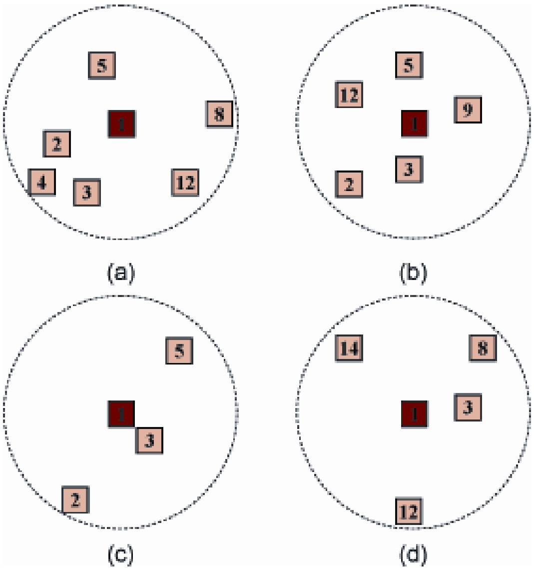


Figure 5 illustrates how mobile node with ID = 1 moves on the plane; as a result of that movement (and the movement of other network nodes), its neighbouring nodes (i.e. those within its transmission range) differ at the end of every BP. For this particular example, the 'neighbourhood vectors' of node #1 at the end of four successive BPs**:** are THT_1 = {2, 3, 4, 5, 8, 12}, THT_2 = {2, 3, 5, 9, 12}, THT_3 = {2, 3, 5}, THT_4 = {3, 8, 12, 14}. Hence, the MR of node #1 within this period of time is given by: $M_1 = \left(3\times\left|\overline{THT_4 - THT_3}\right| + 2\times\left|\overline{THT_3 - THT_2}\right| + \left|\overline{THT_2 - THT_1}\right|\right)$ /3 = (3 × 5+2×2+3)/3 = 7.33[1]. Table 2 presents the THT of node #1, illustrating how its neighbourhood changes and how its MR is evaluated over those four successive BPs.

Table 2 Instance of the THT for the node with ID = 1 during four successive BPs

BP	*Neighbouring nodes*								*MR*
1	2	3	4	5	8		12		–
2	2	3		5		9	12		3
3	2	3		5					2
4		3			8		12	14	5

A main objective of ABP algorithm is to minimise control traffic overhead during clustering maintenance phase, which highly depends on BP duration (i.e. frequency of broadcasting 'Hello' control packets). To achieve that, CHs measure the mean MR of their attached cluster members MR_c (following the above-described method) and accordingly adapt the 'Hello' BP within their cluster. It is also guaranteed that BP duration always lies between two boundaries: $BP_{\min} \le BP \le BP_{\max}$; at startup, BP is globally set to $BP_{\min}$.

4 Performance simulation and analysis

Our simulation work attempts to compare the performance of ABP against LID, HD and VC algorithms in terms of signalling traffic, cluster stability and variance of MHs energy level. Simulations have been performed using the NS-2 simulator package (www.isi.edu/nsnam/ns/), based on the parameters shown in Table 3.

Table 3 Simulation parameters

Parameters	*Value*
Simulation time	180 s
MAC protocol	IEEE 802.11
Simulated plane	600 × 600 m^2
Number of MHs	20–120
Transmission range	71 m
BP_{min}	1 s
Maximum BP (BP_{max})	20 s
MHs average speed	0–15 m/s
Initial battery lifetime	20–100 units
Weight of MH degree on CHC calculation (c_1)	0.5
Weight of battery availability on CHC calculation (c_2)	0.5
'Handover' penalty coefficient (p)	2
Maximum number of MHs per cluster (T)	10
Period of MR monitoring (by CHs)	5 BPs

A square terrain of 600 × 600 m^2 is assumed. The number of MHs moving within the square space varies from 20 to 120. At startup, MHs are randomly positioned on the plane. MHs move with speed 0–15 m/s, in random direction (random waypoint model is used). At the event of reaching the terrain boundary, MHs are bounced back. The BP duration is set to 5 ms for LID, HD and VC approaches while for ABP algorithm it is dynamically adjusted according to MHs mobility behaviour. Initial remaining battery time of MHs is randomly set between 20 and 100 units; energy is assumed to be linearly decreased for ordinary nodes, while for CHs it depends on the number of their attached cluster members. Each simulation run lasts 3 minutes; simulation results presented below have been averaged over 5 runs. Regarding ABP algorithm's execution parameters, CHC values are calculated for $c_1 = c_2 = 0.5$, while the value of penalty coefficient is set to $p = 2$. The maximum number of nodes that may be dominated by a single CH is set to $T = 10$. CHs measure MR through contrasting the topology information they obtain during $n = 5$ successive BPs.

