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Cluster-Adaptive Two-Phase Coding Multi-Channel MAC Protocol (CA-TPCMMP) for MANETs

[a]Lili Zhang, [a]Boon-Hee Soong and [b]Wendong Xiao

[a]Positioning and Wireless Technology Centre
School of Electrical & Electronic Engineering
Nanyang Technological University
50 Nanyang Drive, Singapore 637 553
Email: {PG05078094; EBHSOONG}@ntu.edu.sg
[b]New Initiatives
Institute for Infocomm Research
21 Heng Mui Keng Terrace Singapore 119613
Email: wxiao@i2r.a-star.edu.sg

Abstract

This paper introduces a novel joint clustering and multi-channel Medium Access Control (MAC) protocol for Mobile Ad Hoc Networks (MANETs) based on a scalable two-phase coding scheme, where the first-phase code is used for differentiating the clusters and the second-phase code is employed to distinguish the nodes in a specific cluster. It mitigates the Hidden Terminal Problem (HTP) during data transmission and efficiently incorporates the procedure of code assignment with adaptive clustering. We also introduce the confliction detection and confliction resolution mechanisms for the allocation of the first-phase code in the control channel. Simulation results show that substantial improvement in terms of control overhead can be achieved by the proposed protocol over the traditional distributed Code Division Multiple Access (CDMA) based multi-channel MAC algorithms with clustering or without clustering.

I. INTRODUCTION

Thus far, extensive work has been devoted in CDMA-based multi-channel MAC protocol for MANETs [1] [3] [4] [5] [9] [10]. The basic criterion of code assignment in such protocols is that the same codes are reused more than two hops away such that the HTP [8] can be avoided. However, the complete neighborhood knowledge within two-hop separation is always the assumption and expensive communication overhead is required to exchange such neighborhood information.

Recently, we have proposed multi-cell based Location-Aware Two-Phase Coding Multi-Channel MAC Protocol (LATPCMMP) [6][7] for large-scale dense MANETs, where the first-phase code is used to differentiate cells that are distributed according to hexagonal structure and the second-phase code is used to differentiate nodes in one specific cell. LATPCMMP eliminates the HTP without periodical exchanges of neighborhood information and significantly reduces the control overhead.

Although LA-TPCMMP outperforms traditional CDMA-based multi-channel MAC algorithms, the dependance to the location information limits its applications. Moreover, it requires that there

are always some nodes within the leader residence area acting as the cell leader, which may fail in some situations when nodes move freely and there are frequent network topology changes. This provides the insight into new design to combine TPCMMP with dynamic clustering to develop a comprehensive protocol.

Clustering is an important mechanism employed to build up a hierarchical structure and alleviate the heavy control overhead in a large-scale MANET. Various kinds of traditional distributed clustering algorithms have been proposed [11][12][13]. To the best of our knowledge, only MAPLE clustering scheme proposed in [15] takes the medium access of adjacent clusters into account during the clustering establishment and maintenance, where the cluster heads (CHs) of adjacent clusters respectively occupy their particular time frames to broadcast their beacon messages and maintain their clusters. However, it does not explain how to allocate multi-channel resources by making use of clustering information to broaden the efficient channel spatial reuse.

Motivated by this, in this paper, we will introduce the Cluster-Adaptive Two-Phase Coding Multi-Channel MAC Protocol (CA-TPCMMP) for general large-scale MANETs. Similar to LA-TPCMMP, CA-TPCMMP assigns the first-phase code and second-phase code respectively for adjacent clusters and different cluster members (CMs) in one specific cluster. Moreover, it adaptively assigns the first-phase code to each cluster and second-phase code to the CMs based on dynamic clustering without the requirement of the location information. Confliction detection and confliction resolution mechanisms for the code assignment are also introduced in CA-TPCMMP.

The rest of the paper is organized as follows. Section 2 describes CA-TPCMMP and presents the confliction detection and confliction resolution mechanisms. Section 3 describes the traditional algorithms. Section 4 describes the simulation model and examines the performance of CA-TPCMMP in terms of control overhead. The last section concludes the paper and introduces the future work.

