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Location-Aware Two-Phase Coding Multi-Channel AMS Protocol (LA-TPCMMP) for MANETs

Lili Zhang, Student Member, IEEE, Boon-Hee Soong, Senior Member, IEEE, and Wendong Xiao, Member, IEEE

Abstract—In classical code division multiple access (CDMA) based multi-channel Medium Access Control (MAC) protocols for Mobile Ad Hoc Networks (MANETs), numerous exchanges of neighborhood information are required for code assignment such that nodes within a two-hop separation will adopt different transmission codes and therefore avoid the hidden terminal problem (HTP). However, such expensive communication overhead for code assignment is not desirable since it will cause an under-utilization of bandwidth, energy inefficiency and longer delays, which can significantly degrade the network performance. In this paper, a novel location-aware multi-channel MAC protocol is presented for a large-scale dense 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. A node knows its first-phase code from its location information and requests its second-phase code from its cell leader. This protocol eliminates the HTP during data transmission without the periodical exchange of neighborhood information. Furthermore, the mechanism of collision resolution in the control channel is described. The performance of the proposed protocol is analyzed in terms of the control overhead and delay. The theoretical results are confirmed by extensive simulations and it is shown that the new protocol significantly outperforms the classical CDMA-based multi-channel MAC protocols.

Index Terms—MANETs, multi-channel MAC, CDMA, LATPCMMP, control overhead, delay.

I. INTRODUCTION

MANET addresses a series of challenges due to its characteristics such as the limited bandwidth resource, energy-constrained terminals and dynamic topology, as well as no central administration. So far, multi-channel MAC protocols have been recommended to combat collisions and enable simultaneous transmissions by dividing the available radio spectrum into multiple channels by means of frequency bands, time slots or orthogonal codes. Two central problems should be solved in a multi-channel MAC design, i.e., how to assign different channels to different nodes and how to resolve the contention and collision problems, in particular the HTP [13]. In this paper, we concentrate on CDMA-based multi-channel MAC design.

The basic criterion of code assignment in CDMA-based multi-channel MAC protocols is that the same code can be reused more than two hops away in order to avoid the HTP. In [11], a unified framework for channel assignment is exploited, which extracts the common constraints for converts the channel assignment problem into a graph coloring problem and proposes the collision-free scheduling...
algorithms. However, this uses a centralized algorithm and requires the global topology information. In order to solve this problem, a novel distributed neighbor-aware contention resolution algorithm HAMA is introduced in [10] by defining different priorities to nodes and determining the channel access schedule for each time slot. However, HAMA requires prompt detection and notifying the change within two-hop separation to harmonize the 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). The optimal code assignment schemes for networks with special topologies and heuristic distributed code assignment algorithms are proposed in [5] with the aim to minimize the number of orthogonal codes and eliminate the hidden terminal interference [13]. In SEEDEX algorithm [15], 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. In [12], the communication complexity of distributed assignment of codes in the worst case is given, by considering the case that a node determines its transmission code through broadcasting to all neighbors within two-hop separation.

Although extensive work has been devoted in distributed code assignment to avoid the HTP [3] [5] [6] [10] [12] [15], they always assume that the complete neighborhood information is known, where the nodes will broadcast their holding codes to the neighbors within two-hop separation so that these neighbors will adopt different codes as their transmission codes. However, as the user density in the network increases, more collisions will occur since nodes will try to broadcast their codes, despite the fact that it is done 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 may happen. Under the conditions of a high user density and high mobility, these overhead will seriously degrade the network performance.

Several location-based protocols have been proposed in the literature [7][14]. TBMAC [7] employs a cellular structure to differentiate frequency bands distribution among the cells. Inside each cell, any node that requests to exchange data packets contends for its time slot for communication. The dynamic channel allocation with location awareness proposed in [14] utilizes a static GRID scheme to allocate the transmission codes. When the location accuracy is inadequate, e.g. a node near the border of the adjacent grids may incorrectly identify the grid where it is located, it will cause different nodes in the adjacent grids to select the same default code allocated to that grid. Consequently, HTP might still exist in this case.

In this paper, we propose the Location-Aware Two-Phase Coding Multi-Channel Protocol (LATPCMP). A preliminary version was presented in [8][9]. We introduce a cell-based two-phase coding scheme 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. The sender obtains its first-phase code according to its location information and exchanges control packets with its cell leader in the control channel to obtain its unique second-phase code. Contentions and collisions only occur in the control channel when the nodes contend to obtain the second-phase codes. For the data channel, no HTP will exist, since any two nodes within two-hop separation will assume their unique transmission codes. We also present the detail mechanism of collision resolution in the control channel. Next, the theoretical analysis of LATPCMP in terms of control overhead and delay is developed. Finally, the numerical results are confirmed by detail simulations.

