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Overhead Analysis of Location-Aware Two-Phase Coding Multi-Channel MAC Protocol (LA-TPCMMP) for MANETs

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Abstract

In this paper, we present a novel location-aware multi-channel Medium Access Control (MAC) protocol for large-scale dense Mobile Ad Hoc Networks (MANETs) based on a scalable two-phase coding scheme, where the first-phase code is used for differentiating adjacent cells and the second-phase code is employed for distinguishing nodes in one specific cell. It eliminates the hidden terminal problem (HTP) during data transmission without requiring periodical exchange of neighborhood information. Furthermore, we introduce the mechanism of collision resolution in the control channel. We analyze the performance of the proposed protocol in terms of control overhead. Its theoretical results are confirmed by simulations and it is demonstrated that the new protocol significantly outperforms the classical Code Division Multiple Access (CDMA) based multichannel MAC protocols.

1. Introduction

Thus far, extensive work has been focused on code assignment in CDMA-based multi-channel MAC design. The basic criterion of code assignment in such protocols is that the same codes are reused more than two hops away in order to avoid the HTP [5]. A unified framework and centralized algorithm for channel assignment are exploited in [8], which extracts the common constraints for channel assignment, converts the channel assignment problem into a graph coloring problem and proposes the collision-free scheduling approaches. But it requires the global topology information. In order to solve this problem, a novel distributed neighbor-aware contention resolution algorithm HAMA is introduced in [7] by defining different priorities to nodes and determining the channel access schedule for each time slot. However, HAMA requires promptly detecting and notifying the change within two-hop separation to harmonize code scheduling to avoid the HTP. Various distributed code assignment schemes are discussed in [3], including transmitter-oriented code assignment (TOCA), receiver-oriented code assignment (ROCA) and pairwise-oriented code assignment (POCA). In SEEDEx algorithm [10], nodes exchange the seeds of their pseudo-random number generators within two-hop separation to know the schedules of each other such that the hidden terminals and exposed terminals can be identified in advance and reduced. The algorithm in [9] considers the case that nodes determine their transmission codes through broadcasting to neighbors within two-hop separation when it has data to transmit and gives the communication complexity of distributed assignment of codes

in the worst case.

Although extensive work has been devoted in distributed code assignment to avoid the HTP, the complete neighborhood information is always the assumption in the algorithms investigated in [3] [7] [9] [10]. They assume that nodes broadcast their holding codes to their one-hop and two-hop neighbors such that nodes within two-hop separation adopt different codes as their transmission codes. However, as the user density in the network increases, there will be more collisions in the code broadcasting even in a separated control channel. Furthermore, when the mobility of the network is particularly high, it is difficult for a node to obtain its accurate neighborhood information in real time. Consequently, some nodes within two-hop separation may select the same codes and the HTP can not be avoided. Frequent neighborhood exchanges in code assignment under high density and mobility incur heavy overhead and large delay, which seriously degrades the network performance.

In this paper we give the overhead analysis for Location-Aware Two-Phase Coding Multi-Channel Protocol (LA-TPCMMP) which is proposed in our previous papers [6]. LA-TPCMMP is introduced to enable the simultaneous transmissions, where the first-phase code is used for differentiating adjacent cells and the second-phase code is employed for distinguishing nodes in one specific cell. The salient feature of this protocol is that it completely eliminates the HTP during data transmission without periodical exchange of neighborhood information.

This paper is organized into six sections. Section 1 gives a brief literature review and explains the motivation and major contributions. Section 2 describes LA-TPCMMP. Section 3 analyzes control overhead of LA-TPCMMP. Section 4 reviews the classical code assignment algorithms and approximately analyzes their performance. Section 5 examines the overhead performance of LA-TPCMMP. Section 6 concludes the paper.

2. LA-TPCMMP

LA-TPCMMP is proposed for large-scale dense MANETs, where the whole network is subdivided into cells of hexagonal geographic structure with radius R . The wireless channel is divided into a common control channel (CCC) and data channel (DC). We assume in the CCC nodes operate in time-slotted mode and are synchronized. LA-TPCMMP consists of several mechanisms including initial cell leader (CL) election, leadership handover, code acquisition, code reacquisition and data transmission. The first four functions are implemented in the CCC whereas the last one is implemented in the DC.