II. CA-TPCMMP

A. Two-Phase Coding Scheme

Similar to the two-phase coding scheme introduced in [7], in CA-TPCMMP, the first-phase code is used for differentiating adjacent clusters and the second-phase code is employed for distinguishing the nodes in a specific cluster. The reuse of the first-phase codes greatly increases the scalability of CATPCMMP. In CA-TPCMMP, there exist three different states for nodes, which are respectively the CM, CH and cluster candidate. A CH is responsible for maintaining and assigning the second-phase codes to its CMs in each cluster and all the CMs are one-hop away from their CHs. The wireless bandwidth is divided into a control channel and a data channel.

Assume there exist a set of m pseudo random (PN) codes $C_{FC} = \{C_1^i | i = 1,\ 2, \ldots,\ m\}$ used for the first-phase codes and another set of n PN codes $C_{\mathrm{SC}} = \{C_2^{\mathrm{j}} | \mathrm{j} = 1,\ 2, \ldots,\ \mathrm{n}\}$ for the second-phase codes. The set of the transmission codes is defined as $C_{TC} = \{(C_1^i,\ C_2^{\mathrm{j}}) | C_1^i \in C_{FC},\ C_2^{\mathrm{j}} \in C_{\mathrm{SC}}\}$ with each element being a joint first-phase and second-phase code and any two elements in C_{TC} are quasi-orthogonal. Fig. 1 shows a CM A in cluster 1 with its code $C^a = (C_1^a,\ C_2^a)$.

Let $C(i)$ denote the set of nodes of cluster i and $NeiC_{h1}(i)$ denote the set of one-hop neighboring clusters of cluster i. We call cluster i and cluster j are one-hop neighboring clusters if there exists $u \in C(i)$ and $v \in C(j)$ such that u and v are in the communication range of each other.

B. Code Confliction and Criteria of Code Assignment

We call two nodes within two-hop separation are in code confliction when they adopt the same transmission codes. Actually, there exists three cases that confliction may happen, i.e., two nodes in the same cluster, two nodes in adjacent clusters and two nodes in different clusters that are the one-hop neighbors of one common cluster as respectively shown in Fig. 1 (*a*), (*b*) and (*c*). In order to avoid the confliction, we introduce the Criteria of code assignment in CA-TPCMMP as follows.

As shown in Fig. 1 (*a*), confliction may happen if nodes A and B use the same second-phase code. Therefore, we have

Criterion 1: For any node $A \in C(i)$ and $B \in C(i)$, it requires that

$$C_2^a \neq C_2^b \tag{1}$$

holds to avoid the confliction.

In Fig. 1 (*b*), if $C_2^a = C_2^b$, it is required that $C_1^a \neq C_1^b$ to ensure $C^a \neq C^b$ Therefore, we have

Criterion 2: For any node $A \in C(i)$ and $B \in C(j)$, if $i \in NeiC_{h1}(j)$, it requires that

$$C_1^i \neq C_1^j \tag{2}$$

holds for the first-phase code allocation of nodes A and B to avoid the confliction, where C_1^i and C_1^j denote the first-phase code of clusters i and j.

In some particular cases, two CMs which are not in the neighboring clusters may come into two-hop separation as shown in Fig. 1 (*c*). Therefore, we require

Criterion 3: For any node $A \in C(i)$ and $B \in C(j)$, if there exists a cluster k such that $i \in NeiC_{h1}(k)$ and $j \in NeiC_{h1}(k)$, the first-phase code allocation should satisfy

$$C_1^i \neq C_1^j. \tag{3}$$

Considering the above-defined criteria for code assignment, a cluster i maintains a set of permitted first-phase codes $C_{PFC}(i) = C_{FC} - \{\cup C_1^j \mid \forall j \in NeiC_{h1}(i)\}$ which consists of all the first-phase codes that are different from those of the neighboring clusters of cluster i.

C. Cluster Establishment and Maintenance

Although different clustering algorithms affect the overall system performance with their own characteristics, the selection of the first-phase codes and second-phase codes are independent of the specific clustering algorithms. Therefore, we apply the random competition-based clustering (RCC) [13] where there is no two CHs within the communication range of each other.

