Adaptive Slot Assignment for TDMA Based Dynamic Airborne Ad Hoc Networks

Yueyan Qian[1,2], Mingwu Yao[1(✉)], and Liang Zhang[1,2]

[1] State Key Laboratory on ISN, School of Telecommunications Engineering, Xidian University, Xi'an 710071, China
d689571@126.com, mwyao@xidian.edu.cn, mcliangwlmqzl@163.com

[2] Science and Technology on Communication Networks Key Laboratory, Shijiazhuang, China

Abstract. The time division multiple access (TDMA) is thought a better choice for mobile ad hoc networks, especially for sparse and dynamic airborne wireless networks, and its efficiency largely depends on the slot scheduling method. Fully taking the dynamic characteristics of the 3-dimensional airborne network into account, we proposed an adaptive slot assignment TDMA (ASA-TDMA) scheme. It allows for changeable traffic load of the nodes due to the network topology dynamics in sparse airborne ad hoc networks. Slot allocation is performed not only when nodes request for time slots to access, but also when real-time load level changes. The sharing algorithm realizes concurrent transmissions to achieve high slot utilization. Furthermore, our scheme can flexibly adjust the schedule strategy to deal with network emergencies such as node failures. Simulations are provided to validate the performance our approach, and the results show its advantages over some known methods.

Keywords: Ad hoc · Slot assignment · Time division multiple access (TDMA) 3D airborne networks

1 Introduction

TDMA scheduling scheme is an important issue in medium access control (MAC) protocols for ad hoc networks. Since the conflicts caused by simultaneous transmissions would degrade the network performance, collision-avoidance strategy should be considered. In reservation-based TDMA protocols, like DTRA mechanism [1], node pairs with communication demands would make reservations on channel resource. Usually it takes three stages to complete a transmission: neighbor discovery, reservation and confirmation, and data transmission. SDVCS mechanism [2], a modification of DTRA, uses a frame structure where reservation and data transmission stage are partitioned into several parts which are set alternately. The potential conflicting slots would be declared between a node pair in the reservation stage, thus SDVCS shows better performance in throughput compared with DTRA. In TMRR mechanism [3], active nodes compete for slots, in which nodes would transmit beacon, and nodes with data to transmit would ask for slots reservation in the beacon period (BP) and the

B. Li et al. (Eds.): ChinaCom 2017, LNICST 237, pp. 260–270, 2018.
https://doi.org/10.1007/978-3-319-78139-6_27

data transmission period (DTP) in the way of Carrier Sensing Multiple Access (CSMA) for a multi-hop transmission in order to achieve low delay. If there are no enough slots to assign, the reservation would be performed in the resource reservation period (RP). Reservation-based schemes described above are demand-driven, so some node pairs would suffer starvation because of time slots exhaustion in some cases. Contrastingly, in contention-based mechanisms, no predefined schedule is required, and each node will compete for channel access when it needs to transmit, and naturally is not entitled to any guarantee of success [4]. The resulted packet loss and large access delay may be a serious problem to real-time applications [5]. These schemes are not suitable for networks requiring a certain level of reliability and delay. The benefits of using TDMA protocols include equal access to the channel for all vehicular nodes, efficient channel utilization without collisions, high reliability of communications, deterministic access time even with a high traffic load, and QoS for real-time applications [6]. Some efficient TDMA protocols are specifically designed, such as one for cooperative relaying (CRTDMA) [7], and the P-TDMA [8].

In P-TDMA, a frame is segmented into three epochs: Claim, Response and Info, and each part is further segmented into N slots equal to the number of nodes. Active members send request-to-send (RTS) in the Claim stage without collisions. In the Response stage, the response packets (RSP) are sent out containing the active neighbors ID heard in the previous stage. Learning the active nodes within two hops by the above two stages makes simultaneous collision-free transmissions feasible in the Info stage. However, a large proportion of a frame is used to exchange RTS and RSP, resulting in P-TDMA's low efficiency. Because the stages are structured alternately, inconsecutive epoch for transmission leads to bad performance in delay.

Motivated by reducing delay and improving packet reception rate, we propose an ASA-TDMA scheme for sparse and dynamic airborne wireless networks. In the assumed scenario, nodes are of 100 km in distances more or less in the air, and the maneuvers of the flying vehicles will stochastically form links between nodes via directional antenna, and the link is prone to disconnect frequently. As the nodes are flying in a high speed, the network is seen high dynamics, and the time slot assignment should not be predetermined. Instead, it should change due to the scale of each cluster and the network topology. Thus, an adaptable time slot assignment scheme is needed. Collision-free concurrent transmissions are achieved by performing a time slot sharing algorithm. Additionally, timely node lost detection is included to handle the emergencies, which guarantees the minimal wastes. Simulation shows our scheme provides superior performance than P-TDMA and fixed TDMA in respect of delay and packet reception rate.