Figure 6 illustrates the average number of control messages exchanged over the simulation runs. In LID, HD and VC algorithms, 'Hello' messages are periodically broadcasted, hence, their performance results coincide. As expected though, ABP clearly outperforms the three alternative approaches, especially when MHs exhibit low mobility.

Figure 6 Average number of control messages exchanged (for 50 MHs) (see online version for colours)

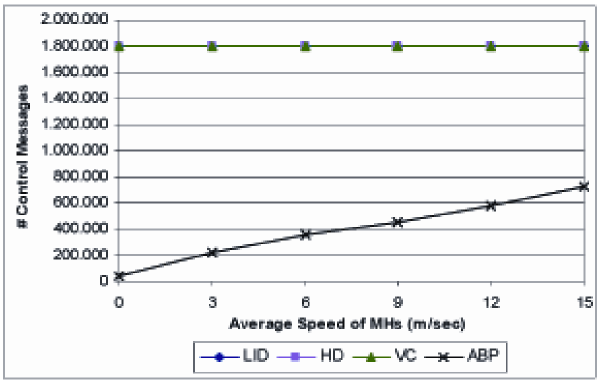
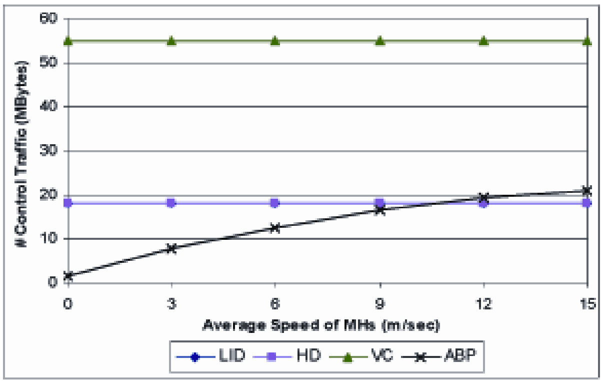


Figure 7 Control traffic volume (for 50 MHs) (see online version for colours)



However, control messages ('Hello' packets) are not of equal size in all four examined approaches. In particular, 'Hello' packet sizes are 8, 8, 32 and 36 bits for LID, HD, VC and ABP, respectively. That certainly affects the scalability of the clustering algorithms, as shown in Figure 7, although the performances of LID and HD still coincide, due to their identical BP duration and control packet size. Thus, in terms of the overall control traffic overhead, ABP is shown to perform better than LID and HD when the average speed of MHs is not larger than 11 m/s (~39.6 km/h), while it presents clearly better results than VC. We believe that this speed threshold identifies ABP as the most cost-effective active clustering solution for the majority of real-world MANET environments (ABP would not represent an adequate method in cases where the users of MHs ride fast-moving vehicles).

Figure 8 compares the average number of CH changes, which is an indicator of the overall cluster structure stability (the more frequent the CH changes, the less stable clusters are). As expected, LID performs better than HD as the former exclusively uses ID and the latter node degree information to decide upon cluster structure. VC performs even worse than HD as the inclusion of power level metric in CHs election dictates that CHs with insufficient power level give up their CH role. ABP clearly outperforms HD and VC on account of the penalty coefficient which prevents frequent CH re-elections, yet, it is marginally outperformed by LID, due to the inclusion of energy metric in the calculation of CHC values (see equation (3)). However, the precedence of LID is partially compensated due to the battery drainage incidents, which frequently occur in the LID resulting to CH changes.

Notably, ABP is mainly suited to relatively static and quasi-static MANETs. As indicated in this simulation test, highly mobile MANETs will likely experience frequent CH changes, significantly degrading the routing performance.

Figure 8 Average number of CH changes (for average speed of 5 m/s) (see online version for colours)

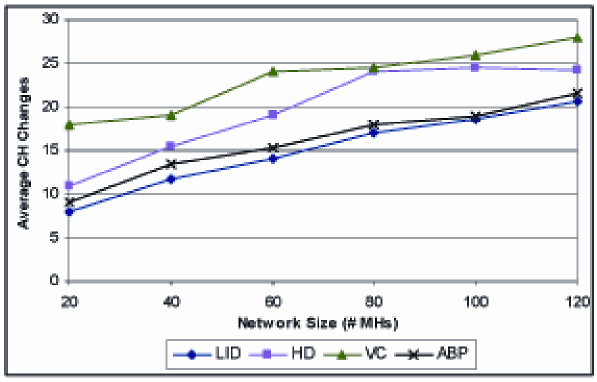


Figure 9 depicts the dependence of the average number of cluster formations on the network size (from these figures, we can easily infer the average cluster size, i.e. the average number of cluster members). Clearly, ABP meets the objective for forming clusters with moderate size, thereby enabling the spatial reuse of the common wireless channel, minimising message delivery delays and extending CHs lifetime. Also, ABP derives smaller cluster sizes than VC as a result of specifying a maximum number of nodes per cluster (see Section 3.2).