D. Access Mechanism of Control Channel

The control channel is time-slotted and divided into super-frames and frames as shown in Fig. 2. Each super-frame consists of M_1 frames and each frame is composed of one beacon slot followed by some fixed number of M_2 maintenance slots. Each frame is dedicated for one cluster and M_1 is the available number of frames that can be used for the adjacent clusters. Similarly, each maintenance slot is dedicated for a CM within a cluster and M_2 is the supported number of CMs in a cluster. The beacon slot is dedicated to probing message, re-probing message or beacon message of a CH. Each maintenance slot is composed of three mini-slots, where the first two mini-slots are dedicated to Request for Slot (RFS) message and Confirmation of Slot (COS) message respectively with the same duration and the third mini-slot is dedicated to broadcasting message of a CM with the same duration as BS. There is a flag that indicates code request and code release in the RFS message and broadcasting message respectively.

Each frame is related to a specific cluster and its corresponding first-phase code. Different frames of a super-frame are dedicated to different clusters and clusters that are spatially separated enough can use the same frame with the same first-phase codes. All the maintenance slots are used by the CMs for maintaining clusters, negotiating the appropriate first-phase codes and allocating the second-phase codes. Different CMs of a cluster will contend to obtain their different maintenance slots in their respective frames to send their broadcasting messages. Therefore, there exists no collisions from broadcasting message of the adjacent clusters if their adopted first-phase codes are different.

E. Selection of The First-Phase Codes and Confliction Detection and Resolution Mechanisms

The selection of the first-phase code for one specific cluster is determined by the first-phase codes held by its neighboring clusters. CH election is completed in the beacon slot. Whenever a cluster candidate upgrades itself as the CH of a cluster i, it listens for a duration of a super-frame, randomly chooses one free first-phase code from $C_{PFC}(i)$ and sends the *probing message* in the beacon slot to determine whether the chosen code is appropriate or not. The CMs that receive the probing message check their store matrixes that record the first-phase codes held by their neighboring clusters and initiate opposition by sending *broadcasting messages* if Criterion 2 is not satisfied. The store matrix of each CM is updated according to the information overheard from the broadcasting messages. Upon collecting all the responses, the CH decides its appropriate first-phase code, which should not be in confliction with any neighboring clusters. After that, it periodically broadcasts the *re-probing message* with the adopted first-phase code piggybacked. If the CH does not receive the opposition messages for continuously 3 times, it considers the current first-phase code to be suitable and periodically broadcasts the *beacon message* that disseminates its first-phase code. Otherwise, it should adjust its first-phase code

such that Criterion 3 can be satisfied. The cluster candidates, which hear this beacon message, will update their status as the CMs and record the corresponding first-phase code information.

Since the CMs send their broadcasting messages conveying the neighboring cluster ID, their first-phase codes and the number of their CMs, a CH may detect that its neighboring clusters with different cluster ID occupy the same frame and adopt the same first-phase code. Let S_u denote the number of CMs within a CH u. Therefore, to ensure Criterion 3 is satisfied, we introduce another criterion,

Criterion 4: Let S_u denote the number of nodes with the same first-phase codes within the coverage of node u. For any $i \in NeiC_{h1}(k)$ and $j \in NeiC_{h1}(k)$, if $C_1^i = C_1^j$ and $S_j < S_i$, we suppose cluster i keep the original first-phase code and the remaining clusters re-obtain their first-phase codes according to the probability-based contention resolution scheme.

As shown in Fig. 3, we observe three cases of confliction in the negotiation of the first-phase codes of neighboring clusters, i.e. confliction of neighboring, star and chain structure. In case (*a*), when cluster i detects $C_1^i = C_1^j$, it will re-compete for its frame if $S_i < S_j$ while the cluster j keeps the original frame, i.e., it keeps the original first-phase code. In case (*b*), when cluster l detects $C_1^h = C_1^i = C_1^j$, if $S_h < S_i < S_j$, we suppose cluster j keeps the original frame and clusters h and i re-compete for their frames. Consequently, clusters h and i may again select the same frame in the following contention. However, within the limited number of trials, clusters h and i will come into harmony on the negotiation of the first-phase codes. In case (*c*), when cluster l detects $C_1^i = C_1^j$ and cluster m detects $C_1^h = C_1^i$, if $S_h < S_i < S_j$, we suppose cluster j keeps the original frame and clusters h and i re-compete for their frames. Likewise, the confliction can be resolved within a limited number of trials.