The rest of the paper is organized as follows. Section 2 gives an overview and then key procedures of ASA-TDMA. Simulation results and performance comparison of ASA-TDMA scheme with existing works are analyzed in Sect. 3. Section 4 concludes our work.

2 The ASA-TDMA Scheme

The network comprises of a dozen of high speed airborne vehicles, e.g., a flock of Unmanned Aerial Vehicles (UAVs) flying in one formation. Basically, these nodes are bearing to one same destination but have some freedom to choose their own routes or trajectories during working in a 3-dimensional (3D) space. A communication link is possible to be formed during the flying when two nodes are within each other's radio transmission range. Several neighboring nodes will form one cluster, and a cluster head is selected to control the communication and networking in a TDMA mode. To cope with the high dynamics in the whole flying process, during which communication links are prone to be disconnected and re-formed, clusters should be able to divide or merge. Our TDMA scheme is featured in its adaptive time slot assignment as well as suitability to this dynamic topology change.

2.1 Frame Structures

The length of an ASA-TDMA frame is denoted by l_{frame} and a frame is divided into T_{slot} slots. In this paper, we choose the two parameters to be 250 ms and 10 respectively. The first slot of each frame is exclusively occupied by the cluster head for broadcasting slot assignment and cluster management information. Each idle slot is further divided into M_{mini} = 5 mini-slots. Mini-slot in any idle slot is randomly chosen by nodes to send Access Request (AR) to join the network. The last slot of each frame is always reserved for this purpose.

2.2 Overview of ASA-TDMA

The implementation of wireless airborne networks requires QoS guarantee of the MAC protocols. In this new ASA-TDMA scheme, an effective time slots allocation scheme is introduced to mainly improve ETE delay and packet reception rate performance. Table 1 gives the parameters that help describing the protocol.

Table 1. Parameters

Parameters for ASA-TDMA	
N^i	The identifier of mobile node i
CLU^i	The cluster formed on the basis of the head node N^i
RT	The relaying node table carried by AR, records intermediate nodes along the path
sT	Slot assignment table, recording slot assignment information and is broadcast by head
rT	Forwarding node record table, created by source nodes in a cluster and contained in AR, to be appended by the nodes along the path to the cluster head
TR	Contains traffic load amount of each member, maintained by head
sraT	Reassigned slots record, is created by the head, recording reassigned slots according to actual work load of all nodes in the cluster
tx_cnt	Records the amount of transmission of each source node in the current TDMA frame, maintained and refreshed by the head, flushed when reassignment is done

The proposed MAC protocol has five states. In Cluster Access state, node sets a timer and listens for Beacon (Beacons will be firstly forwarded by members in their slots before other types of data are transmitted). It will send an AR if it hears a Beacon before timer expires or simply becomes a head. In the Work state of a head, head is responsible for allocating time slots, handling access requests, and managing the cluster. In the Work state of a common node, packets in the queue are scheduled to be sent in the assigned slots. The Send_AR state indicates the node is sending AR. All nodes can send AR to request accessing to a new cluster if the condition satisfies. As shown in Fig. 1, N^7 of CLU^7 hears several Beacons with higher priority from N^1 directly or via N^{10}, it sends AR to request accessing, then, N^3 and N^8 listen for Beacons and request to access. Clusters merge in this way, which is in one hand more efficient to manage nodes in a centralized way by reducing network overhead, and in the other hand reasonable for adjacent clusters to converge into one. When two clusters are flying close enough it is necessary to combine to avoid transmission interference, to efficiently utilize the time resource and to facilitate information sharing. Wait-response state is a transient stage after Send-AR state, in this state the node is waiting for cluster access grant and slot allocation information.

2.3 Key Procedures of ASA-TDMA

With an overview of ASA-TDMA in mind, the key steps that differentiate our work from other current works are presented in detail in the following.