Figure 9 Average number of clusters (for average speed of 5 m/s and maximum of ten nodes per cluster in ABP method) (see online version for colours)

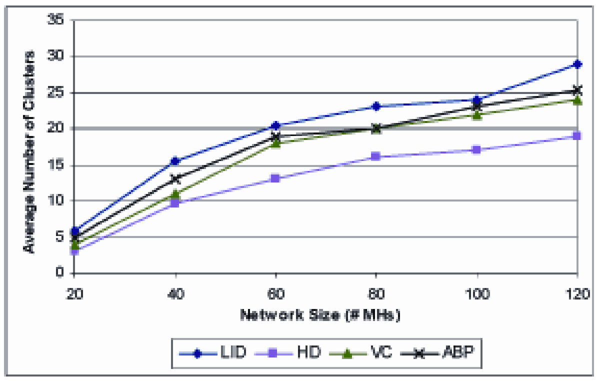
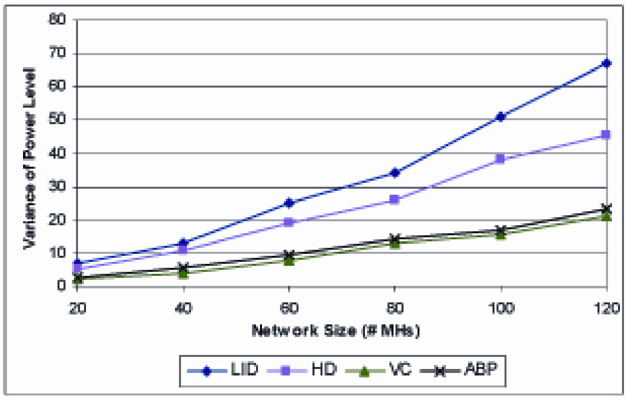


Figure 10 illustrates the variance of power level among MANET's MHs. Large variance values indicate that specific nodes are engaged on CH role for long periods, hence, their energy level soon falls far below the average. This simulation result highlights the mean limitation of LID algorithm: in LID, CHs election is biased in favour of nodes with low ID values; these nodes are likely to serve as CHs for long time and their energy supply rapidly deplete. ABP results in a more fair distribution of energy consumption compared to LID and HD as it takes into account remaining power level for CHs election. However, ABP demonstrates marginally worse performance than VC, as the inclusion of penalty coefficient extends CHs serving time, i.e. it prevents CHs with slightly lower battery power to give up their CH role. That represents an interesting trade-off between stable and energy-balanced clustering.

Figure 10 Variance of energy level among MHs (for average speed of 5 m/s) (see online version for colours)



Similar conclusions are extracted from Figure 11 which depicts the number of node failures due to battery drainage (most of these events occur on nodes serving as CHs); this metric is of particular importance as node failures cause network discontinuities and may create 'islands' of isolated groups of nodes. To enforce a higher number of power drainage events, we have simulated a rapid (linear) decrease of CHs power over time (low N_2 value in equation (2)).

Figure 11 Battery drainage events (for average speed of 5 m/s) (see online version for colours)