The rest of the paper is organized as follows. Section 2 describes LA-TPCMMP in detail. Section 3 presents the analysis of the average overhead of LA-TPCMMP. Section 4 gives the analysis of the average delay. Section 5 approximately analyzes the performance of the classical code assignment algorithms. Section 6 examines the performance of LA-TPCMMP in terms of average control overhead and delay by using NS-2 simulations, and compared it with the classical CDMA-based multi-channel
II. LA-TPCMMP

LA-TPCMMP is proposed for large-scale dense MANETs. The wireless channel is divided into the control channel and data channel. We assume in the control channel nodes operate in time-slotted mode and are synchronized. LA-TPCMMP consists of several mechanisms which includes the initial cell leader election, leadership handover, code acquisition and data transmission. The first three functions are implemented in the control channel whereas the last one is implemented in the data channel. The details of LA-TPCMMP will be described in this section.

A. Two-Phase Coding

The protocol uses a 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. As shown in Fig. 1(a), the whole network is sub-divided into cells of hexagonal geographic structure with radius $R$. The first-phase code (0-6) is used for differentiating adjacent cells and covers the whole network. Similar to frequency reuse in cellular, the reuse of the first-phase codes greatly increases the scalability of LA-TPCMMP. Suppose that each node has its location information by means of a positioning technology such as global positioning system (GPS). Within each cell, a cell leader is responsible for maintaining and assigning the second-phase codes to its cell members. As shown in Fig. 1(b), to ensure that any node in a cell is within the communication range of its cell leader $E$, it is required that the cell leader should be located in the leader residence area defined as the circular area with the center $G$ and radius $R'$, where $G$ is the cell center.

Let us assume there exist a set of pseudo noise (PN) orthogonal codes for data transmission. We allocate this set of PN codes to $m$ cells, with each cell assigned with $n$ codes. Let $C^i_1$ denote the $i$th cell and $C^j_2$ denote the $j$th PN code for the $i$th cell, then $C_{FC} = \{C^i_1| i = 1,2,\ldots,m\}$ is defined as the set of the first-phase codes, and $C_{SC} = \{C^j_2| j = 1,2,\ldots,n\}$ is defined as the set of the second-phase codes. The set of the transmission codes in LA-TPCMMP is defined as $C_{TC} = \{(C^i_1,C^j_2)| C^i_1 \in C_{FC}, C^j_2 \in C_{SC}\}$ with each element being a joint first-phase and second-phase code and any two elements in $C_{TC}$ are orthogonal. A cell member $A$ in cell $i$ is assigned with a code $(C^a_1,C^a_2)$ with $C^a_1 = C^i_1$ as shown in Fig. 1(b).

B. Sizes of Cell and Leader Residence Area

Let us assume $R_d$ is the default transmission range, i.e., the maximal communication range of a node. Since the maximum possible distance between the cell leader and a cell member is $R + R'$, we have $R + R' \leq R_d$. Since two different cells may be allocated the same first-phase codes, it is possible that two nodes located within these two cells separately are allocated the same second-phase codes, which will cause the HTP when these two nodes are within two-hop separation and they attempt to transmit data simultaneously. As shown in Fig. 1(a), the minimum distance between any two nodes in different cells with the same first-phase codes is calculated as $\sqrt{7}R$. Thus, in order to avoid the HTP, we require that $\sqrt{7}R > 2R_d$ to ensure that the same transmission codes appear at least two hops away. Accordingly, we have the lower and upper bound of $R$,

$$\frac{2}{\sqrt{7}}R_d < R < R_d$$

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

$$R' \leq R_d - R < (1 - \frac{2}{\sqrt{7}})R_d$$
C. Operations of LA-TPCMMP

1) Initial cell leader election and leadership handover: We divide the leader residence area into \( N_p \) different priority regions with the highest priority level to be 0. As shown in Fig. 1(c), a node inside the leader residence area is located in region \( i \) (\( i = 0, 1, \ldots, N_p - 1 \)) when its distance \( R_c \) to the cell center follows \( i = \left\lfloor \frac{R_c}{\delta} \right\rfloor \), where \( \delta = R'/N_p \). In this figure, we denote \( d_i = i\delta \). During the initial cell leader election and leadership handover, a node located in region \( i \) has higher priority to be a leader than another node located in region \( j \) if \( i < j \).

a) Initial Cell Leader Election: Initial cell leader is elected from all the nodes inside the leader residence area in a distributed way. If a node within region \( i \) can not get any response from the cell leader after \( \xi \) trials for code acquisition, it assumes that there is no cell leader in the current cell and starts the competition by broadcasting a leader declaration (LDCL) message to declare itself as a cell leader after deferring a priority region-dependent period

\[
T_i = T_{Li} + T'_{Ui},
\]

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 bounded of \( T'_{Ui} \). Obviously, \( T_{Li} \leq T_i \leq T_{Li} + T_{Ui} \). Now since the nodes closer to the cell center is preferred, \( T_{Ui} \) and \( T_{Li} \) are respectively defined as

\[
T_{Ui} = \omega \left(1 - e^{-(d_{i+1}^2-d_i^2)/R'^2}\right)
\]

and

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

where \( \omega \) 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 each different priority regions adopt a different \( T_{Li} \) and nodes within the same priority region adopt an additional random values between \([0,T_{Ui}]\) for competition. This selection is referred as the priority-based random competition strategy.

