Applying a Flocking-Inspired Algorithm to Fair Resource Allocation of Vehicle-Mounted Mobile Relays

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Abstract. Previous studies for applying bio-inspired algorithms to resolve the traditional issues in wireless networks were motivated by some excellent characteristics of the bio-inspired algorithms including convergence, scalability, adaptability, and stability. In this paper, we apply the bio-inspired flocking algorithm to fair resource allocation in vehicle-mounted mobile relay (VMR) deployed networks. Although a VMR-deployed network has an advantage of the provision of high-quality communication services to mobile devices inside the vehicle, it is more susceptible to inter-VMR and base station (BS)-VMR interferences because both the mobility and geographical position of the VMRs and pedestrian mobile stations (MSs) cannot be artificially controlled. Therefore, the proposed flocking-inspired algorithm is designed to achieve the adaptive alleviation of the inter-VMR and BS-VMR interferences, and the attainment of a fair and distributed resource allocation among competing VMRs. We verify its self-adaptiveness under the dynamically changing network topology. The results show that the proposed flocking-inspired resource allocation method adaptively alleviates the inter-VMR and BS-VMR interferences.

Keywords: Flocking · Resource allocation · Vehicle-mounted mobile relay

1 Introduction

Over recent years, the widespread use of mobile devices equipped with wireless technologies such as LTE, WiMAX, and WLAN has enabled a nearly ubiquitous access to communication networks. The existing cellular networks, however, suffer from problems such as propagation loss, and the coverage and capacity at the cell borders remain relatively small because of a low Signal-to-Interference-plus-Noise-Ratio (SINR) [1]. To resolve this problem, relay stations (RSs) that can be deployed in existing cellular networks have been introduced to next-generation

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mobile networks [2]. The RSs are classified into the following three types: fixed, nomadic, and mobile. Fixed RSs are permanently installed at fixed locations; nomadic RSs are temporarily installed to extend the wireless service coverage and for the provision of improved performances when many users simultaneously use a wireless service; and mobile RSs are fully mobile and can therefore be installed in moving vehicles [3–5]. The advantage of vehicle-mounted mobile relays (VMRs) is a capability that can provide high-quality communication services to mobile users inside a vehicle with the help of smart antenna and multi-antenna technologies; while it is almost impossible to apply these antenna technologies to mobile devices because of a limited space and the low transmission power of mobile devices.

Up until now, research on the VMRs has been widely conducted. The authors of [6] evaluated the performance of VMRs in consideration of the density of the mobile RSs and the ratio of the access zones to the relay zones. In [7], a new scheduling method was suggested for the mitigation of the interference that occurs when a VMR is moving into a cell wherein a fixed relay is installed. To resolve the frequent handover problem that is due to the high speed of mobile relays, an enhanced handover scheme that uses an accelerated measurement procedure and a group in-network handover procedure is suggested in [8]. The authors of [9] proposed an optimal VMR handover method that adjusts the handover interval according to a vehicle's speed. In [10], a quantitative study has been performed to investigate the benefits of mobile relays in cellular networks with respect to the extension of base station coverage and the enhancement of wireless connection throughput.

As observed in previous studies, one of the important characteristics of VMRs is that they are deployed in scenarios wherein frequent and rapid network topology changes caused by a vehicle's mobility occur; this characteristic feature causes a dynamically changing and uncontrollable interference among the VMRs. When the density of VMRs increases (for example, the gathering of VMRs in a specific area due to traffic congestion or a traffic signal), the inter-VMR interference decreases the throughput of the mobile devices in a vehicle. Moreover, VMR interference to pedestrian MSs that are directly connected to the BS and located in nearby VMRs causes BS-VMR interference, and thereby deteriorating the cell throughput performance. An efficient resource allocation method that operates self-adaptively is therefore required to mitigate the effects of dynamically changing inter-VMR and BS-VMR interferences.