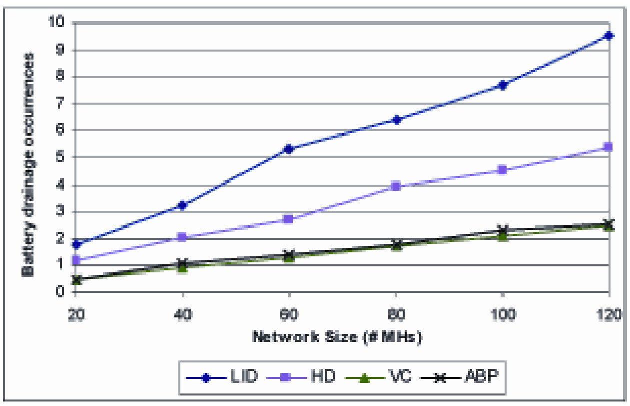
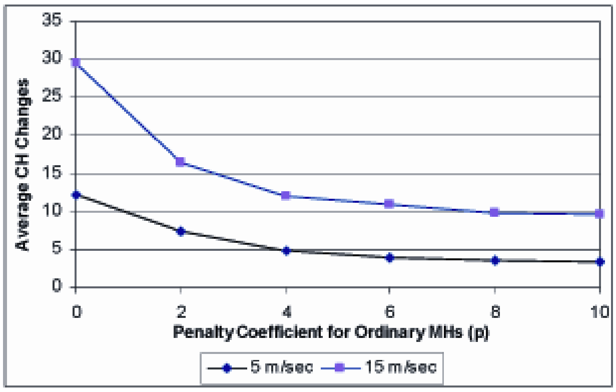
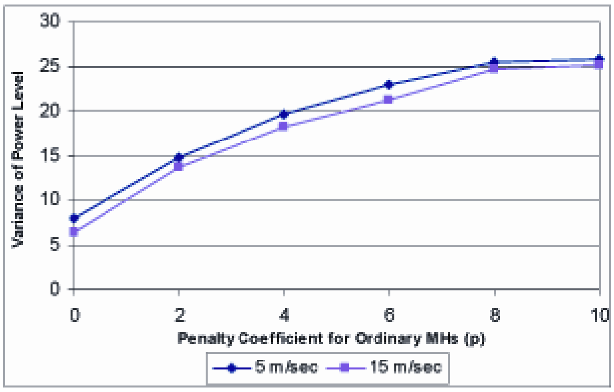


Figure 12 Average number of CH changes as a function of the penalty coefficient p (for 80 MHs, $c_1 = 4$, $c_2 = 6$) (see online version for colours)



A last set of simulation results investigates the effect of 'handover' penalty coefficient p values on cluster stability and energy distribution among MHs. Figure 12 illustrates that, initially, a slight increase on p-value drastically drops the average number of CH changes. Yet, further increase of p-value does not considerably increase clusters' stability.

Figure 13 Variance of energy level among MHs as a function of the penalty coefficient p (for 80 MHs, $c_1 = 4$, $c_2 = 6$) (see online version for colours)



Finally, Figure 13 shows that the increment of p values has a negative effect on the variance of power level among MHs. This is because larger p values imply that many CH handovers are prevented, thereby prolonging CHs serving time. Hence, CHs run the risk of rapid energy depletion. Concluding, the selection of an appropriate p-value represents an interesting trade-off between cluster stability and energy consumption distribution. According to Figures 12 and 13 for a MANET of 80 MHs and for coefficient values c1 = 4 and c2 = 6, a near-optimal value for p should be in the range between 1 and 2.

5 Conclusions and future work

Mobile ad hoc networks represent an actively evolving technology that allows the establishment of instant communication infrastructures for civilian and military applications. In multi-hop MANETs, the routing protocol is key to an efficient operation. However, the design of an effective and efficient routing protocol in MANETs is extremely challenging because of mobility, limited battery energy, unpredictable behaviour of radio channel and time varying bandwidth. Clustering of mobile nodes among separate domains has been proposed as a promising approach to address MANETs routing problem.

In this paper, we introduced a novel active clustering algorithm. Its contributions, compared to existing solutions, are summarised in the following: (1) clustering procedure is completed within two 'Hello' cycles, (2) both location and battery power metrics are taken into account in clustering process, (3) derived cluster formations exhibit enhanced stability by preventing unnecessary CH re-elections, (4) cluster sizes are controlled so as not to expand beyond a specified threshold, (5) for relatively static and quasi-static network topologies, control traffic volume is minimised, (6) a novel technique for MR measurement is proposed and (7) fast packet forwarding and delivery is enabled, as clusters are pro-actively formed and topology information is available when actual user data exchange is required. The abovementioned contributions are achieved at the expense of slightly increased control packet sizes which may result in increased control traffic volume in highly mobile environments.

Simulation results demonstrated that APB algorithm achieves cost-effective clustering in terms of signalling traffic, especially for MANETs with low to moderate MR. Also, it represents a balanced solution between cluster stability and energy efficiency compared to existing approaches.

As a future extension, we intend to incorporate mobility metric in the calculation of CHC, and also introduce a mobility prediction method, e.g. similar to (Sivavakeesar et al., 2004), to identify group mobility patterns and provide steadier cluster formations.

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Website

The Network Simulator – NS-2, at http://www.isi.edu/nsnam/ns/

Note

1 The MR within a given BP, i.e. the difference between two successive THT vectors, is simply calculated as the sum of nodes that either moved away or joined the cluster within that BP.