If a node inside the leader residence area hears a LDCL message from another node before it sends its own message, it gives up its competition without broadcasting its LDCL message. The first node, which broadcasts the LDCL, will upgrade itself as the cell leader. Obviously, if \( i < j \), then \( T_i < T_j \). Hence, a node within higher priority region always owns higher competition priority. In this way, the elected node is usually closer to the cell center of its cell and more suitable to act as a cell leader. However, for the nodes within the same priority region, a random competition strategy is adopted.

b) Leadership Handover: If necessary, a cell leader will hand over the leadership and available second-phase codes to a more suitable node. As shown in Fig. 2(a), it initiates the leadership handover procedure by broadcasting Handover Request (HREQ) message and suspends its code allocation operations when it moves out of the leader residence area of its current cell. The nodes within the leader residence area 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 cell leader. After receiving HREA, the cell leader replies with the Agree to Handover (HAGR) message with the set of the available second-phase codes piggybacked. Upon receiving the HAGR message from the original leader, the inheritance will upgrade itself to the cell leader by duplicating the set of the available second-phase codes, resume its right of code allocation and send the Handover
Acknowledgement (HACK) message. When the original cell leader receives the HACK message, it will downgrade itself as a normal cell member and discard its set of the available second-phase codes. If a cell leader cannot receive the responses from its cell members after a predefined period of $\tau_{pp}$, it will try to hand over the leadership again.

2) Code Acquisition: When node $i$ wants to send data to node $j$, transmitter-oriented data transmission [4] is adopted. Node $i$ knows its first-phase code $C_1$ according to its location, and acquires its unique second-phase code $C_2$ from its cell leader by sending the Code Request (CREQ) message with its reservation period $T_{sc}(i)$ piggybacked, as shown in Fig. 2(b). After receiving the CREQ message successfully, the cell leader allocates a unique second-phase code from the set of the available second-phase codes, records the $T_{sc}(i)$ and replies with the Code Reply (CREP) message to node $i$. Upon hearing the CREP message, node $i$ sends the Code Acknowledgement (CACK) message which includes the information of the selected second-phase code such that the cell leader can update the set of the available second-phase codes and record the expiration time of node $i$ to use the assigned code. Then, node $j$ achieves the code synchronization after overhearing the CACK message and node $i$ can start its data transmission to node $j$ in the data channel. Otherwise, node $i$ retransmits CREQ until CREP is received or when $\xi$ times code acquisitions trials are reached.

A second-phase code for a node $i$ can be used for the reservation period $T_{sc}(i)$, which can be predicted by the node according to its traffic demand. After this period, if node $i$ still needs the second-phase code for data transmission, it could require the time-interval extension of the holding code for another period of $T_{sc}(i)$ using the CREQ message with one flag marked as code extention. The cell leader will take over the code allocated to node $i$ and add it to the set of the available second-phase codes after the reservation period $T_{sc}(i)$ if there is no extension request. That is, the valid period of an allocated second-phase code of node $i$ is the reservation period $T_{sc}(i)$. In this way, the second-phase code can be reused by other nodes.

When a node migrates from one cell to another, it should change its first-phase code that corresponds to the new cell and obtain its new second-phase code from the cell leader of the new cell.

D. Collision Resolution in the Control Channel

Suppose that nodes operate in time-slotted mode in the control channel and each time slot is of duration $\tau_p$. Fig. 2(c) shows four modes, i.e., code acquisition mode, leadership handover mode, switching 1 and switching 2 mode. Code acquisition mode consists of the time frames and each frame is divided into three times slots that are dedicated for CREQ, CREP and CACK messages, respectively. CREQ is only initiated by the cell members in the first slot, and in turn CREP and CACK messages are initiated by the cell leader and members respectively, in the following subsequent slots. If a cell leader wants to hand over its leadership, it will send a HREQ in the second slot of a frame of code acquisition mode, which forms the switching 1 mode. If a cell member under the coverage of more than two cell leaders sends CREQ, the cell leaders within its coverage either encounter collisions or receive its CREQ message. Since only its cell leader that successfully receives the CREQ will respond to the cell member, the cell member will receive its CREP message free of interference. Therefore, whenever CREQ of a node wins the contention within 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 cell members. We employ the binary splitting strategy [17] 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. As pointed out in [17], this procedure will terminate in several frames with high probability. Additionally, if collisions are not resolved within the $\xi$ trials for code acquisition, nodes will abort by themselves.