2.1. Two-Phase Coding

The protocol introduces two-phase coding scheme, where the first-phase code is used for differentiating adjacent cells and the second-phase code is employed for distinguishing nodes in one specific cell. Different first-phase codes are required to cover the whole network. The reuse of the first-phase codes greatly increases the scalability of LA-TPCMMP.

We suppose each node in the network has its location information by means of positioning technology such as GPS. The CL is responsible for maintaining and assigning the second-phase codes to its cell members (CMs). The circular central part with radius R' of each cell is defined as the Leader Residence Area (LRA) as shown in Fig. 1, where G is the cell center and E is the CL.

Assume there exist a set of m pseudo random (PN) codes $C_{FC} = \{C_1^i | i = 1, 2, \dots, m\}$ used for the first-phase codes and another set of n PN codes $C_{SC} = \{C_2^j | j = 1, 2, \dots, n\}$ for the second-phase codes. The set of the transmission codes is defined as $C_{TC} = \{(C_1^i, C_2^j) | C_1^i \in C_{FC}, C_2^j \in C_{SC}\}$ 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 cell i with its code (C_1^a, C_2^a) .

2.2. Sizes of Cell and LRA

Assume R_d is the default transmission range of the nodes. As shown in Fig. 1, since a CL is located in the LRA with radius R' , it should satisfy $R + R' \leq R_d$ to ensure that all nodes in its cell are within its transmission range. Considering all cells are of the same radius R , it is easy to know that the minimal distance between any two nodes in different cells with the same first-phase codes is $\sqrt{7}R$. In order to ensure that the same transmission codes appear at least two hops away, we demand $\sqrt{7}R > 2R_d$. Accordingly, we have ensure that the same transmission codes appear at least two the lower and upper bound of R ,

$$\frac{2}{\sqrt{7}}R_d \doteq 0.7559R_d < R \leq R_d. \quad (1)$$

Thereby, the upper bound of R' can be derived from the following inequality

$$R' \leq R_d - R < (1 - \frac{2}{\sqrt{7}})R_d \doteq 0.244R_d. \quad (2)$$

2.3. Operations of LA-TPCMMP

We divide the LRA into N_p different priority regions. A node inside the LRA is located in region i ($i = 0, 1, \dots, N_p - 1$) when its distance R_c to the geographical center of the current cell follows $i = \lfloor \frac{R_c}{\delta} \rfloor$, where $\delta = R/N_p$. Here, we define $d_i = i\delta$. The priority level starts from 0. During the initial CL election and leadership handover, a node located in region i has higher priority to another node located in region j if $i < j$.

Initial CL is elected from the CMs inside the LRA in a distributed way. If a node within region i cannot get any response from the CL after ζ trials for code acquisition, it assumes that there is no CL in the current cell and begins the competition by broadcasting a Leader Declaration (LD) message to declare itself as a CL after deferring a priority region-dependent period

$$T_i = T_{Li} + T'_{Ui}, \quad (3)$$

where T_{Li} is the minimal deferring value related to the priority region i and T'_{Ui} is the incremental deferring value which is randomly selected from $[0, T_{Ui})$ with T_{Ui} being the upper bound of T'_{Ui} . Since nodes closer to the cell center is more preferred, T_{Ui} and T_{Li} are respectively defined as

$$T_{Ui} = \omega(1 - e^{-(d_{i+1}^2 - d_i^2)/R'^2}) \quad (4)$$

and

$$T_{Li} = \begin{cases} 0, & i = 0 \\ \sum_{j=0}^{i-1} \omega (1 - e^{-(d_{j+1}^2 - d_j^2)/R'^2}), & i \geq 1 \end{cases} \quad (5)$$

where ω is a pre-defined parameter which should be determined by the distribution density of nodes and transmission time of the specified control packets. The normalized ratio of area of region i can be derived as $(d_{i+1}^2 - d_i^2)/R'^2 = ((i+1)^2 - i^2)/N_p^2$. With these definitions, nodes within different priority regions adopt different T_{Li} and nodes within the same priority region adopt the random values between $[0, T_{Ui})$ for competition. The first node, which broadcasts the declaration, upgrades itself as the CL. If $i < j$, then $T_i < T_j$. In this way, the elected node is usually closer to the geographic center of its cell and more suitable to act as a CL. However, for the nodes within the same priority region, a random competition strategy is adopted.