F. Selection of The Second-Phase Codes and Collision Avoidance Mechanism

Whenever a cluster is established, a CH maintains its available slots set (ASS) in its cluster and periodically broadcasts it in the beacon message. Meanwhile, the CMs that have joined this cluster contend to obtain their respective maintenance slots in the specific frame of this cluster. Since it is difficult for all CMs to coordinate their response and not collide with each other in each frame, we employ binary splitting strategy [6] to resolve collisions during the slot acquisition. New CMs will always listen for a period of their respective frame to know the ASS from the beacon message before participating in the contention for their maintenance slots.

The second-phase code of a node is allocated by its CH. A CM that has obtained its slots can acquire its second-phase code from its CH free of contention. A CH records the available second-phase codes (ASC) in its cluster. Whenever a CM is in request for data transmission, it transmits the RFS message by marking the code request field in it, listens to the COS message of its CH to acquire its second-phase code and acknowledges its CH by sending broadcasting message in its allocated slot such that its CH can update the ASC. The broadcasting message of a CM disseminates its ID, cluster ID, its first-phase code, the first-phase codes hold by neighboring clusters and other parameters such as remaining energy and the number of nodes within coverage with the same first-phase codes that reflect its appropriateness of being a CH. Transmitter-oriented data transmission [2] is adopted. As soon as the data transmission finishes,

the CM will return its second-phase code to its CH by marking the code release field in its broadcasting message. When a CM migrates into another cluster, usually it releases its original second-phase code to the former CH and re-obtains its new second-phase code in the new cluster.

G. Mitigation of HTP during Data Transmission

Three cases that HTP may happen are illustrated in Fig. 1. Suppose the transmission codes of nodes A and B are $C^a = (C_1^a, C_2^a) \in C_{TC}$ and $C^b = (C_1^b, C_2^b) \in C_{TC}$ respectively. As shown in Fig. 1 (a), when A and B are in the same cluster 1, then $C_1^a = C_1^b$ and $C_2^a \neq C_2^b$ according to Criterion 1, thus $C^a \neq C^b$. In Fig. 1 (b), when A and B are in the adjacent clusters 1 and 2, then $C_1^a \neq C_1^b$ according to Criterion 2. In Fig. 1 (c), when A and B are respectively in cluster 1 and 3 that are the neighbors of cluster 2, then $C_1^a \neq C_1^b$ according to Criterion 3. Thereby, no matter what second-phase codes nodes A and B use in the second and third cases, one always has $C^a \neq C^b$. In all three cases, C^a and C^b are always quasi-orthogonal. Therefore, there is no HTP in CA-TPCMMP if Criteria 1-3 are satisfied.

III. TRADITIONAL ALGORITHMS (TAS)

In TAs, code assignment requires the exchanges of two-hop neighborhood information. Based on the criterion that nodes need to know the information of nodes within two-hop separation, the algorithm in [5] gives the communication complexity of distributed assignment of codes in the worst case as $O(N_n d_m^2)$, where N_n is the total number of nodes and d_m is the network degree. We simulate the TAs without clustering according to [5], i.e, a node sends a Code Assignment Message (CAM) to all its one-hop neighbors when a new node comes into transmission range and all receivers are required to acknowledge the sender to ensure the reliable transmission of CAM. In TAs with clustering, the same code assignment algorithm is employed except the underlying clustering mechanism, where each node has to wait for its maintenance slot to send its CAM.

IV. SIMULATION RESULTS

The simulation is conducted using ns-2 [14] with CMU wireless extensions. The performance is evaluated in terms of control overhead versus transmission range R and average speed V . We calculate the mean value of control overhead per second for a node to get average control overhead. We choose the topology as 1000m x 1000m with 100 nodes and 30 traffic flows randomly distributed and vary the transmission range to get the varying number of one-hop neighbors. We adopt two-ray ground propagation model and AODV routing protocol. The mobility model is random way point mobility model with average speed up to 20m/s. The channel rate is 2$Mbps$ with control channel rate of 0.3$Mbps$. The traffic type is UDP with packet size 512$bytes$. Assume the duration of BS is 50$bytes$ and the duration ratio of BS to MS is 5/7. The simulation time is 500s. The simulation results are averaged 8 runs with different movement patterns for each value of V and R. The parameters M_1 = 20 and $M_2 = \mu + \sigma$, where μ and σ are respectively the mean value and standard deviation of the number of CMs within the communication range of a CH.