Leadership handover mode has higher priority than code acquisition mode. Whenever a cell leader wants to hand over its leadership, it switches the cell to the leadership handover mode by immediately initiating the HREQ in the corresponding slot referring to Fig. 2(c). The cell members within the coverage of this cell leader should defer their control messages for code acquisition in the control channel once they hear HREQ until HACK is received. The cell members within the leader residence area always defer their access at the duration of an idle slot after they transmit HREA messages. When there is no collisions of HREA occurring at the cell leader, the cell member can hear HAGR from the previous cell leader in the subsequent slot after it transmits HREA. Then, it can transmit HACK. Thus, the leadership handover, which is composed of several unsuccessful HREA trials and one successful HREA contention following the priority-based random competition strategy, can be accomplished free of interference. Since leadership handover can be completed in any slot, the length of the frame for leadership handover is variable with its frame terminating either at a new frame of code acquisition mode or at the slot for CREP or CACK messages that forms the switching 2 mode as shown in Fig. 2(c) with dash line. Next, the nodes in the cell will change to code acquisition mode and start the new frame for contention.

E. Elimination of HTP in Data Channel

To show this, suppose the transmission codes of nodes $A$ and $B$ are $C^a = (C^a_1, C^a_2) \in C_{TC}$ and $C^b = (C^b_1, C^b_2) \in C_{TC}$ respectively. 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 $C^a_1 = C^b_1$ and $C^a_2 \neq C^b_2$, 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 $\sqrt{7}R > 2R_d$ (see equation (1)), one has $C^a_1 \neq C^b_1$. Thus, no matter what second-phase codes nodes $A$ and $B$ use, one always has $C^a \neq C^b$. For both cases, $C^a$ and $C^b$ are always orthogonal. Therefore, with this kind of assignment of transmission codes, HTP is eliminated in LA-TPCMMP.

III. ANALYSIS OF AVERAGE OVERHEAD

A. Analysis Assumption

It is assumed that nodes are spatially distributed throughout the network according to the Poisson process in two dimensions with density $\rho$. The traffic arrival process is Poisson arrivals with mean arrival rate $\lambda$. Nodes operate in half-duplex mode. We choose a time interval $\tau_2$ 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 that contend during this interval. In the following analysis, we compute the average incurred control overhead and delay over the predefined $\tau_2$ interval for a node.

B. Mobility Model and Handover Probability

The random walk-based mobility model [2] is adopted here, where each node’s movement consists of a sequences of random length mobility intervals called epochs. The epoch lengths are independent and identically distributed (IID) and exponentially distributed, the direction of a mobile node during each epoch is IID uniformly distributed over $[0, 2\pi]$ and the speed of a mobile node is an IID uniformly distributed random variable between $[0, V_{max})$ and remains constant during each epoch. Suppose $R_{eq}$ is the radius of a circle with the same area as the hexagonal cell. It is easy to show that
\[ R_{eq} = \frac{3\sqrt{3}}{2\pi} R. \]

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 cell leader handover and initial status of cell member migration, while the latter approximates to the steady status of cell member migration.

Let \( f_{T_{m}}(t) \) denote the probability density function (pdf) of the residence time in a cell of a mobile node that hands over from a neighbouring cell before crossing into another cell and \( f_{T_{l}}(t) \) denote pdf of the average residence time in the leader residence area of a cell leader. We have

\[
f_{T_{m}}(t) = \begin{cases} \frac{4R_{eq}}{\pi v_{max} t^2} \left(1 - \sqrt{1 - \left(\frac{v_{max}}{2R_{eq}}\right)^2}\right)^2, & 0 \leq t \leq \frac{2R_{eq}}{v_{max}} \\ \frac{8R_{eq}}{3\pi v_{max} t^2}, & t \geq \frac{2R_{eq}}{v_{max}} \end{cases}
\]

\[
f_{T_{l}}(t) = \begin{cases} \frac{8R_{eq}}{3\pi v_{max} t^2} \left(1 - \sqrt{1 - \left(\frac{v_{max}}{2R_{eq}}\right)^2}\right)^2, & 0 \leq t \leq \frac{2R_{eq}}{v_{max}} \\ \frac{8R_{eq}}{3\pi v_{max} t^2}, & t \geq \frac{2R_{eq}}{v_{max}} \end{cases}
\]

according to [2]. Therefore, the mean cell residence time \( E[T_{m}] \) for a mobile node handing over from one cell into another cell and the mean leader residence area residence time \( E[T_{l}] \) for a cell leader can be computed as

\[
E[T_{m}] = \int_0^\infty t f_{T_{m}}(t) dt,
\]

\[
E[T_{l}] = \int_0^\infty t f_{T_{l}}(t) dt.
\]