On the other hand, many researchers have studied the mathematical modeling of natural phenomena, which is called as "biologically inspired" (bio-inspired) algorithms. Bio-inspired algorithms are modeled on the behavior of organisms on Earth, which have evolved with the goal of achieving given purposes whereby the optimal results are ultimately obtained through the iterative and distributed executions of simple, heuristic operational rules without the aid of a central coordinator. As we can observe from previous successful attempts to utilize the bio-inspired algorithms [11–15], they have excellent characteristics including convergence, scalability, adaptability, and stability. In particular, the flocking model analyzes the velocity and position control mechanisms of a group of living organisms in an ecosystem such as large numbers of birds or fish [16,17]. The flocking model has been evaluated as useful for distributed networking systems because it can obtain global emergent behavior while each autonomous entity obeys only simple rules, and the information about local neighbors is used without the aid of a centralized coordinator. It is therefore expected that flocking-based resource allocation method is a suitable solution that may cope with the severe environment of a vehicular network where network topology changes dynamically and available bandwidth varies accordingly.

2 Flocking Model

The flocking model shows the phenomenon whereby each autonomous entity with its own moving direction and velocity flocks and moves in the same direction, as shown in Fig. 1. Each entity adjusts its velocity by interacting with its neighbor entities. Suppose that there are N entities. Let the position and velocity of the i-th entity in $\mathbb{R}^3$ at the discrete time $t \in \mathbb{N}$ be $x_i(t)$ and $v_i(t)$, respectively. The interaction between the neighbor entities is given by the following:

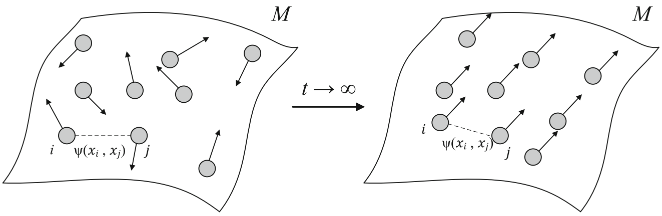


Fig. 1. Flocking behavior

$$\frac{dx_i}{dt}(t) = v_i(t), \tag{1}$$

$$v_i(t+1) - v_i(t) = \frac{\lambda}{N}\sum_{j=1}^{N} \psi(|x_j(t) - x_i(t)|)(v_j(t) - v_i(t)) \tag{2}$$

for $1 \leq i \leq N$ and $t > 0$, where λ and $\psi(\cdot)$ are the non-negative learning factor and a communication range function that quantifies the way the agents influence each other, respectively [17]. Generally, $\psi(\cdot)$ is a non-negative function of the distance between two agents. Some examples for $\psi(\cdot)$ are as follows:

$$\psi_1(|x_j - x_i|) = 1, \tag{3}$$

$$\psi_2(|x_j - x_i|) = 1_{|x_j - x_i| \leq r}, \tag{4}$$

$$\psi_3(|x_j - x_i|) = \frac{1}{(1 + |x_j - x_i|^2)^{\beta}} \tag{5}$$

for positive r and non-negative β. (2) explains the interaction among the entities, as follow: each entity adjusts its velocity according to the weighted average of the differences between its own past velocity and the velocities of the other entities in the flock. By obeying this simple rule iteratively and independently, the collective behavior of each agent, namely flocking, is obtained. In this model, time-asymptotic flocking phenomena are explained by the following two conditions:

$$\lim_{t\to\infty} |v_i(t) - v_j(t)| = 0 \text{ for } i \neq j, \tag{6}$$

$$\sup_{0\leq t<\infty} |x_i(t) - x_j(t)| < \infty \text{ for } i \neq j, \tag{7}$$

which mean that the relative velocity of each agent converges to zero and the distance between each particle does not diverge.

3 Proposed Fair Resource Allocation Method

This subsection details a method that fairly allocates resources across adjacent VMRs in the context of the IEEE 802.16j relay network. An IEEE 802.16j-based relay transmits data to its associated users in a down link (DL) access zone (see Fig. 2). Because all of the relays use the same DL access zone, the inter-VMR interference experienced by the MSs increases as the density of VMRs increases, which deteriorates the throughput performance of the VMRs. Moreover, the resources for the pedestrian MSs are allocated in the DL access zone, causing BS-VMR interference between the inner-vehicle MSs and the pedestrian MSs and the cell throughput performance is lowered. We have therefore designed the flocking-inspired fair resource allocation method, so that the DL resource allocated to each of the VMRs is mutually exclusive and fair among nearby and competing VMRs, and the operation is conducted self-adaptively for a dynamically changing network topology.