Fig. 4 shows average control overhead with 95% confidence interval versus the transmission ranges when λ = 50$Pkts/s$ and v = 10m/s. Obviously, the control overhead of TAs is worse than

that of CA-TPCMMP and aggravates seriously with the increasing transmission ranges no matter it is based on flat topology or clustering. When the network is considerably loose with $N \doteq 3$ ($R = 100m$), the control overhead of TAs without clustering is even less than that of CA-TPCMMP. This is due to that when the network is loose, the neighborhood update of TAs is less frequent and the probability of collisions is small. Whereas, in CA-TPCMMP, extra control overhead is caused by cluster establishment and maintenance and the appropriate frame and slot acquisition, which makes it less advantageous. TAs with clustering show a superior performance than TAs without clustering with the increasing number of one-hop neighbors. However, CA-TPCMMP significantly outperforms TAs when the network is becoming dense. When $N \doteq 20$ with $R = 250m$, the control overhead incurred in TAs with clustering is almost 11 times higher than that of CA-TPCMMP. Moreover, the confidence interval of CATPCMMP is much smaller than those of TAs with clustering and without clustering. Control overhead of CA-TPCMMP is not affected significantly by density since the acquisition of the first-phase and second-phase codes is completely incorporated in the clustering maintenance.

In Fig. 5, average speed is varied from 5*mps* to 20*mps* for observation of the average control overhead with 95% confidence interval when $R = 200m$ and $\lambda = 50Pkts/s$. With the speed increasing, there is higher chance for a new node to migrate into transmission range, which requires more updating of neighborhood information in TAs. Consequently, the control overhead of TAs under both topology almost aggravates linearly with the increasing speed. CA-TPCMMP also requires more control packets in response to increasing speed since high mobility requires more cluster maintenance. However, the upward trend of TAs is significantly worse and the confidence interval is much bigger than those of CATPCMMP.

V. CONCLUSION

This paper proposes a novel multi-channel MAC protocol for MANETs named as CA-TPCMMP, which seamlessly integrates two-phase coding scheme with dynamic clustering, mitigates the HTP during data transmission and substantially reduces control overhead for a sufficiently dense or high mobility network. Furthermore, we introduce the confliction detection and confliction resolution mechanisms during the negotiation of the first-phase code in the control channel. Theoretical analysis of CA-TPCMMP will be presented in a later paper.

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List of Figures

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Figure 2 Control Channel Access Format

Figure 3 Three cases of the first-phase code confliction

Figure 4 Average control overhead versus transmission range

Figure 5 Average control overhead versus average speed

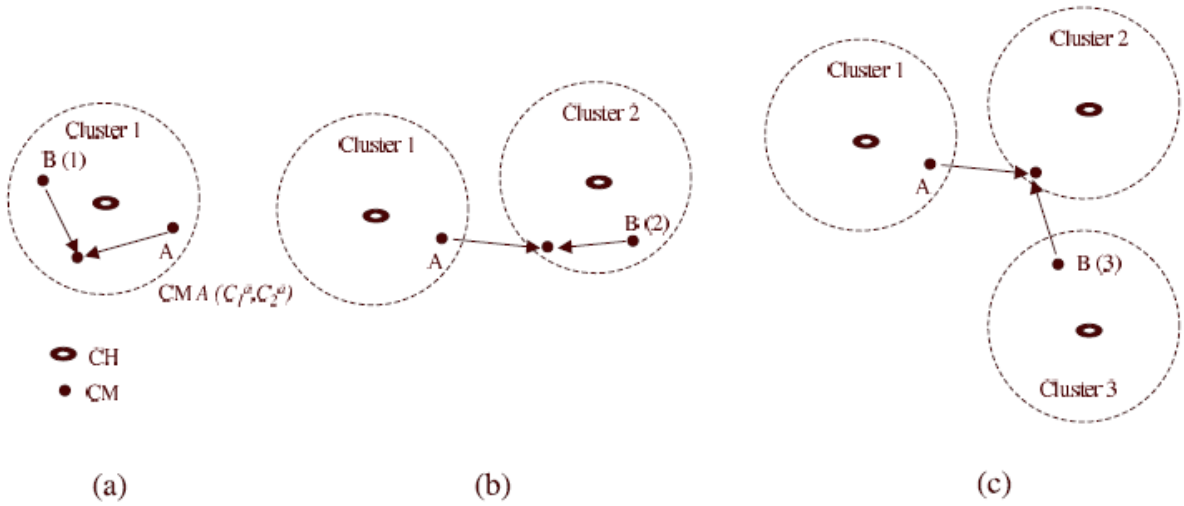
Cluster 1
B (1)
A
CM A (C_1^a,C_2^a)
CH
CM
(a)
Cluster 1
Cluster 2
A
B (2)
(b)
Cluster 1
Cluster 2
A
B (3)
Cluster 3
(c)