If necessary, a CL will hand over the leadership and Available second-phase Code Set (ACS) to a more suitable member. It initiates the leadership handover procedure by broadcasting Handover Request (HREQ) message when it moves out of the LRA of its current cell and suspends its code allocation operations. CMs within the LRA of the current cell will respond according to the above-mentioned priority-based random competition strategy, where a node with a higher priority level has more chances to send a Ready to Handover (HREA) message and the node that successfully transmits the HREA will become the new CL. After receiving HREA, the CL replies with the Agree to Handover (HAGR) message with the ACS information piggybacked. Upon receiving the HAGR message from the original leader, the inheritance will upgrade itself to the CL by duplicating the ACS information, resume its right of code allocation and send the Handover Acknowledgement (HACK) message. When the original CL receives the HACK message, it will downgrade itself as a normal CM and discard its ACS information. If a CL can not receive the responses from its CMs after a predefined period of τ_{to} , it will try to hand over the leadership again.

Transmitter-oriented data transmission [4] is adopted. In LA-TPCMMP node i knows its first-phase code C_1^i according to its location and acquires its unique second-phase code C_2^i from its CL by sending the Code Request (CREQ) message with its reservation period $T_{sc(i)}$ piggybacked. After receiving the CREQ message successfully, the CL allocates an unique available second-phase code from the ACS, records $T_{sc(i)}$ and replies with the Code Reply (CREP) message to the requesting CM. When node i hears the CREP message, it sends the Code Acknowledgement (CACK) message which includes the information of the selected second-phase code such that the CL can update the ACS and record the expiration time of node i to use the assigned code. Then node i can start its data transmission to node j in the DC. Otherwise, it retransmits CREQ until CREP is received or ξ times code acquisitions trials are reached.

After the period $T_{sc(i)}$, if node i still needs the second-phase code for data transmission, it should reacquire the code from the CL for another period of $T_{sc(i)}$ using the CREQ message. The CL will take over the code allocated to node i and add it to the ACS after the period of $T_{sc(i)}$. In this way, the second-phase code can be reused by other nodes. When a node migrates from one cell to

another, it should tune its first-phase code corresponding to the new cell and obtain its new second-phase code from the CL of the new cell.

2.4. Collision Resolution in the CCC

Suppose each time slot in the CCC is with duration τ_1 . As shown in Fig. 2, there are four modes, i.e., code acquisition (CA) mode, leadership handover (LH) mode, switching 1 (ST1) and switching 2 (ST2) mode. CA mode consists of several time frames and each frame is divided into three times slots respectively dedicated for CREQ, CREP and CACK messages. CREQ is only initiated in the first slot, and in turn CREP and CACK messages are respectively initiated in the subsequent slots. If a CL wants to hand over its leadership, it will send a HREQ in the second slot of a frame of CA mode, which forms the ST1 mode. If a CM under the coverage of more than two CLs sends CREQ, the CLs within its coverage either encounter collisions or receive its CREQ message. Since only its CL that successfully receives the CREQ will respond to the CM, the CM will receive CREP message free of interference. Therefore, whenever CREQ of a node wins the contention in its cell, it will definitely acquire its second-phase code in the subsequent slots unless CREP is interrupted by HREQ.

The code acquisition procedure is initiated only when a node has data transmission requirement and does not hold any second-phase code. However, there exists the contention and collision among the CREQ messages from multiple CMs. We employ the binary splitting strategy [12] to resolve the collision problems, i.e., each node will decide with probability 0.5 whether it will continue to transmit CREQ in the next frame and wait for the response. A successful reception of CREP means that the node wins the contention and other nodes involved in the collision will restart the contention following this strategy. Otherwise, they continue to decide whether to transmit in the subsequent CREQ slot as before. If collisions are not resolved within the ξ trials for code acquisition, nodes will abort by themselves.

LH mode has higher priority than CA mode. Whenever a CL wants to hand over its leadership, it switches the cell to the LH mode by immediately initiating the HREQ in the corresponding slot. The CMs within the coverage of this CL should defer their control messages for code acquisition in the CCC once they hear HREQ until HACK is received. When there is no collisions of HREA occurring at the CL, CMs within LRA can hear HAGR in the subsequent slot after they transmit HREA. Then, they can transmit HACK. Thus, the leadership handover, which is composed of several unsuccessful HREA trials and one successful HREA contention, can be accomplished free of interference. Since leadership handover can be completed in any slot, the length of a frame of CLs is variable with its frame terminating either at a new frame of CA mode or at CREP or CACK slot that forms the ST2 mode, after which nodes in the cell change to CA mode and start the new frame for contention.