Suppose that there is an available resource with a normalized amount of 1. We grant an *address* to each VMR that is arbitrarily chosen from the range of 0 to 1, which will act as a reference for the resource allocation. Let the address of VMR_i at time t be $\alpha_i(t)$ ($0 \leq \alpha_i(t) < 1$). We then apply (2) of the flocking model to the VMR address with the identity function of ψ, which is expressed as the following:

$$\alpha_i(t+1) - \alpha_i(t) = \frac{\lambda}{N}\sum_{j\neq i}(\alpha_j(t) - \alpha_i(t)). \tag{8}$$

Here, we define the *resource address* of a VMR as $\widetilde{\alpha}_i := \left(\alpha_i + \frac{i-1}{N}\right)$ *mod* 1. Without loss of generality, we reassign MSs in ascending order according to the resource address of each MS, resulting in $0 \leq \widetilde{\alpha}_1(t) < \widetilde{\alpha}_2(t) < \cdots < \widetilde{\alpha}_N(t) \leq$

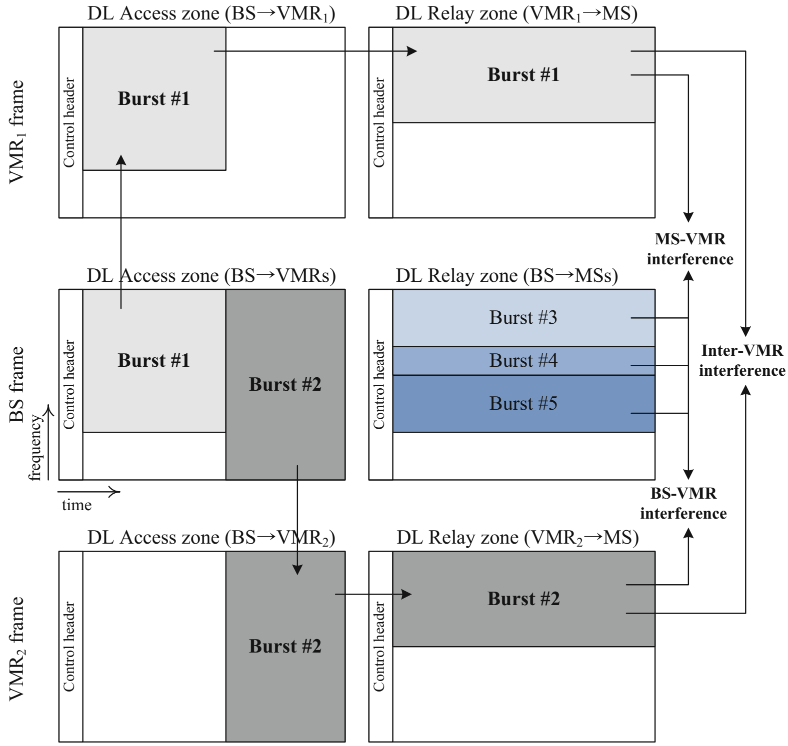


Fig. 2. Relay frame structure in IEEE 802.16j

1. The dedicated resource allocation to VMR_i at time t is determined by the following:

$$\Delta_i(t) = [\frac{\widetilde{\alpha}_{i\ominus 1}(t) + \widetilde{\alpha}_i(t)}{2}, \frac{\widetilde{\alpha}_i(t) + \widetilde{\alpha}_{i\oplus 1}(t)}{2}] \tag{9}$$

where $\oplus$ and $\ominus$ represent the addition and deletion operations modulo N, respectively (Fig. 3).