- Adaptable slot assignment to fit for the changes of the cluster size
- Dynamically-performed load-based slot reassignment strategy
- Efficient slot sharing mechanism for collision-free concurrent transmissions
- Improvement in slot resource utilization by virtue of timely node state detection and slot resource retrieval

2.3.1 Cluster Establishment

A cluster is defined as a node group where the head manages common nodes, gathers sensing data (SD) and delivers them to a ground station. Each node is configured as a backup of the head. The formation of clusters is intrinsically determined by the change of the distances between nodes over time. This complex dynamic network behavior incurs some difficulties and challenges in the protocol design.

Cluster priority is the same as cluster head priority. We assume each node to be pre-assigned an priority.

In Cluster Access state, a node listens for Beacons. This state is essential in determining whether a node joins an existed cluster as a common member or becomes a head of a new cluster. We depict a diagram of this state to explain all the complicated cases, as Fig. 2 shows.

Cluster head would perform initial slot assignment when an AR arrives. *rT* in the AR will be evaluated at first, which is appended along the path by its intermediate nodes. If the number of residual idle slots is enough to assign to the new member and its intermediate hops, then the head assigns the resource directly without retrieving. Or else, the required number of slots recorded in *sraT* would be retrieved (see the traffic based slot reassignment below). Here, we assume that nodes request accessing always have higher priority than nodes that have already been recently assigned slots but with the demand for more transmission chance.

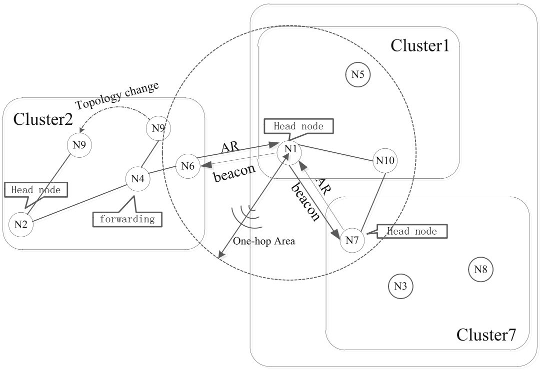


Fig. 1. Scenario1

2.3.2 Traffic Load Based Slot Reassignment

As stated in Sect. 1, the mismatch between resource and demand which leads to waste and starvation in resource needs to be addressed. Since our scheme aims at improving the resource utilization, a traffic load based slot reassignment scheme is proposed to address this issue. As described in Sect. 2.3.1, initial slot assignment is performed in the Cluster Access stage, each of the requesting node as well as intermediate hops is assigned only one slot. However, in consideration of resource utilization, residual idle slots would be reassigned, with which the slot allocation scheme becomes more sound and flexible.

Reassignment begins at the start of each TDMA frame. Cluster head refreshes TR based on piggybacking traffic load information from each member, and reassignment is performed according to TR by the head node. For example, as depicted in Fig. 1, head N^2 manages CLU^2 which accommodates N^4, N^6 and N^9, N^4 serves as intermediate hop in path <N^2-N^4-N^6> and <N^2-N^4-N^9>, if the condition that equal rate of traffic flow from the upper layer of each node is assumed, N^4 bears more traffic due to its role in forwarding. Nodes with heavier traffic load, like N^4, are granted higher priority and hence should be assigned more slots in reassignment process. Once a packet is received by N^2, the value in field "tx_num" of the packet will be extracted. This value is the number of packets that are transmitted by a certain node. However, packets with more recent information may come earlier than ones with obsolete statistics and thus the statistic may be overridden. For instance, in Fig. 1, N^9 sends pkt67, containing the current transmission count value10, to N^2 via N^4 at time t1, so pkt67 waits in a very long queue at N^4 to be forwarded. Since network topology dynamically changes, N^9 may become a one-hop neighbor of head N^2, so it sends pkt71 in the next transmission slot of N^9 directly to N^2. In this case pkt71 contains the current transmission count value14 at time t2 without participation of any forwarding nodes, therefore pkt71 with newer "tx_num" information arrives at N^2 earlier than pkt67. Thereby, it's incorrect to refresh *tx_cnt* only based on the packets' arrival time, because the newly arrived packet may suffer delay but with a small packet identifier. In anyway, "tx_num" information contained in a packet with a smaller packet identifier should be ignored.

In our scheme, each packet is given a sequence number to identify its sending order from the source. In this way, though a packet suffers from heavy delay in wireless network, its sending order is the sole criteria according to which the *tx_cnt* refresh decision is made. In the example above, pkt67 cannot override the statistic recorded by the head, since pkt71 has already submitted a more reliable data.

This method is capable of adaptively modifying slot assignment strategy. The adaptive feature of our scheme is beneficial to improving the network performance.