2.5. Elimination of HTP in DC

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. Actually, when A and B are within two hops and transmitting simultaneously to the same receiver, there are two cases that HTP may happen: 1) A and B are in the same cell, then $C_1^a = C_1^b$ and $C_2^a \neq C_2^b$, thus $C^a \neq C^b$. 2) A and B are in different cells, then the maximum distance between A and B is $2R_d$. Since the minimal distance between any two nodes in different cells with the same first-phase codes is $\sqrt{7}R$ and $\sqrt{7}R > 2R_d$, one has $C_1^a \neq C_1^b$.

Thus, no matter what second-phase codes nodes A and B use, one always has $C^a \neq C^b$. In both cases, C^a and C^b are always quasi-orthogonal. Therefore, HTP is eliminated in LA-TPCMMP.

3. Overhead Analysis of LA-TPCMMP

3.1. Analysis Assumption

It is assumed that nodes are spatially distributed throughout the network according to the Poisson process in two dimensions with density ρ . The traffic arrival process is Poisson arrivals with mean arrival rate λ . Nodes operate in half-duplex mode. We choose a time interval τ_2 which is long enough to resolve a collision, i.e., the duration of slots required to resolve a collision when k nodes are involved in the contention and binary splitting strategy is employed to resolve the collision. We assume that there is no other new nodes to participate in the contention during this interval. In the following analysis, we compute the average incurred control overhead over the predefined τ_2 interval for a node.

3.2. Mobility Model and Handover Probability

The random walk-based mobility model [2] is adopted here. Suppose R_{eq} is the radius of a circle with the same area as the hexagonal cell. It is easy to calculate that $R_{eq} = \sqrt{\frac{3\sqrt{3}}{2\pi}}R$.

From [1] [2], we know that there are two kinds of activation models, i.e., node activation model and link activation model. Node activation model usually refers to that nodes become active in a cell at a specified moment. Whereas, link activation model refers to that mobile nodes move into a cell at a specified moment. The former tends to represent the status of CL handover and initial status of CM migration, while the latter approximates to the steady status of CM migration. Let $f_{T_{mh}}(t)$ denote the probability density function (pdf) of the residence time in a cell of a mobile node that hands over from a neighboring cell before crossing into another cell and $f_{T_{lh}}(t)$ denote pdf of the average residence time in the LRA of a CL. Thus, we have

$$f_{T_{mh}}(t) = \begin{cases} \frac{4R_{eq}}{\pi V_{max} t^2} \{1 - \sqrt{1 - (\frac{V_{max} t}{2R_{eq}})^2}\}, & 0 \leq t \leq \frac{2R_{eq}}{V_{max}} \\ \frac{4R_{eq}}{\pi V_{max} t^2}, & t \geq \frac{2R_{eq}}{V_{max}} \end{cases} \quad (6)$$

$$f_{T_{lh}}(t) = \begin{cases} \frac{8R_{eq}}{3\pi V_{max} t^2} \{1 - \sqrt{1 - (\frac{V_{max} t}{2R_{eq}})^2}\}, & 0 \leq t \leq \frac{2R_{eq}}{V_{max}} \\ \frac{8R_{eq}}{3\pi V_{max} t^2}, & t \geq \frac{2R_{eq}}{V_{max}} \end{cases} \quad (7)$$

according to [2]. Thereby, the mean cell residence time $E[T_{mh}]$ for a mobile node handing over from one cell into another cell and the mean LRA residence time $E[T_{lh}]$ for a CL can be computed as

$$E[T_{mh}] = \int_0^\infty t f_{T_{mh}}(t) dt, \quad (8)$$

$$E[T_{lh}] = \int_0^{\infty} t f_{T_{lh}}(t) dt. \quad (9)$$

Let the CM handover probability $P_{mh}(\tau_2)$ and CL handover probability $P_{lh}(\tau_2)$ respectively denote the probability of the CMs to walk out of the current cell and probability of the CL to walk out of the LRA of its cell in interval τ_2 . Then we have

$$P_{mh}(\tau_2) = \frac{1}{E[T_{mh}]} \tau_2, \quad (10)$$

$$P_{lh}(\tau_2) = \frac{1}{E[T_{lh}]} \tau_2. \quad (11)$$

3.3. Overhead Analysis

In LA-TPCMMP, the overall control overhead results from code acquisition, code reacquisition and leadership handover.

