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A Permutation-Based Model for Analysis of Resource Allocation Overheads in Vehicular Ad Hoc Networks

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ABSTRACT This paper considers the theoretical limits of resource allocation overheads in vehicular ad hoc networks (VANETs), where the resource allocation procedure may consume extensive system resources. A permutation-based model is proposed to analyze the overhead limits where the unordered resource allocation patterns are considered as a permutation process. The minimum bits to represent the resource allocation information can be derived based on the permutation-based model. The bipartite graph is applied to describe the resource reuse in the respective domains for practical scenarios, and the dynamicity is taken into consideration. The proposed permutation-based model is applied to analyze the resource allocation overheads of two typical resource allocation schemes in VANETs: time-division multiple access (TDMA) and cluster-based algorithms. The proposed methodology provides new insights in a tradeoff analysis between overheads and system efficiency when analyzing the capacity of the VANETs.

INDEX TERMS Overhead, resource allocation, vehicular ad hoc networks, and theoretical limit.

I. INTRODUCTION

Vehicular ad hoc network (VANET) is a self-organizing network without centralized administration. Vehicles will exchange their status information periodically containing their velocity, position, etc to improve the road safety and traffic efficiency. In VANET, the resource allocation process are conducted in the distributed method, which will introduce much more overheads caused by complicated control messages. Vehicles will select and occupy the resource for transmission based on the resource allocation information in the neighborhood.

To meet the requirements of various applications in VANET in terms of high reliability and low latency, a considerable number of resource allocation algorithms are proposed, which can be generalized into two typical sorts of schemes: TDMA and cluster-based algorithm.

Various TDMA-based protocols have been proposed to improve the performance of VANET. In [1], a TDMA-based MAC protocol VeMAC is proposed. In VeMAC each node must acquire exactly one slot in a frame to transmit data and slot allocation information of neighbors for implicit acknowledgement. Authors in [2] present a novel Adaptive TDMA based MAC (VAT-MAC) in VANET. In VAT-MAC, the frame length is adjusted based on the estimated number of competing nodes in the subsequent time frame, and the adjusted frame length will be announced in each frame. A mobility-aware TDMA-based MAC is proposed in [3], where the slots are assigned according to the nodes topology.

A considerable number of algorithms are proposed based on cluster structures. The authors in [4] present a distributed multichannel and mobility-aware cluster-based MAC (DMMAC) protocol, which allows vehicles to send updated status messages to the cluster head every 100 ms. The authors in [5] proposed an architecture design algorithm for geographical static clustering, which the cluster is formed depending upon the nodes density of road network, and the cluster head is static within each cluster. A vehicular multi-hop algorithm for stable clustering (VMaSC) is presented in [6]. In VMaSC, the cluster head selection is

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based on the speed difference between neighboring nodes. A cluster-based protocol is proposed in [7] to improve the stability in VANET, where the cluster head selection is based on the Life-Time in each zone.

Due to the unique attributes of VANET service and the dynamic topology, vehicles use distributed resource allocation to select and occupy the resource for transmission. In order to improve the performance of the resource allocation process, extra control information (location, slot allocation information, etc) is introduced in the existing resource allocation algorithms. Different types of control information in these resource allocation algorithms will cause extensive overheads, which will degrade the network efficiency and performance. Various overhead control algorithms are proposed to reduce the overheads in the resource allocation process. A Control Overhead Reduction Algorithm(CORA) is presented in [7] to minimize the number of the control overhead messages by optimizing the period for updating or exchanging control messages between the cluster member and the cluster head. Authors in [8] propose a hybrid clustering algorithm in VANET using the average relative speed in the cluster head selection, and overheads introduced are reduced by increasing the cluster duration. A overhead reduction algorithm is presented in [9], where the control overhead is reduced by announcing the cluster head advertising messages in specific predicted period of time.

The overheads problem in mobile ad hoc networks has been widely investigated in recent years [10]–[12]. Most of these works focus on the routing overheads resulting from the dynamic topology, and the overheads introduced by the initial resource allocation process are neglected. The resource allocation overhead is a significant challenging problem in VANET, since the resource allocation process may occur frequently due to the unstable connections and the dynamic topology. Most of the existing models focus on the overheads of a certain protocol, where the overheads are calculated by aggregating different control information supporting the algorithms [1], [4], [13]. The resource allocation overheads are analyzed in [14], where a centralized controller is in charge of the resource allocation and scheduling. To our knowledge, there is no related work on the resource allocation overhead in the self-organized networks, where the resource allocation is conducted in a more complicated method. In addition, the majority of the existing models for overhead analysis are simplified, where all nodes are in the same collision domain and the number of nodes is constant without considering the dynamicity. Besides, most of the previous works implicitly assume that nodes can access resources in order, and only the overheads needed for updating state information are considered [15], which means the resource allocation overhead problem in initial access is ignored where there is no previous acknowledgement. Therefore, it is important to fill the gap by developing a methodology to quantify the resource allocation overhead in VANET.