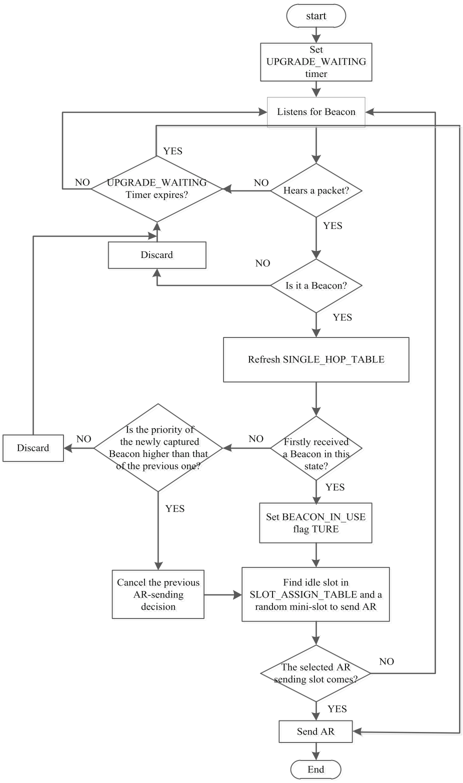


Fig. 2. Cluster access state diagrams

2.3.3 Slot Sharing for Collision-Free Concurrent Transmissions

Conflict-free transmission and adjustable resource scheduling strategy based on the real-time traffic load of nodes is described above. We go a step further to exploit a method that implements concurrent transmissions for the purpose of higher slot utilization efficiency.

As each node keeps a record of its neighbors within two hops, it is allowed to reuse the time slots assigned to any nodes in the same cluster 3-hops away. In this way, the concurrent transmissions are boosted to improve spatial reuse. If all members make the slot sharing decision locally, regardless of other's potential attempts to acquire the

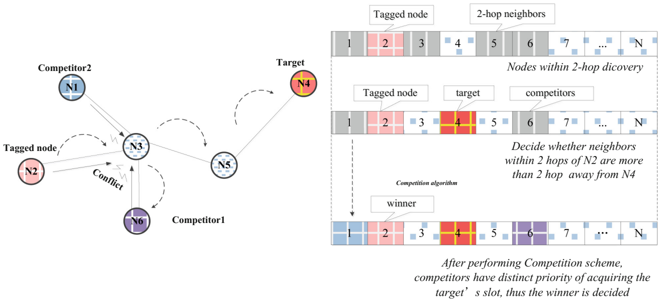


Fig. 3. Competition for shared slot

same slots, however, collisions may occur. For instance, in Fig. 3, N^1, N^2 and N^6 consider sharing slot with N^4 is conflict-free. Actually, if slot sharing among N^1, N^2, N^6 and N^4 are all approved, conflicts caused by simultaneous transmissions may occur.

To avoid such collisions, with the help of the broadcast network topology messages, we introduce a slot sharing competition mechanism. In Fig. 3, the winner in one competition cycle comes from N^1, N^2 and N^6 by performing the competition algorithm. The algorithm is described as follows:

Let Id_x denote the id number of node N^x, target (time slots of which competitors compete for) Id_n, S_m is the set records competitors of N^m.

Obtain:

$$\underset{Id_k}{argmin}|\mathrm{Id}_k - \mathrm{Id}_n| \tag{1}$$

$$\mathrm{Id}_k \in S_m \cup \mathrm{Id}_m,\ \mathrm{Id}_k \neq \mathrm{Id}_n \tag{2}$$

If there exists p, and p satisfies

$$\left|\mathrm{Id}_p - \mathrm{Id}_n\right| = min|\mathrm{Id}_k - \mathrm{Id}_n| \tag{3}$$

$$winner = \mathrm{Id}_p \tag{4}$$

Else if there exist p and q, and satisfy

$$\left|\mathrm{Id}_p - \mathrm{Id}_n\right| = \left|\mathrm{Id}_q - \mathrm{Id}_n\right| = min|\mathrm{Id}_k - \mathrm{Id}_n|; \tag{5}$$

$$winner = min\left\{\mathrm{Id}_p,\ \mathrm{Id}_q\right\} \tag{6}$$

As each node in S_m knows the winner in this competition cycle, the winner is alternately chosen from the residual nodes in S_m in subsequent competition cycles, which guarantees the fairness among competitors.