Let the cell member handover probability \( P_{m}(\tau_2) \) and cell leader handover probability \( P_{l}(\tau_2) \) respectively denote the probability of the cell members to walk out of the current cell and probability of the cell leader to walk out of the leader residence area of its cell in interval \( \tau_2 \). Then, we have

\[
P_{m}(\tau_2) = \frac{1}{E[T_{m}]} \tau_2,
\]

\[
P_{l}(\tau_2) = \frac{1}{E[T_{l}]} \tau_2.
\]

C. Overhead Analysis of LA-TPCMMP

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

1) Overhead Analysis of Code Acquisition: Let \( N = \rho \pi R_d^2 \) be the average number of nodes in the transmission range. A successful code acquisition requires the correct reception of the CREQ, CREP and CACK messages. However, CREQ may encounter collisions, since the nodes in the coverage area of a cell leader 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 cell leader 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 \( \sum_{i=1}^\infty B(i,p_1,k)P(N,i) \), 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 $\tau_2$ is $e^{-\lambda \tau_2}$. Thereby, we have the contention probability $p_1 = (1 - e^{-\lambda \tau_2})P_{mh}(\tau_2)$ during interval $\tau_2$. Given $\zeta_k$ as the average number of CREQ slots required to resolve one collision, it follows the recursive relationship

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

(12)

according to the binary splitting strategy in [17]. Consequently, the average number $\beta_k$ of the CREQ messages to resolve the collisions within the interval $\tau_2$ can be computed as

$$
\beta_k = \sum_{j=0}^{k-1} k(\zeta_j^2) 
$$

(13)

After the successful reception of CREQ, CREP and CACK messages will be transmitted correspondingly for only once, which adds 2 to the overhead. Therefore, denoting $\chi_1$ as the average number of required control messages to win the contention for each node involved in the contention, we have

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

(14)

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

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

(15)

Recall that the second-phase code allocated to node $i$ will be recycled after $T_{sc(i)}$ and a node in request for data transmission has to re-extend its code after the currently holding code is invalid. For the simplification of analysis, the period $T_{sc(i)}$ 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 $\phi_{CE}(\tau_2)$ of code extension is also

$$
\phi_{CE}(\tau_2) = \chi_1.
$$

(16)

according to the above-mentioned computations.

2) Overhead Analysis of Leadership Handover: During the leadership handover, the cell members within the leader residence area send HREA messages according to the priority order determined by their distances to the center of the leader residence area. The deferring timer $T_{li}$ ensures two nodes respectively from different priority regions free of collision and $T_{li}$ is used to avoid the HREA collisions between two nodes within the same priority regions since it is a random multiple of $2\tau_1$ in [0, $T_{li}$]. Define $x_i = \rho(\delta_i^2 - d_i^2)$. To ensure the successful reception of HREA, it requires only one HREA message is initiated in a slot with the probability $\omega_i = 1/\bar{\omega}_i$, where $\bar{\omega}_i = \left[\frac{T_{li}}{2\tau_1}\right]$. Therefore, the average number of HREA messages of $y_i$ within priority region $i$ is

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

(17)

where $s_i = (\bar{\omega}_i)^i(1 - \omega_i)^{x_i-1}$.

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

$$
z_i = \left\{ \begin{array}{ll}
y_i, & i = 0 \\
\prod_{k=0}^{i-1}(1 - s_k)y_i, & i \geq 1 
\end{array} \right.
$$

(18)

Let $\chi_2$ be the average number of HREA messages for one successful reception at the cell leader, we have
\[ x_2 = \sum_{i=0}^{N_p-1} z_i. \]  

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

\[ \phi_{LH}(\tau_2) = x_2 + 3. \]  

3) Average Total Control Overhead: The probabilities of a node to be the cell member and cell leader are respectively \( p_3 = \frac{N'-1}{N'} \) and \( p_3 = \frac{1}{N'} \), where \( N' = \rho \pi R_{eq}^2 \). The probability of initiating code acquisition and extension are both equal to the contention probability \( p_1 \). Therefore, within the interval \( \tau_2 \), the total average control overhead \( \phi \) of LA-TPCMMP is

\[ \phi(\tau_2) = p_3 p_1 x_1 + p_4 P_{lh}(\tau_2) \phi_{LH}(\tau_2). \]  