3.3.1. Code Acquisition and Reacquisition Let $N = \rho \pi R_d^2$ be the average number of nodes in the transmission range. CREQ messages may encounter collisions, since the nodes in the coverage area of a CL may initiate their communications at the same time. According to the Poisson distribution, the probability that there are i nodes within the transmission range of a CL is $P(N, i) = e^{-N} N^i / i!$. The probability that among i nodes there are k nodes simultaneously participating in the contentions with the probability p_1 follows the Binomial distribution $B(i, p_1, k) = \binom{i}{k} p_1^k (1 - p_1)^{i-k}$. Hence, the probability that k nodes are involved in the contention simultaneously is $\sum_{i=0}^{\infty} B(i, p_1, k) P(N, i)$, where p_1 is determined by the transmission probability and handover probability. According to the Poisson process, the probability that there is no traffic arrival during τ_2 is $e^{-\lambda \tau_2}$. Thereby, we have the contention probability $p_1 = (1 - e^{-\lambda \tau_2}) P_{mh}(\tau_2)$ during interval τ_2 . Given ζ_k as the average number of CREQ slots required to resolve one collision, it follows the recursive relationship

$$\zeta_k = \begin{cases} 1, & k = 1 \\ \frac{1 + 2^{-k} \sum_{j=1}^{k-1} \binom{k}{j} \zeta_j}{1 - 2^{-k} + 1}, & k > 1 \end{cases} \quad (12)$$

according to the conclusion of binary splitting strategy in [12]. Consequently, the average number β_k of the CREQ messages to resolve the collisions within the interval τ_2 can be computed as

$$\beta_k = \sum_{j=0}^{\zeta_k - 1} k \left(\frac{1}{2}\right)^j. \quad (13)$$

After the successful reception of CREQ, CREP and CACK messages will be transmitted correspondingly for only once, which add 2 to the overhead. Therefore, denoting x_1 as the average number of required control packets to win the contention for each node involved in the contention, we have

$$\chi_1 = \sum_{i=1}^{\infty} \sum_{k=1}^i B(i, p_1, k) P(N, i) (\beta_k + 2). \quad (14)$$

Thus, the average number $\phi_{CA}(\tau_2)$ of required control packets for a successful code acquisition of a node is

$$\phi_{CA}(\tau_2) = \chi_1. \quad (15)$$

Recall that a node in request for data transmission has to re-obtain its code after the period $T_{sc(i)}$. For the simplification of analysis, $T_{sc(i)}$ is chosen as the average duration for node i in a cell. Thus, we can equivalently consider the probability of initiating code reacquisition as p_1 . Hence, the average control overhead $\phi_{CR}(\tau_2)$ of code reacquisition is also

$$\phi_{CR}(\tau_2) = \chi_1. \quad (16)$$

according to the above-mentioned computations.

3.3.2. Leadership Handover Define $x_i = \rho\pi(d_{i+1}^2 - d_i^2)$. To ensure the successful reception of HREA, it requires only one HREA message is initiated in a slot with the probability $\omega_i = \frac{2\tau_1}{T_{Ui}}$. Thereby, the average number of HREA messages of y_i within priority region i is

$$y_i = s_i \frac{x_i}{2} + (1 - s_i)x_i, \quad (17)$$

where $s_i = \binom{\omega_i}{1} \omega_i (1 - \omega_i)^{x_i - 1}$.