2.3.4 Node Lost Detection and Slot Resource Retrieval

Node lost has significant influence on network performance. Two-way judgment on "lost" is made by the head or the member node.

A member node is considered lost if it has not been heard by the head for continuous LOST_COUNT TDMA frames. A member in a cluster without hearing Beacons for continuous LOST_COUNT frames consider itself to be lost, and it reenters the Cluster Access state.

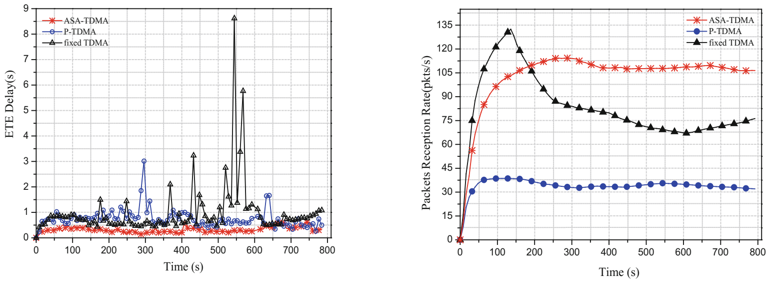
Since the node gets lost, all the slots related to it should be retrieved, including the slots assigned to its intermediate hops in the path from it to the head. Resource retrieval is a key procedure in resource utilization improvement and the detailed algorithm for slot retrieval is described in Algorithm 1. According to the descriptions of the scheme in above sections, a node is assigned slots in several circumstances: (1) when its access request is permitted; (2) it is an intermediate node of another node whose access request is permitted; (3) idle slots reassignment is performed based on the traffic load; (4) it wins the slot sharing competition.

Algorithm 1 Slot Retrieving Algorithm

Procedure Slot_retrieve (N^i) //ID number of the lost node
Begin
<sT traversal>
Retrieve the particular slot assigned to N^i in initial slot assignment;
if intermediate hops exist between N^x and head **then**
Decrease the number of slots possessed by intermediate hops by 1;
end if
if N^i has child N^x **then**
    Child node N^x is sentenced to lost;
    Perform recursion Slot_retrieve(N^x);
end if
Retrieve slots marked "assigned" which are used to forward other nodes' traffic;
Retrieve slots won in shared slot competition;
<rT traversal>
if N^i has been assigned slots in reassignment **then**
    Retrieve these slots;
end if
end

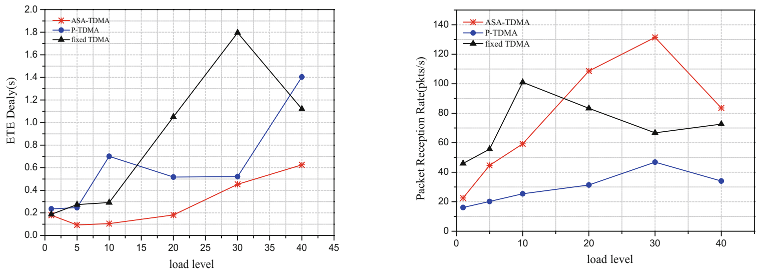
3 Simulation Evaluations

In this section, we provide simulation results of the proposed protocol, which is implemented in OPNet. Mobile nodes are configured moving in air with 3-dimensional trajectory, with their attitudes change over time. The data rate of transceivers is set to be



(a) ETE Delay (b) Packet Reception Rate

Fig. 4. Simulation results A



(a) ETE Delay versus load level (b) Packet Reception Rate versus load level

Fig. 5. Simulation results B

2 Mbps, and antenna pattern is ideal with a 70-degree-wide main lobe. We ran simulations for 800 s and compared the performance of ASA-TDMA with that of P-TDMA and fixed TDMA. Figure 4(a) shows the delay curves over the simulation time. Our scheme outperforms the other two as the figure shows. The feedback traffic load amount information to the head is vital in TDMA scheduling, which implies that nodes with heavy load can request more slots. Both the waste of unavailable slots of lost nodes, and the lack in transmission chances of nodes with heavy load can be the reason of the high delay in fixed TDMA scheme. Under multi-hop circumstances, because the phases of neighbor discovery, response and data transmission are structured alternately, inconsecutive epoch for data transmission leads to bad performance in P-TDMA. Figure 4(b) depicts packet reception rate curves over the simulation time. Overall, the proposed scheme outperforms others. In the early stage, fixed TDMA, benefiting from omitting the process of requesting slots and the grant information delivery, shows good performance. As the network complexity growing with time advancing, the fixed scheme can neither keep up with the dynamic slot demands, nor cope with the lost case flexibly, and the insufficient utilization of time slots resources is consequently inevitable.