Figure 1

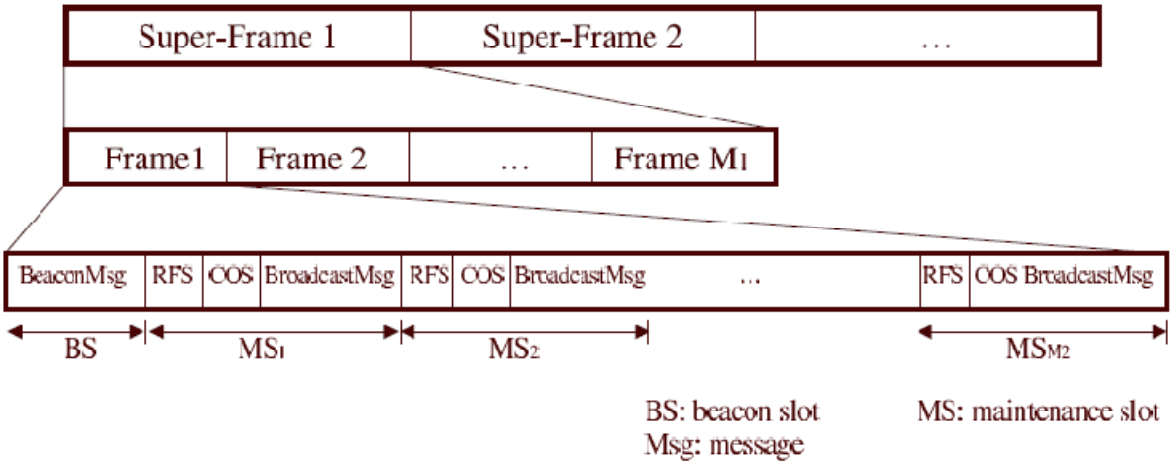
Super-Frame 1
Super-Frame 2
…
Frame1
Frame 2
…
Frame M1
BeaconMsg
RFS
COS
BroadcastMsg
RFS
COS
BroadcastMsg
…
RFS
COS BroadcastMsg
BS
MS1
MS2
MSM2
BS: beacon slot
Msg: message
MS: maintenance slot