In turn, nodes within region i initiate the HREA messages only if there is no successful reception within region $i - 1$. Hence, when $i \geq 1$, the conditional probability of nodes within region i to initiate HREA is $\prod_{k=0}^{i-1} (1 - s_k)$. Then we have

$$z_i = \begin{cases} y_i, & i = 0 \\ \prod_{k=0}^{i-1} (1 - s_k) y_i, & i \geq 1 \end{cases} \quad (18)$$

Given x_2 as the average number of HREA messages for one successful reception at the CL, we have

$$\chi_2 = \sum_{i=0}^{N_p-1} z_i. \quad (19)$$

Recall that HREQ owns higher priority than CREP and nodes will defer their access for the CCC as soon as they hear any control message of leadership handover. Consequently, HREQ, HAGR and HACK are initiated without collisions and these add 3 to the overall overhead. Therefore, the average overhead $\phi_{LH}(\tau_2)$ of leadership handover is

$$\phi_{LH}(\tau_2) = \chi_2 + 3. \quad (20)$$

3.3.3. Average Total Control Overhead The probabilities of a node to be the CM and CL are respectively $p_3 = \frac{N'-1}{N'}$, and $p_4 = \frac{1}{N'}$, where $N' = \rho\pi R_{eq}^2$. We have known the probabilities of initiating code acquisition and code reacquisition are both equal to the contention probability p_1 . Therefore, within the interval τ_2 , the total average control overhead ϕ of LA-TPCMMP is

$$\phi(\tau_2) = p_3 p_1 \chi_1 + p_4 P_{lh}(\tau_2) \phi_{LH}(\tau_2). \quad (21)$$

4. Overhead Analysis of Classical CDMA-Based Multi-Channel Algorithms (CAs)

In CAs, 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 [9] 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. Actually, the control overhead results from the number of broadcasting packets for the refresh each time and updating frequency. Since there is always a minimal interval to obtain the neighborhood information under a certain mobility and density in case of conflict in adopting codes, we will derive this appropriate interval to ensure the timely neighborhood updating and compare the incurred overhead with LA-TPCMMP.

According to [9], a node sends a Code Assignment Message (CAM) to all its one-hop neighbors when a new node comes into transmission range. All receivers are required to acknowledge the sender to ensure the reliable transmission of CAM. Let N_{h1} denote the average number of one-hop neighbors and N_{m-h1} denote the total number of nodes which migrate into the one-hop distance in the pre-specified small timer $\varepsilon = \tau_2$. Notice that $v\varepsilon$ is far smaller than R_d . Therefore, given l as the distance between two nodes, the average number of new coming one-hop neighbors can be approximately derived as

$$N_{m-h1} = \int_{R_d}^{R_d+v\varepsilon} \theta \rho(2\pi l) dl, \quad (22)$$

where $\theta = \frac{2\arccos((l-R_d)/(v\varepsilon))}{2\pi}$ denotes the angle along which nodes can migrate into the required area. Thereby, the control overhead $\phi_{CA}(\tau_2)$ of CAs within the interval τ_2 is at least

$$\phi_{CA}(\tau_2) = (1 - e^{-\lambda\tau_2})N_{m_h1}(N_{h1} + 1). \quad (23)$$

5. Numerical and Simulation Results

The simulations are conducted using ns-2 [11] with CMU wireless extensions combined with our own C++ models. We calculate the mean value of control overhead over the predefined τ_2 interval for a node to get average control overhead. To ensure the simulation immune from the influences of the borders as presented in [2], we assume that two opposite borders of the simulated area are seamed to form a closed area, which approximates an area without border with the uniform distribution of nodes. Although it is desired that the whole area is divided into the complete hexagonal cells consistent with 7 first-phase codes reuse in the closed area, in this paper, due to the scalability limitation of our simulation tool, we choose the topology as $800m \times 700m$ and $R = 100m$ with nodes and traffic flows randomly distributed and ignore the impact of inconsistent first-phase code reuse near the border. We use two-ray ground model as the propagation model. The channel rate is $2Mbps$ with control channel rate of $0.3Mbps$. The traffic type is UDP with packet size $512bytes$. Assume all the control packets are of the same length $50bytes$. Accordingly, we have $\tau_1 = \tau_3 = 0.00133s$. We choose $\tau_2 = 0.05s$. The simulation time is $500s$ and to approximate the effect of the steady status, the first $100s$ is discarded. The simulation results are averaged 8 runs with different movement patterns for each value of the traffic arrival rate, speed and density. The previously mentioned parameters $\zeta = \beta_k$ and $\tau_{to} = 2\chi_2\tau_1$. In the partition of the priority regions, we choose the parameter $\omega = \frac{2\rho\pi\delta^2\tau_1}{1-e^{-1/N_p^2}}$.