In this paper, we develop a permutation-based model to analyze the resource allocation overheads in vehicular ad hoc networks. The analysis model in this paper considers the general resource allocation process without previous acknowledgement. Compared with the existing works on analysis of overheads which focus a specific resource allocation algorithm. The analytical model in this paper describes the general resource allocation process regardless of the structure of the control information. The paper provides a new perspective of permutation to explore the minimum information needed in the resource allocation overhead. The proposed model is presented based on the general resource allocation process, which could be extended to other similar scenarios sharing the same networks features, such as the 5G cellular network, C-V2X or software defined networking [16]. The analysis model could be applied in overhead reduction in massive access scenarios and hierarchical networks management [17], where the corresponding process will introduce extensive overheads.

To model the realistic resource allocation process, the geographic distribution of nodes and dynamicity are considered. The bipartite graph is used to describe the resource reuse when nodes are in respective domains. Each resource allocation pattern is treated as a permutation to derive the theoretical limits of the overhead. The proposed analytical model is applied in two typical resource allocation schemes (TDMA and clustering) to provide a more intuitive understanding of the model. The main contributions of this paper are summarized as follows:

- This paper presents a general methodology to analyze the resource allocation overheads in vehicular ad hoc networks. The model considers the essential resource allocation problem, which is not confined to any certain protocol compared with previous works.
- The model is formulated based on practical scenarios considering the nodes distribution, resource reuse, and dynamicity. The bipartite graph is applied to describe the resource reuse process.
- The unordered resource allocation patterns are modeled as permutations. The minimum bits required for reliable access are derived based on the permutation-based model.

It is important to note that this paper focuses on analyzing the resource allocation overheads without previous acknowledgement and exploring the minimum overhead in the resource allocation process. The control information design to reach the theoretical limit derived in this work is not within the scope of this paper. The rest of the paper is organized as follows. Section II introduces the permutation-based model of resource allocation. The theoretical limits of the overheads in different scenarios are described in Section III. The numerical results are presented in Section IV. Section V concludes the research and suggests some future works.

II. SYSTEM MODEL

In this section, we present the permutation-based model to describe the general resource allocation problem in VANET.

The limit of resource allocation overhead is analyzed based on the permutation-based model considering the node distribution, resource reuse and dynamicity. To simplify the analysis, the analytical model are formulated based on the assumptions as follows:

1) The linear topology are considered where all nodes are distributed with node density λ (in nodes per km).
2) The transmission range L_S for each node is equal.
3) The link status are decided according to the distance the transmission range.
4) There are two states for each node: *active* and *idle*. The active state represents the node will contend for the resource for transmission, and idle means the node will keep silent in the resource allocation process. The active probability is denoted by ρ.

As mentioned in the assumption 1, all nodes are distributed in the linear topology to describe the road scenarios. To simplify the analysis process, nodes are distributed uniformly-spaced in the model. As widely adopted in the related works on overhead analysis and protocol design [18], [19], a bidirectional link exists if the distance between two nodes is smaller than the communication range, and nodes locating within the communication range choosing the same resource elements will lead to collisions to all nodes in the overlap area. Different from the SINR type analysis, the link status are decided according to the distance and the transmission range, and the transmission range of all nodes are same. Besides, the analytical model in this paper focuses on analyzing the theoretical results of overheads needed to guarantee the non-collision resource allocation. Given the constraints on the length of the paper, the trade-off analysis and protocol design are not included in this paper.

There are M available resource elements (frequency bands, time slots, preambles, etc.) in the system, and resource allocation for each node occurs in the respective domain related to the node distribution. In the existing works of overhead analysis, the model describing the process is simplified where all nodes are in the same collision domain and the number of nodes is constant. As shown in Fig. 2, constant number of nodes are in the same resource contention domain in these models, which means the hidden terminal problem and the resource reuse in respective domains are not considered.