Figure 2

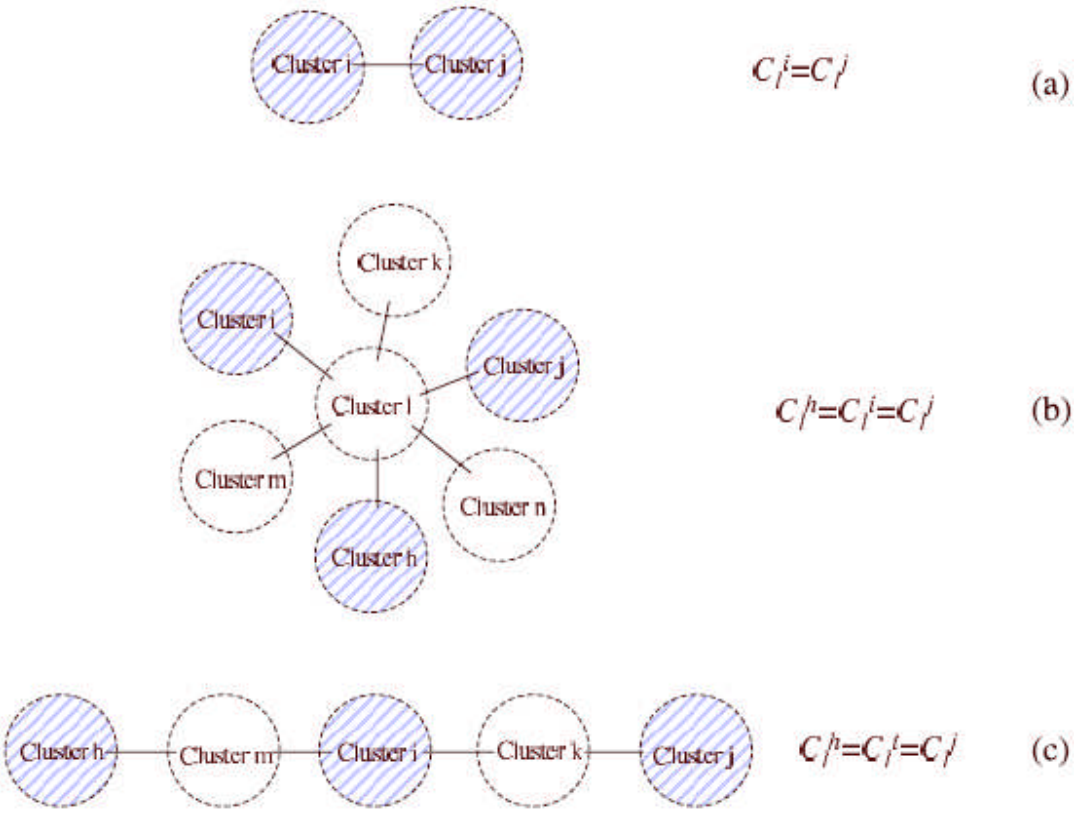
Cluster i
Cluster j
$C_j^i=C_j$
(a)
Cluster k
Cluster i
Cluster j
Cluster l
Cluster m
Cluster n
Cluster h
$C_j^h=C_j^i=C_j$
(b)
Cluster h
Cluster m
Cluster i
Cluster k
Cluster j
$C_j^h=C_j^i=C_j$
(c)

Figure 3

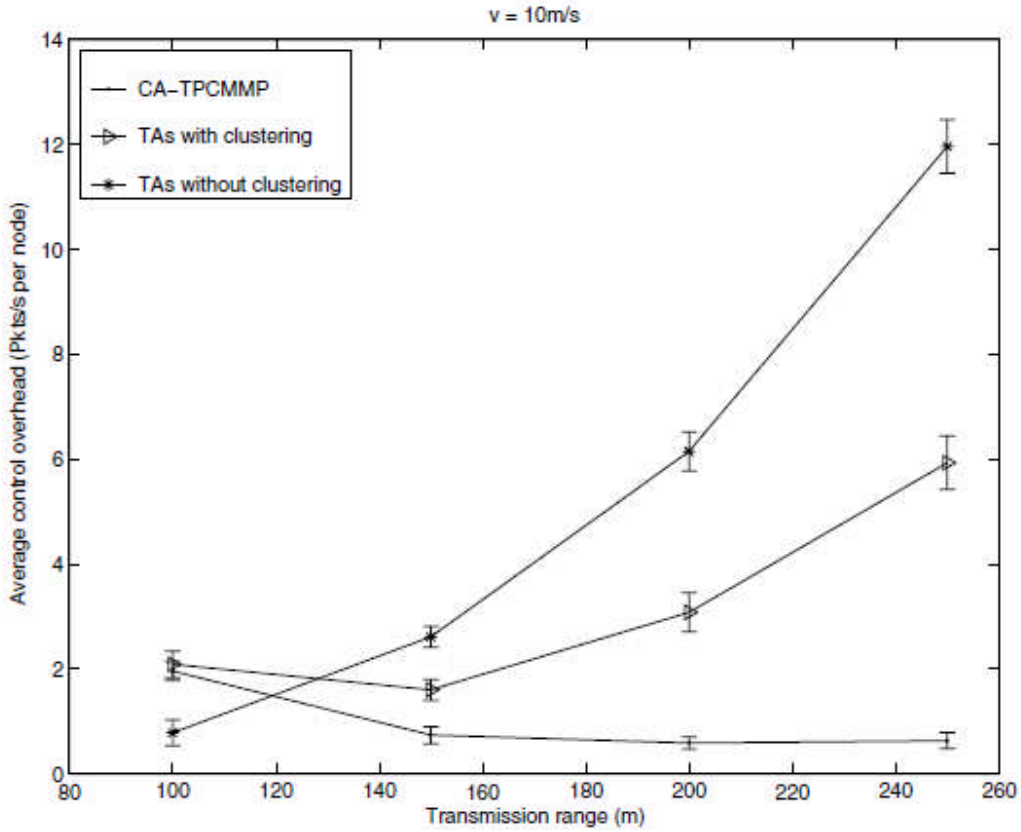
v = 10m/s
CA–TPCMMP
TAs with clustering
TAs without clustering
Average control overhead (Pkts/s per node)
Transmission range (m)
0
2
4
6
8
10
12
14
80
100
120
140
160
180
200
220
240
260