Fig. 3 and Fig. 4 show average delay and control overhead for leadership handover versus density for different number of priority regions. Average delay and control overhead increase with the increase of density and become less with the incremental number of priority regions. When $\rho \geq 0.001$, they are sensitive to the density. Whereas, with N_p increasing, they are not significantly affected by the density. This is due to with more partition of priority regions there is less chances of collisions from the HREA messages even under high density. Consequently, there is less ensuing delay and control packets. However, under a certain density, there is no significant reduction of delay and overhead with more partition of priority regions when N_p is very large. Moreover, increasing regions partition is unpractical considering the additional computation overhead. Hence, in the following analysis and simulation, when $N_{h1} < 30$ we adopt N_p as 1. When $30 < N_{h1} < 50$, N_p is chosen as 2.

In Fig. 5, the number of one-hop neighbors is varied to observe average control overhead under varying traffic load when $V = 10m/s$. Obviously, the control overhead of CAs is worse than that of LA-TPCMMP with the increasing number of one-hop neighbors and almost aggravates exponentially with the increasing density. When the network is considerably loose with $N_{h1} = 5$, the control overhead of CAs when $\lambda = 2Pkts/s$ is even less than that of LA-TPCMMP. This is due to that when the network is loose, the neighborhood update of CAs is less frequent and the probability of collisions is small. Whereas, in LA-TPCMMP, extra control overhead is caused by CLs migration and leadership handover, which makes it less advantageous. Although CAs show a superior performance for the loose distribution, they are vulnerable to the network density. LA-TPCMMP significantly outperforms CAs when the network is becoming dense. When $N_{h1} = 50$, the control overhead incurred in CAs is almost 16 times that of LA-TPCMMP when $\lambda = 2Pkts/s$. Furthermore, when $\lambda = 10Pkts/s$, the control overhead incurred in CAs is almost 162 times that

of LA-TPCMMP. Control overhead of LA-TPCMMP is not affected significantly by density since there is small handover probability $P_{mh}(\tau_2) \doteq 0.0042225$ when $V = 10m/s$ and $R = 100$ which causes less contentions even under high density. The performances in both algorithms become worse when the offered load increases since bigger transmission probability causes more contentions and collisions among control packets. Due to the scalability of y axis, the simulation and numerical results of average control overhead of LA-TPCMMP are separately illustrated in Fig. 6. The simulation data of LA-TPCMMP confirm our analysis. Control overhead of LA-TPCMMP is not affected significantly by the offered load due to the small handover probability. However, as shown in Fig. 5, the performance of CAs almost aggravates linearly with the increasing traffic load since bigger transmission probability requires more frequent neighborhood update. Therefore, LA-TPCMMP substantially reduces control overhead for a sufficiently dense or heavy-loaded network.

Fig. 7 shows average control overhead versus average speed under different traffic load when $N_{h1} = 30$. The average speed V is varied from $2mps$ to $15mps$ to observe the incurred control overhead. With the speed increasing, there is bigger chance for the CMs and CLs to migrate out of the cell and LRA, i.e. the CMs handover probability and CL handover probability increase. Consequently, the control overhead of LA-TPCMMP increases when the speed increases. The simulation data of LA-TPCMMP verify the numerical results. In CAs, with increasing speed there is more chances for a new node migrating into two-hop separation, which results in more updating of neighborhood information. Therefore, CAs also requires more control packets in response to increasing mobility. However, the up trend of CAs is significantly worse than that of LA-TPCMMP.

6. Conclusion and Future Work

In this paper, we present an efficient multi-channel MAC protocol named as LA-TPCMMP, where the first-phase code is used to differentiate between different cells and the second-phase code is used to differentiate between nodes in one cell. This approach eliminates the HTP during data transmission in MANETs without periodical exchange of neighborhood information.

We analyze the constraints that the cell size should be satisfied to ensure the same transmission codes appear more than two hops away, show the priority-based random competition strategy for the initial CL election and leadership handover and present the mechanism of collision resolution to reduce control overhead. Furthermore, we give the comprehensive theoretical analysis of average overhead according to the migration probability of nodes. Simulation results verify our theoretical analysis and it is shown that LA-TPCMMP significantly outperforms the existing CDMA-based algorithms with regards to control overhead.

Due to the limitation of space, the performance of the delay and bandwidth utilization of LA-TPCMMP will be investigated in future. During the priority-based random competition strategy, other factors such as the remaining power of a node as well as the mobility might be comprehensively considered to prolong the network life.

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Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7