IV. ANALYSIS OF AVERAGE DELAY

A. Delay Analysis of LA-TPCMMP

In order to simplify our analysis, we assume the cell leaders (CL1, CL2 and CL3...) are at the centers of their respective cells. As shown in Fig. 3, the shaded areas \( S_1, S_2 \) and \( S_3 \) are respectively the areas covered by one cell leader, two cell leaders and three cell leaders. The probabilities that the nodes stay within \( S_1, S_2 \) and \( S_3 \) are denoted as \( p_{S_1}, p_{S_2} \) and \( p_{S_3} \), respectively. Since the nodes are uniformly distributed, we can get the probability of a node to be in \( S_1, S_2 \) or \( S_3 \) is

\[ p_{S_1} = \frac{S_1}{\pi R_d^2}, \]
\[ p_{S_2} = \frac{6S_2}{\pi R_d^2}, \]
\[ p_{S_3} = \frac{6S_3}{\pi R_d^2}. \]

Let \( S_f \) denote the area of the slice centered at CL2 and with radius \( R_d \) and angle \( \alpha = 60^\circ \); and \( S_t \) denote the area of the equilateral triangle with \( d = \sqrt{3}R \), then we have \( S_t = 3S_f - 3\left(\frac{S_2}{2} + S_3\right) + S_3 \). Given \( S_o \) as the cross area of two circles with radius \( R_d \) and distance of the circle centers \( d \), we have

\[ S_o = 4\left(\frac{\pi R_d^2}{2\pi} - \frac{d}{2} \sqrt{R_d^2 - \left(\frac{d}{2}\right)^2}\right). \]

Obviously, it can be shown that,

\[ S_f = \frac{\pi R_d^2}{6}, \]
\[ S_t = \frac{\sqrt{3}d^2}{4}, \]
\[ \frac{S_2}{2} + S_3 = \frac{S_o}{2}. \]

Thus, we have
\[
S_3 = S_t - 3S_f + 3\frac{S_o}{2} = \frac{\sqrt{3}d^2}{4} - \frac{\pi R_d^2}{2} + 3\frac{S_o}{2},
\]
\[
S_2 = 2\left(\frac{S_o}{2} - S_3\right),
\]
\[
S_1 = \pi R_d^2 - 6S_2 - 6S_3.
\]

The probability that a node in \(S_k\) hears \(i\) leadership handover is given by \((k)P_{lh}(\tau_2)^i(1 - P_{lh}(\tau_2))^{k-i}\), \((k=1,2,3)\). Given that \(\psi_{LH}(\tau_2)\) is the upper bound of the average delay of leadership handover, we have the delay of the node suffering from leadership handover is upper bounded by \(i\psi_{LH}(\tau_2)\). For the simplification of analysis, we assume the duration of each control packet \(\tau_3\) is equal to \(\tau_1\). Since the code acquisition requires the correct reception of the CREQ and CREP messages and a node wins the contention after an average \(\zeta_k\) CREQ slots, the upper bound \(\psi(\tau_2)\) of average delay spent in code acquisition for a node can be computed as

\[
\psi(\tau_2) = \sum_{k=1}^{\Omega_1} \rho_{SR} \sum_{i=0}^{k} (k)P_{lh}(\tau_2)^i(1 - P_{lh}(\tau_2))^{k-i}(i\psi_{LH}(\tau_2)) + \sum_{i=1}^{\Omega} \sum_{k=1}^{\Omega}(3(\zeta_k - 1) + 2)\tau_3 B(i, p_i, k)P(N, i).
\]

(22)

Next, for the computation of \(\psi_{LH}(\tau_2)\), recall from the protocol that nodes have to defer one slot after transmitting HREA. When HREA messages of nodes within region 0 are received by the corresponding cell leader with probability \(s_o\), and the delay is upper bounded by \(T_{L1}\). Otherwise, according to the conditional probability \(1 - s_o\), the delay is correspondingly upper bounded by \(T_{L2}\). In turn, when HREA messages of nodes within region \(i\) are received by the corresponding cell leader, we have the upper bound of \(\prod_{k=0}^{i-1}(1 - s_k)T_{Li}\). In addition, the delay due to the HREQ, HAGR and HACK messages is \(3\tau_3\). Therefore, we have

\[
\psi_{LH}(\tau_2) = S_o T_{L1} + \left(\sum_{i=1}^{\Omega} \rho_{SR} (\prod_{k=0}^{i-1}(1 - s_k)T_{Li})\right) + 3\tau_3.
\]

(23)

V. 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 [12] 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 each updating and the updating frequency. Since there is always a minimal interval to obtain the neighborhood information under a certain mobility and user density for case of a conflict in adopting the codes, we will derive this appropriate interval to ensure the timely neighborhood updating and compare the incurred control overhead and delay with LA-TPCMMP.