Figure 4

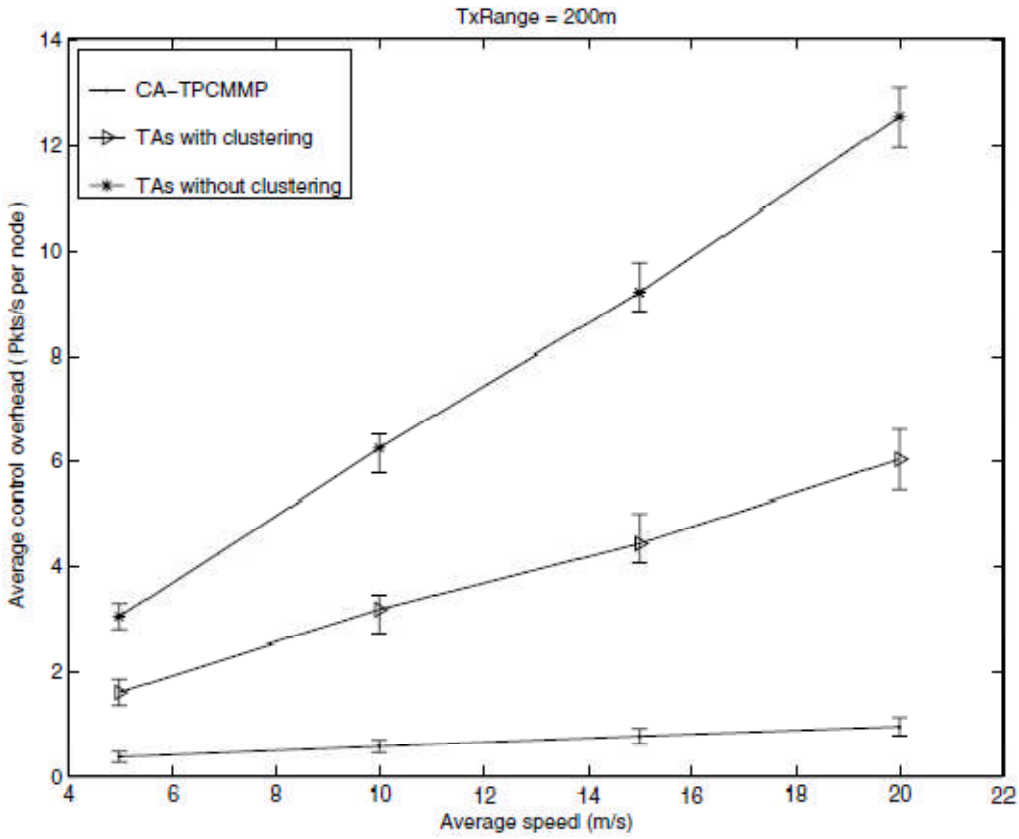
TxRange = 200m
CA–TPCMMP
TAs with clustering
TAs without clustering
Average control overhead (Pkts/s per node)
Average speed (m/s)
0
2
4
6
8
10
12
14
4
6
8
10
12
14
16
18
20
22

Figure 5