We present a more practical model considering the resource reuse and the dynamicity. A node can reuse the same resource element with nodes out of 2-hop range. As shown in Fig. 3, in the 2-hop range of the tagged node, two nodes connected by an arrow means they can use the same resource element without collisions, because the distance between the nodes is larger than 2-hop range. For instance, node 1 can reuse the same resource element with any node from node $n+2$ to node $2n+1$ and node n can only reuse the same resource element with node $2n+1$. Therefore, a unit in the resource allocation process could be a single node or a pair of nodes reusing the same resource element.

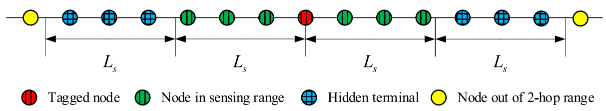

FIGURE 1. The linear topology of resource allocation.

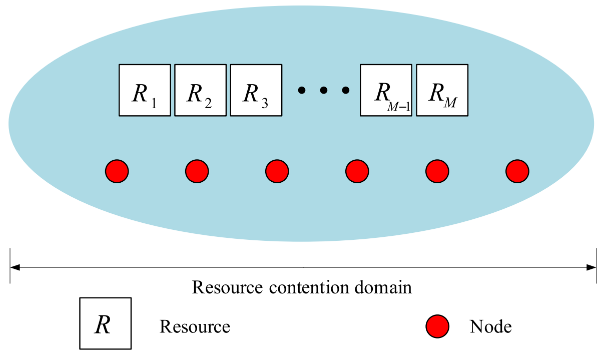

FIGURE 2. Resource allocation in the same resource contention domain.

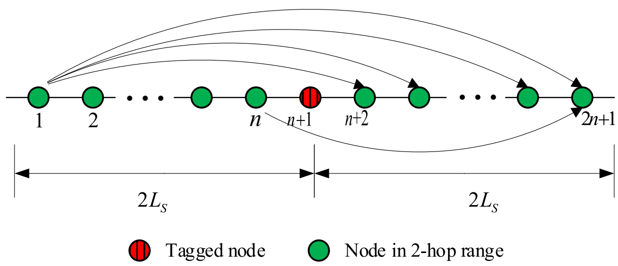

FIGURE 3. Resource reuse situation.

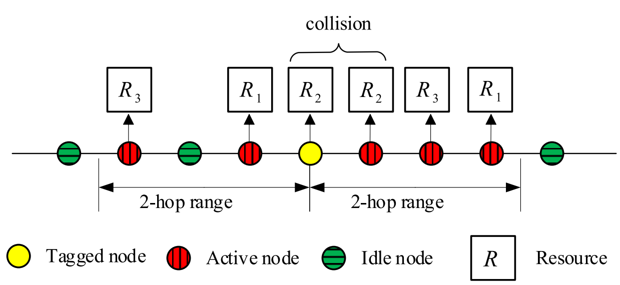

FIGURE 4. Resource collision in resource allocation.

The essential goal of resource allocation in VANET is to utilize resources without collisions. As shown in Fig. 4, two active nodes within the 2-hop range choosing the same resource element will lead to collision. In Fig. 5, the active node doesn't occupy any resource for transmission when it can reuse the resource R_2 with the node out of 2-hop range. In other words, the resource is wasted in this case. Thus, based on such a principle in resource allocation mentioned above, the rules to describe the resource allocation process are as follows:

1) Each active node attempts to acquire one resource element for transmission.
2) There is no previous acknowledgement of resource allocation.

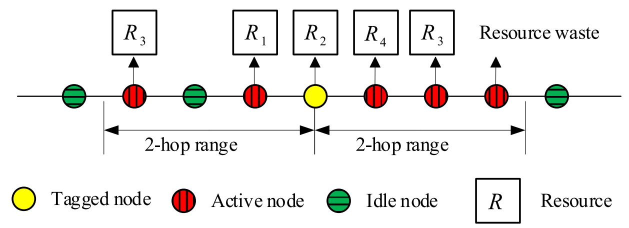

FIGURE 5. Resource waste in resource allocation.

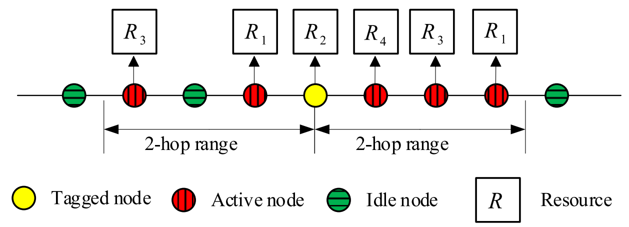

FIGURE 6. Valid resource allocation.