According to [12], a node sends a Code Assignment Message (CAM) to all its one-hop neighbors when a new node comes into its 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 \(\varepsilon = \tau_2\). Note that \(\varepsilon\) is far smaller than \(R_d\). Therefore, given \(l\) as the distance between two nodes, the average number of new one-hop neighbors can be approximately derived as

\[
N_{m,h1} = \int_{R_d}^{R_d+\varepsilon} \theta \rho(2\pi l)dl,
\]

where \(\theta = \frac{2\arccos((l-R_d)/(\varepsilon \cdot ve))}{2\pi}\) denotes the angle along which nodes can migrate into the required area. Therefore, the control overhead \(\phi_{CA}(\tau_2)\) of CAs within the interval \(\tau_2\) is,
\[ \phi_{CA}(\tau_2) = \left(1 - e^{-\lambda \tau_2}\right)N_{m,h1}(N_{h1} + 1). \] (25)

Before initiating its transmission, a node should first listen to the neighborhood broadcast for at least a period of \( \tau_c = (1 - e^{-\lambda \tau_2})N_{m,h1}(r + 1)\tau_3 \) to ensure the adopted code is appropriate to avoid the HTP. The chosen value of \( r \) of a node should ensure that each neighbor within transmission range at least broadcasts once for acknowledgement. According to the occupancy problem in combinatorial mathematics in [18][19], the probability that \( u \) nodes get no chance to successfully broadcast itself is

\[ p(u; r, N_{h1}) = N_{h1}^{-r}C_{N_{h1}}^{u} \sum_{v=0}^{N_{h1} - u} (-1)^v C_{N_{h1} - u}^v (N_{h1} - u - v)^r. \] (26)

Thus, to ensure \( p(0; r, N_{h1}) = 1 \), i.e., almost each node can successfully broadcast itself in this duration, a node should defer \( \tau_c \) before initiating its data transmission. Therefore, the delay \( \psi_{CA}(\tau_2) \) of CAs is lower bounded by \( \tau_c \).

VI. NUMERICAL AND SIMULATION RESULTS

The simulations were conducted using NS-2 with CMU wireless extensions [16], and combined with C++ models that implement the detail LA-TPCMMP. The performance is evaluated in terms of control overhead and delay, for various density and mobility conditions under different traffic loads. The average values of control overhead and delay are calculated over a predefined \( \tau_2 \) interval for a node. To ensure the simulation is immune from the influences of the borders as reported in [2], we assume that the two opposite borders of the simulated area are joined to form a closed area, which approximates an area without border with a 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, 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 a two-ray ground propagation model for the channel. The data channel’s bit rate is \( 2M \) bps while the control channel’s bit rate is \( 0.3M \) bps. The data traffic type is UDP with a packet size of 512 bytes. All the control packets are assumed to be the same length of 50 bytes. Accordingly, we have \( \tau_1 = \tau_3 = 0.00133s \). We choose \( \tau_2 = 0.05s, R_d = R/0.76 \) and \( R' = 0.24R_d \). The simulation time is set at 500 s and to better approximate the status of the steady state, the first 100 s is discarded. The simulation results are averaged over 8 runs with different movement patterns, and for each value of traffic arrival rate, speed and density. As mentioned in Section II-C, the number of code acquisition trials \( \xi \) and the predefined period \( \tau_{pp} \) are equal to \( \beta_k \) and \( 2\chi_2 \tau_1 \), respectively. For the partition of the priority regions, we choose the parameter \( \omega = \frac{2\rho m \delta^2 \tau_1}{1 - e^{-1/N_p^2}} \).