ASA-TDMA is capable of handling complex network behavior and it shows superiority in pursuing high slot utilization. Though P-TDMA scheme is provided with collision-free concurrent transmissions, bad performance is unavoidable owing to the high overhead. The scheme achieves collision-free transmissions at the cost of high expense. Little specific resource is needed in our scheme, on the contrary, neighbor discovery and nodes access information exchange is done in an explicit and piggy-backing way by a good packet design.

In most realistic scenarios, networks show bad performance or simply crash under high load level. Thus, a protocol with high-load-adaptability property is urgently needed. We performed further simulations to verify the performance under different load levels and high-load-adaptability of ASA-TDMA scheme. As shown in Fig. 5(a), the delay increase as load level grows, and ASA-TDMA always gives the lowest ETE delay compared with others. Our scheme gives the best even under high load level, as the figure depicts: ASA-TDMA achieves approximately 55.44% decrease compared with P-TDMA, and 44.15% decrease compared with fixed TDMA under the level 40. Figure 5(b) shows packets reception rate versus load level. It is observed that the ASA-TDMA outperforms P-TDMA under all load levels, and gives higher performance under high load level than Fixed TDMA. This demonstrates the superiority of ASA-TDMA in adaptability under high load level circumstance. ASA-TDMA achieves 145.68% increase compared with P-TDMA, and 15.06% increase compared with fixed TDMA under the level 40.

4 Conclusion

In this paper, we propose a new TDMA-based scheme for dynamic airborne ad hoc networks, i.e. ASA-TDMA. It achieves high efficiency by assigning time slots not only when there are demands for accessing, but also periodically at the beginning of each TDMA frame based on real-time traffic load of all members. By virtue of the slot sharing scheme, ASA-TDMA achieves collision-free concurrent transmissions to realize higher slot utilization. Furthermore, ASA-TDMA can flexibly change previous slot schedule to cope with lost or failure of nodes. Simulation results in 3-D scenario show that the ASA-TDMA has lower delay and higher packet reception rate compared with P-TDMA and fixed TDMA, and the high-load-adaptability of our proposed scheme is also verified. The deeper insights of the self-adaptive protocol, and its improvements to suitable for more dynamic characteristics, e.g., fast flying nodes with beamforming antenna, are left to our future works.

Acknowledgements. This work is supported by the National Natural Science Foundation of China under Grant 61671353, and partly by the 111 Project (B08038) of MOE, China, and the Foundation of Science and Technology on Communication Networks Laboratory.

References

1. Zhang, Z.: DTRA: directional transmission and reception algorithms in WLANs with directional antennas for QoS support. IEEE Netw. **19**(3), 27–32 (2005)

2. Tu, Y., Zhang, Y., Zhang, H.: A novel MAC protocol for wireless ad hoc networks with directional antennas. In: 2013 15th IEEE International Conference on Communication Technology, pp. 494–499. IEEE Press, Guilin (2013)
3. Cha, J.R., et al.: TDMA-based multi-hop resource reservation protocol for real-time applications in tactical mobile ad hoc network. In: 2010 Military Communications Conference, MILCOM 2010, pp. 1936–1941. IEEE Press (2010)
4. Felemban, E., Lee, C.-G., Ekici, E.: MMSPEED: multipath Multi-SPEED protocol for QoS guarantee of reliability and timeliness in wireless sensor networks. IEEE Trans. Mob. Comput. **5**(6), 738–754 (2006)
5. Ye, F., Yim, R., Zhang, J., Roy, S.: Congestion control to achieve optimal broadcast efficiency in VANETs. In: 2010 IEEE International Conference on Communications, pp. 1–5. IEEE Press, South Africa (2010)
6. Hadded, M., et al.: TDMA-based MAC protocols for vehicular ad hoc networks: a survey, qualitative analysis, and open research issues. IEEE Commun. Surv. Tutorials **17**(4), 2461–2492 (2015)
7. Lee, J.K., Noh, H.J., Lim, J.: TDMA-based cooperative MAC protocol for multi-hop relaying networks. IEEE Commun. Lett. **18**(3), 435–438 (2014)
8. Gexin, P., Shengli, X., Caiyun, C.: A collision-avoid dynamic slots assignment algorithm based on fixed TDMA. China Inf. Secur. **11**, 115–120 (2005)