3) The resource reuse within 2-hop range will cause collisions, known as the hidden terminal problem.

Based on the assumptions and rules above, for a tagged node, each resource allocation process among nodes or pairs in the 2-hop range can be described as a permutation. As shown in Fig. 4 to Fig. 6, the mappings between nodes and available resource elements in the 2-hop range of the tagged node can be treated as permutations. Based on the principle in resource allocation process mentioned above, only the resource allocation permutation in Fig. 6 conforms the rules where the resource elements are efficiently utilized without collisions. Therefore, such permutation is considered as a *valid permutation* which represents a certain resource allocation pattern conforming the principle in resource allocation process.

Based on the analysis above, the essential goal of resource allocation algorithms is try to guarantee that the access attempts of all nodes can follow the order of a certain valid permutation through control messages. The theoretical limits of resource allocation overheads caused by control messages in VANET can be derived by calculating the minimum bits to represent a valid permutation. The minimum overhead is intuitively a function of the amount of total valid permutations. All valid permutations as shown in Fig.6 constitute a *valid permutation set* in this paper. Thus we can capture the minimum bits to represent a valid permutation through the Minimum Expected Codeword Length (MCL) based on the cardinality of the valid permutation set.

It should be noted that this paper focuses on the initial resource allocation process without previous acknowledgement, and the subsequent allocation process after the initial resource allocation are not in the scope of this paper. In addition, the mobility of nodes is not considered in this paper because the mobility only impact the existing link and resource allocation patterns. In the initial resource allocation process, there is no existing links and previous resource allocation information. Therefore, the mobility of nodes won't bring extra overhead.

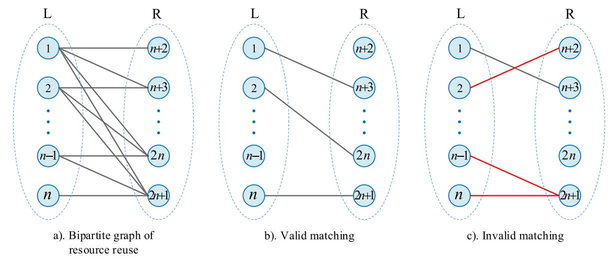

FIGURE 7. Bipartite graph for nodes pairing in resource reuse.

III. MINIMUM EXPECTED CODEWORD LENGTH BASED ON PERMUTATION-BASED MODEL

In this section, we derive the MCLs of resource allocation overheads in VANET based on the permutation-based model in Section II. The MCLs are deduced according to the cardinality of the valid permutation set. TDMA and cluster-based algorithms are considered in this paper, which are two typical resource allocation schemes in VANET. In the TDMA-based algorithms, the resource allocation process is conducted in distributed manners, where nodes choose the resource elements based on the resource allocation information. In the cluster-based structures, there is a center node in a cluster taking in charge of the resource allocation within the cluster.

A. TDMA-BASED ALGORITHM

In the TDMA-based algorithm in VANET, the time is divided into consecutive frames consisting of constant number of slots, and one vehicle can access the channel in one slot for data transmission. Without the central administration in TDMA-based VANET, all the nodes are flattening in the resource allocation process, which means each node must be aware of the neighbors slot allocation information to avoid collision and resource waste. These allocation information will be transmitted along with the data message in each slot, which will introduce extensive overheads. In addition, extra information such as the location is needed to overcome the impact of high vehicle mobility in VANET in the existing algorithms, which will bring more overheads in the resource allocation process.

According to the rules describing the resource allocation processes in Section II, each node should be aware of the global resource allocation in the 2-hop range to avoid collisions. Compared with the simplified model where all nodes are in the same contention domain, we use the bipartite graph to describe the nodes pairing in resource reuse as shown in Fig. 7. The nodes are distributed in the linear topology as shown in Fig. 3. In the 2-hop range of the tagged node, nodes in the left side and right side are divided into two sets $\mathcal{L}$ and $\mathcal{R}$. As shown in Fig. 7(a), each edge represents a valid reuse pair candidate. A matching illustrates a node pairing pattern. The matching shown in Fig. 7(b) is a valid matching while

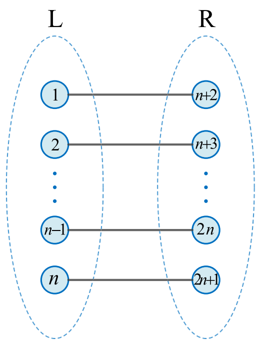

FIGURE 8. Resource reuse pattern when $M \leq n + 1$.