Fig. 4 and Fig. 5 show average delay and control overhead for leadership handover versus density for different number of priority regions \( N_p \). Average delay and control overhead increase when the density becomes larger but decrease with each incremental addition in the number of priority regions. For \( N_p = 1 \) and when \( \rho \geq 0.001 \), they are sensitive to the density. However, by increasing \( N_p \), they become less significantly affected by the density. This is due to the fact that with more partition of priority regions there will be less chances of collisions from the HREA messages even under high density. Consequently, this results in less outstanding delays and control packets. However, under a certain density, there appears to be no significant reduction of delay and overhead with more partition of priority regions, i.e., when \( N_p \) is large. Moreover, increasing regions partition is unpractical considering the additional computation overhead. Hence, in the following subsequent analysis and simulations, we adopt \( N_p \) as 1 when \( N_{h1} \leq 30 \) and choose \( N_p \) as 2 when \( 30 < N_{h1} \leq 50 \).
In Fig. 6, the number of one-hop neighbors is varied to observe average control overhead under varying traffic load when \( V = 10m/s \). The average control overhead of CAs is much worse than that of LA-TPCMMP with an increasing number of one-hop neighbors. For CAs, the control overhead increases exponentially. When the network is less dense, i.e., with \( N_{h1} = 5 \), the control overhead of CAs when \( \lambda = 2\text{Pkts/s} \) is even less than that of LA-TPCMMP. This is due to the fact that with a less dense network, the neighborhood update of CAs is less frequent and the probability of collisions is small. However, in LA-TPCMMP, an extra control overhead is caused by cell leaders migration and leadership handover, which might make it less advantageous in this case. Although CAs show a superior performance for the low network density, they are vulnerable to the changes in 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 \( \lambda = 2\text{Pkts/s} \). Furthermore, when \( \lambda = 10\text{Pkts/s} \), 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 \( P_{mh}(\tau_2) = 0.0042225 \) when \( V = 10m/s \) and \( R = 100 \) which causes less contentions even under high density. The performances for both algorithms degrade when the offered load increases since a bigger transmission probability causes more contentions and collisions among the control packets. Due to the scale of y axis in Fig. 6, the simulation and numerical results of average control overhead of LA-TPCMMP are illustrated separately in Fig. 7. The simulation results of LA-TPCMMP confirm our analysis. Note that the control overhead of LA-TPCMMP is not affected significantly by the offered load due to the small handover probability. However, as shown in Fig. 6, the performance of CAs degrades significantly with an increasing traffic load since a bigger transmission probability requires a more frequent neighborhood update. Therefore, LA-TPCMMP substantially reduces the control overhead for a sufficiently dense or a heavy-loaded network.

Fig. 8 shows average control overhead versus average speed under different traffic load when \( N_{h1} = 30 \). The average speed \( V \) is now varied from \( 2mps \) to \( 15mps \) to observe the incurred control overhead. With the speed increasing, there is bigger chance for the cell members and cell leaders to migrate out of the cell and leader residence area, i.e., the cell members handover probability and cell leader handover probability will increase as a result. Consequently, the control overhead of LA-TPCMMP increases as the speed increases. In CAs, with increasing speed there is more chances for a new node migrating to a 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 upward trend of CAs is worse than that of LA-TPCMMP.

Fig. 9 shows how average delay varies with the number of one-hop neighbors for both algorithms and Fig. 10 compares the simulation and numerical results of average delay of LA-TPCMMP. There is substantial reduction of average delay of LA-TPCMMP due to less exchanges of the control packets. Average delay of CAs almost degrades exponentially with the increasing density but the delay of LA-TPCMMP is only minimally affected. Fig. 11 shows average delay versus average speed under different traffic load when \( N_{h1} = 30 \). With the increasing speed, the increasing cell members and cell leader handover probabilities cause the delay of LA-TPCMMP to increase. Note that in CAs, more updating of neighborhood information results in the delay to increase. However, LA-TPCMMP still incurs less delay and it degrades less significantly than that of the CAs.

Fig. 12 demonstrates average control overhead and delay of LA-TPCMMP versus speed when \( \lambda = 10\text{Pkts/s} \) and \( N_{h1} = 30 \). Both the overhead and delay increase linearly with the increasing average speed. Furthermore, the simulation data verifies our numerical results.

VII. CONCLUSION AND FUTURE WORK

The basic idea of CDMA-based multi-channel algorithms is that nodes within a two-hop separation should adopt different transmission codes such that the HTP can be avoided. However, CAs rely on the periodic exchange of neighborhood information to assign transmission code, which results in expensive
communication overhead. In this paper, we present an efficient cell-based 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 the periodical exchange of neighborhood information.

We analyze the constraints that the cell size should satisfy in order to ensure that the same transmission codes appear more than two hops away, and introduce the priority-based random competition strategy for initial cell leader election and leadership handover. The mechanism of collision resolution is presented to reduce control overhead and delay. Furthermore, we provide the comprehensive theoretical analysis of average overhead and delay for LA-TPCMMP 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.

Future improvements and work are currently underway for the LA-TPCMMP. The bandwidth and energy efficiency that results from the significant reduction of control packets is worth investigating. During cell leader election and leadership handover, other factors such as the remaining power of a node as well as the mobility, etc., might be considered, to improve the reliability of cell leaders and observe the frequency of leadership handover.
Reference


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(a) Cell Distribution with the First-phase Code

Cell $i$ with the first-phase code $C_i$

Leader residence area
Cell leader $E$
Cell member $A$

(b) Cell Structure

(c) Leader Residence Area

Fig. 1.
Fig. 2.
Fig. 4.

The figure shows the average delay for cell leader handover ($s$) as a function of density. The curves represent different numbers of cells ($N_p$), with $N_p=1$, $N_p=2$, $N_p=3$, $N_p=4$, and $N_p=5$. The delay increases significantly as the density increases.
Fig. 5.
Fig. 6.
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