Fig. 7(c) presents an invalid matching where the resource reuse will cause collisions. As demonstrated in Fig. 7(c), node 2 and node n + 2 are located within the 2-hop range, and the resource reuse will lead to the hidden terminal problems.

When existing n active nodes in one side of the tagged node, there will be $2n + 1$ nodes in the 2-hop range of the tagged node including itself. Considering the node pairing in resource reuse, the total number of units (single node or node pair) n_{unit} ranges from $n + 1$ (there are n pairs) to $2n + 1$ (there are all single nodes), and the number of pairs n_{pair} is $2n + 1 - n_{unit}$. Thus, the sum of possible combinations of n_{unit} units with n active nodes in one side is equivalent to the number of matchings with n_{pair} valid edges, which is denoted by $S\left(n, n_{pair}\right)$. Because counting the matchings with specific edges is a NP-hard problem, we use iterate search to derive $S\left(n, n_{pair}\right)$.

When the number of available resource elements $M \leq n + 1$, all nodes are paired based on the rules in Section II, and n_{unit} is equal to $n + 1$. There is only one valid matching with n edges as shown in Fig. 8, which means $S(n, n) = 1$. Thus, the cardinality of the valid permutation set is given as

$$C_T(n) = \frac{(n+1)!}{(n+1-M)!}. \tag{1}$$

When $n + 1 < M \leq 2n + 1$, part of the nodes should be paired to guarantee the efficient use of resource. Therefore, the number of unit n_{unit} should range from $n + 1$ to M. Thus, the cardinality of the valid permutation set is derived as

$$C_T(n) = \sum_{i=n+1}^{M} \frac{M!}{(M-i)!} S(n, 2n+1-i). \tag{2}$$

When $2n + 1 < M$, the number of resource elements is always greater than n_{unit}. Thus, the cardinality of the valid permutation set is given as

$$C_T(n) = \sum_{i=n+1}^{2n+1} \frac{M!}{(M-i)!} S(n, 2n+1-i). \tag{3}$$

In the TDMA-based algorithms, a node should be aware of the resource allocation in its 2-hop range to avoid transmission collisions and receive data messages provided in dedicated resource elements. From (1) to (3), the MCL of resource allocation in VANET when existing n active nodes in one side of the tagged node is derived as

$$I_T(n) = \log\left(C_T(n)\right). \tag{4}$$

In addition, the dyamicity of nodes are considered in the resource allocation process as mentioned in Assumption 3. The number of active nodes is dynamic in each resource allocation process. Only the active nodes will participate in the resource allocation process. Therefore, when existing N nodes in one side ($2L_s\lambda = N$), the average resource allocation overhead in VANET considering the dynamicity is given as

$$I_T = \sum_{i=1}^{N} C_N^i \rho^i (1-\rho)^{N-i} I_T(i). \tag{5}$$

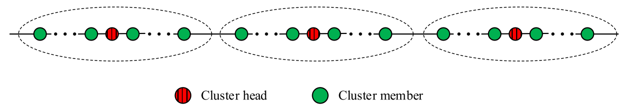

FIGURE 9. Cluster-based model.

B. CLUSTER-BASED ALGORITHM

In the cluster-based resource allocation algorithms in VANET, nodes will form a cluster with surrounding nodes as shown in Fig. 9. One node will be selected as a cluster head in each cluster, which will take charge of the intra-cluster resource allocation and inter-cluster communication. Other nodes in the cluster are regarded as cluster members, scheduled by the cluster head. In the cluster-based algorithms [4], resource elements are divided into different sets, and the nodes in the same cluster will access the same resource elements set.

The overhead of resource allocation in VANET under cluster-based structure is analyzed in this section. As a cluster member, only the local resource allocation information in the same cluster is necessary, since the message for the node from other clusters will be forwarded by the cluster head. Different from the flattening TDMA-based structure, the cluster members only need to be aware of the resource allocation information in the range of a cluster. As for the cluster head, it should be aware of the global resource allocation information in the 2-hop range. However, it is important to note that this paper concentrates on the overheads in resource allocation process, and the cluster formation and corresponding overheads are not within the scope of this paper.

In the cluster-based model, it is assumed that the resource elements are divided into K sets equally, which means the average number of resource elements for each cluster is $\tilde{M} = \left\lceil \frac{M}{K} \right\rceil$. The size of the cluster is $\frac{1}{K}$ of the 2-hop range. Therefore, the number of nodes in one side in the 2-hop range of a cluster head is n, which is $\left\lceil \frac{n}{K} \right\rceil$ for a cluster member, denoted by $\tilde{n}$. For cluster members, only the local resource allocation information of the nodes in the same cluster is required, but for the cluster heads, they should be aware of the global resource allocation in the 2-hop range.

Based on the analysis above, we derive the resource allocation overheads of cluster heads and cluster members respectively as follows, which are similar to the derivation process in the TDMA structure. For the cluster head, when the number of available resource elements $M \le n+1$, all nodes are paired in the 2-hop range, and n_{unit} is equal to $n+1$. There is only one valid matching, which means $S(n,n) = 1$. Thus, the cardinality of the valid permutation set is given as

$$C_{CH}(n) = \frac{(n+1)!}{(n+1-M)!}. \tag{6}$$

When $n+1 < M \le 2n+1$, part of the nodes will reuse the same resource elements to guarantee the efficient use of resource. Therefore, the number of unit n_{unit} should range from $n+1$ to M. Thus, the cardinality of the valid permutation set of the cluster head is described as

$$C_{CH}(n) = \sum_{i=n+1}^{M} \frac{M!}{(M-i)!} S(n, 2n+1-i). \tag{7}$$

When $2n+1 < M$, the number of resource elements is always greater than n_{unit}. Thus, the cardinality of the valid permutation set of the cluster head is derived as

$$C_{CH}(n) = \sum_{i=n+1}^{2n+1} \frac{M!}{(M-i)!} S(n, 2n+1-i). \tag{8}$$

For cluster members, when the number of available resource elements in a cluster $\tilde{M} \le \tilde{n}+1$, n_{unit} in a cluster is equal to $\tilde{n}+1$. There is only one valid matching, which means $S(\tilde{n},\tilde{n}) = 1$. Thus, the cardinality of the local valid permutation set is given as

$$C_{CM}(\tilde{n}) = \frac{(\tilde{n}+1)!}{\left(\tilde{n}+1-\tilde{M}\right)!}. \tag{9}$$

When $\tilde{n}+1 < \tilde{M} \le 2\tilde{n}+1$, part of the cluster members will reuse the same resource elements in the cluster to guarantee the efficient use of resource. Therefore, the number of unit n_{unit} should range from $\tilde{n}+1$ to $\tilde{M}$. Thus, the cardinality of the local valid permutation set of cluster members is derived as

$$C_{CM}(\tilde{n}) = \sum_{i=\tilde{n}+1}^{\tilde{M}} \frac{\tilde{M}!}{\left(\tilde{M}-i\right)!} S(\tilde{n}, 2\tilde{n}+1-i). \tag{10}$$

When $2\tilde{n}+1 < \tilde{M}$, the number of resource elements in a cluster is always greater than n_{unit}. Thus, the cardinality of the local valid permutation set of the cluster member is given as

$$C_{CM}(\tilde{n}) = \sum_{i=\tilde{n}+1}^{2\tilde{n}+1} \frac{\tilde{M}!}{\left(\tilde{M}-i\right)!} S(\tilde{n}, 2\tilde{n}+1-i). \tag{11}$$

From (6) to (11), in the cluster-based resource allocation algorithm, the MCLs of the cluster head and the cluster member in the resource allocation process when existing n active nodes in one side of the tagged node are given as

$$I_{CH}(n) = \log\left(C_{CH}(n)\right). \tag{12}$$

$$I_{CM}(\tilde{n}) = \log\left(C_{CM}(\tilde{n})\right). \tag{13}$$

From (12) and (13), the average overhead of cluster-based resource allocation process is derived as

$$I_C(n) = \frac{K}{n} I_{CH}(2n+1) + \frac{2n+1-K}{2n} I_{CM}(\tilde{n}), \tag{14}$$

where $\tilde{n} = \left\lceil \frac{n}{K} \right\rceil$.

Considering the dyamicity of nodes in the resource allocation process as mentioned in Assumption 3, when existing N nodes in one side ($2L_s\lambda = N$), the average resource allocation overhead in cluster-based algorithm considering the dynamicity is given as

$$I_C = \sum_{i=1}^{N} C_N^i \rho^i (1-\rho)^{N-i} I_C(i). \tag{15}$$

TABLE 1. Value of parameters.

Parameter	Value
Density (λ)	15-115 vehicles/km
Transmission range (L_S)	50 m
Active probability (ρ)	0.2, 0,5, 0.8
Resource element number (M)	10, 15
Resource set (K)	3, 5

IV. NUMERICAL RESULTS

In this section, we present the numerical results of the proposed methodology to demonstrate the theoretical results of resource allocation overheads in two typical scenarios of VANET. The resource allocation overheads of TDMA-based algorithms and cluster-based algorithms are presented respectively using the permutation-based model. The analysis results are compared with the ALOHA-based algorithm [20], [21] and VeMAC [1] to show the gap between the theoretical results in this paper and the existing works. The theoretical results of the overheads derived based on the analytical model the overheads of existing algorithms are compared using MATLAB. The main parameters are illustrated in TABLE 1.

To guarantee the fairness of the comparison, necessary simplifications are made when calculating the overheads of ALOHA-based algorithm and VeMAC. Only the overheads related to the resource allocation are considered in this section. In the VeMAC, the resource allocation related overheads in each packet consist of the ID of neighbor nodes and the time slot used by each node. Therefore, the average overhead for each node in VeMAC is described as $I_{Ve} = N\left[\log(N) + \log(M)\right]$. For the ALOHA-based algorithm, we consider the status (busy or free) and the allocation information of each slot, which are transmitted with data messages. The overhead of the ALOHA-based algorithm is $I_{AL} = M\left[\log(N) + b_{busy}\right]$, where $b_{busy} = 1$ bit.

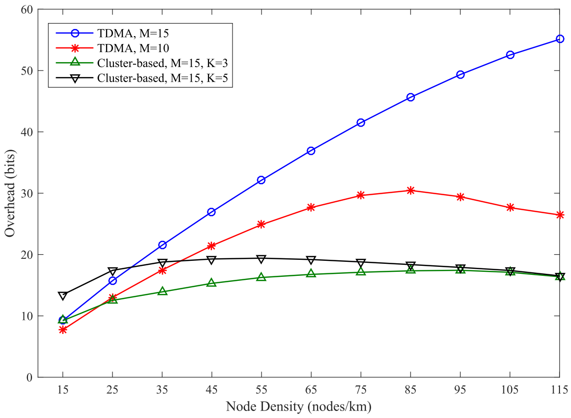

FIGURE 10. Theoretical results of resource allocation overhead in VANET ($\rho = 0.8$, $L_S = 50$ m).

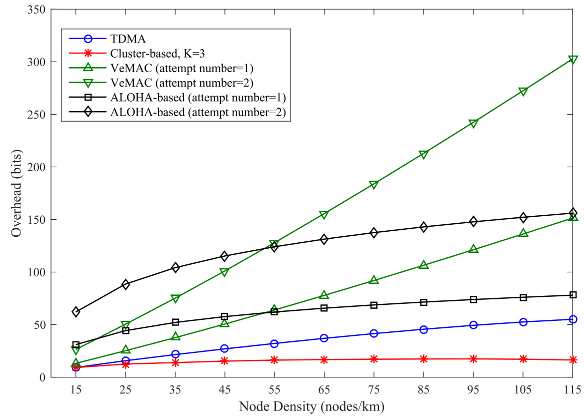

FIGURE 12. Theoretical results of resource allocation overhead compared with existing protocols with different attempt number ($\rho = 0.8$, $L_S = 50$ m).

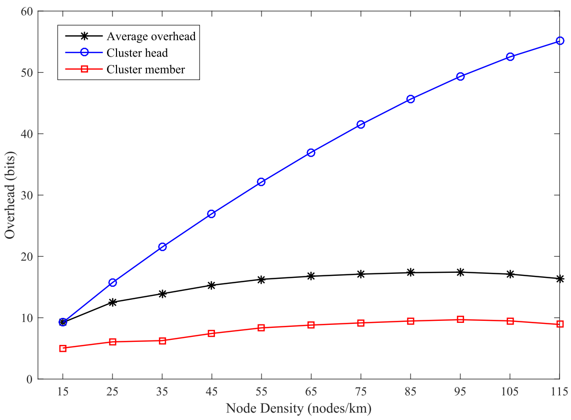

FIGURE 11. Theoretical results of resource allocation overhead of cluster-based algorithms ($\rho = 0.8$, $L_S = 50$ m).

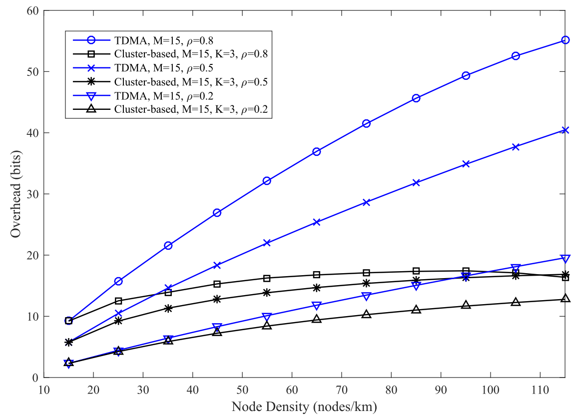

FIGURE 13. Theoretical results of resource allocation overhead with different active probability ρ.

It is important to note that the aforementioned overheads of the existing algorithms refer to the overheads of a single access attempt. In the practical scenario, multiple transmissions are often applied to improve the transmission reliability of control information. The resource allocation process may include multiple access attempts. In other words, a node will attempt multiple times before it can access a resource element successfully, which will introduce much more overhead than single access attempt. Therefore, the overheads of these existing algorithms are presented with different attempt times when compared with the results described based on the permutation model in this paper.

Fig. 10 shows the theoretical results of the resource allocation overheads in VANET based on the permutation model in this paper considering the node distribution (λ from 15 nodes/km to 115 nodes/km) and dynamicity ($\rho = 0.8$, $L_S = 50$ m). As illuminated in Fig. 10, the average overhead increases with the node density at first and then decreases when the minimum units in 2-hop range approaches the available resources. This is because most of the resource elements will be reused which means the majority of nodes are paired, thus decreasing the total possible combinations. In cluster-based scenario, only the local resource allocation information is requisite for cluster members. For this reason, the overhead of cluster-based scenario is dramatically reduced compared with the flattening structure. It can also be observed that dividing the nodes into more clusters will decrease the cluster members in a cluster which sequentially decrease the local resource allocation information. However, it may lead to extra overheads in cluster formulation and message forwarding in the practical system, which is beyond the scope of this paper.

Fig. 11 shows the results of the resource allocation overheads under cluster structures, when the number of resource elements M is 15 and the they are divided in to 3 sets ($K = 3$). It can be observed that the overhead of cluster head is much more than the cluster member's. It is because that the cluster head has to be aware of the global resource allocation information in the 2-hop range, and for cluster members, only the local resource allocation information of the nodes in the range of the cluster is required. When increasing the node density, the average overhead will converge to the cluster members overhead because the percentage of the cluster members will increase.

Fig. 12 shows the comparison between the theoretical results in this paper and the existing resource allocation algorithms, when the number of resource elements M is 15. It can be observed that there is a large gap between the state-of-the-art systems and the results in this paper. This is because the control messages of these algorithms often contain a lot of redundant information to improve the reliability of the resource allocation process. Furthermore, multiple transmissions are often applied to improve the transmission reliability of control information, which will bring more overheads. It should be noted that all possible resource allocation patterns are treated equally in this paper based on the assumption that there is no previous acknowledgement in the resource allocation process. Further research will consider the possible diversified revenue when resource allocation patterns have different possibilities in certain scenarios

Fig. 13 shows the theoretical results of the resource allocation overheads with different ρ under TDMA and cluster-based structures, when the number of resource elements M is 15. It can be observed that the resource allocation overheads will increase with a larger active probability ρ. This is because a larger ρ represents that the nodes are more likely in active state, which means the buffer of the node is non-empty and the node will participate in the resource allocation process. Therefore, more nodes will be involved in the resource allocation process and the overheads will increase in certain range of density.

V. CONCLUSION

In this paper, we build a general model to analyze the resource allocation overheads in VANET. The unordered random access pattern is considered as a permutation, and the theoretical result is derived through MCL by calculating all valid resource allocation permutations. The node distribution, resource reuse and dynamicity are considered, which are seldom involved in the existing works of overheads analysis. The methodology can be extended to capture the overheads of resource allocation in various decentralized networks, and the overheads analysis of the consecutive resource allocation could be conducted based on the model in this paper. Our future work will focus on further theoretical analysis of the tradeoff between system performance and overheads considering the channel condition information in different scenarios.

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