4 Performance Evaluation

First, we verify the self-adaptiveness of the proposed resource allocation method under various network topologies[1]. In the line topology shown in Fig. 4(a), node A is connected only to node B; therefore, node A changes its resource address considering only node B. Similarly, the resource address of node C is changed considering only node B. Consequently, the final resource addresses of both node A and node C are placed at the same value. Figure 4(b) shows that every node

[1] Hereafter, we assume that the total amount of available resources is 1024.

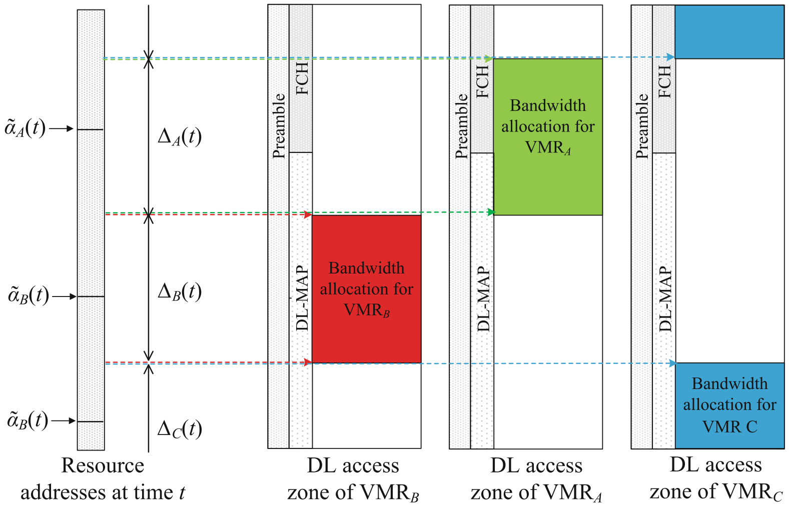
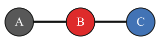
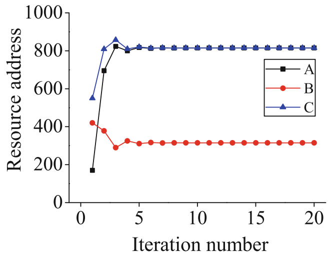


Fig. 3. Example of resource allocation among VMR$_A$, VMR$_B$ and VMR$_C$

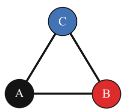


(a) Line topology

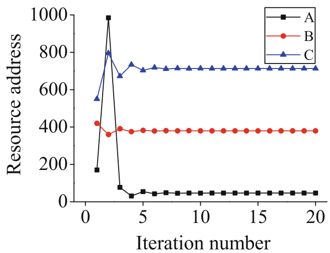


(b) Variation of FI signal

Fig. 4. Line topology and the variation of address of FI signal



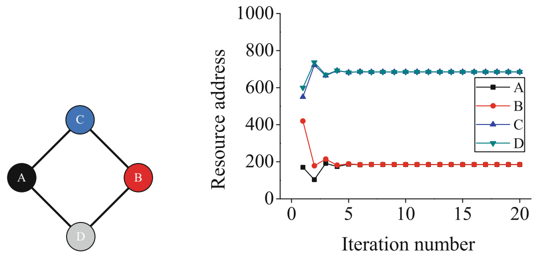
(a) Triangular topology



(b) Variation of FI signal

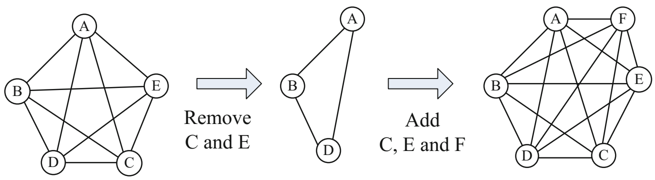
Fig. 5. Triangular topology and the variation of address of FI signal

is assigned 50% of the total bandwidth. For the triangular topology in Fig. 5(a), all nodes are connected to each other; therefore, the entire bandwidth is evenly allocated to each node, namely, 33.3% of the total bandwidth. For the square topology shown in Fig. 6(a), each node is connected to two adjacent nodes. In this case, each node has the same network topology as that of node B used in the line

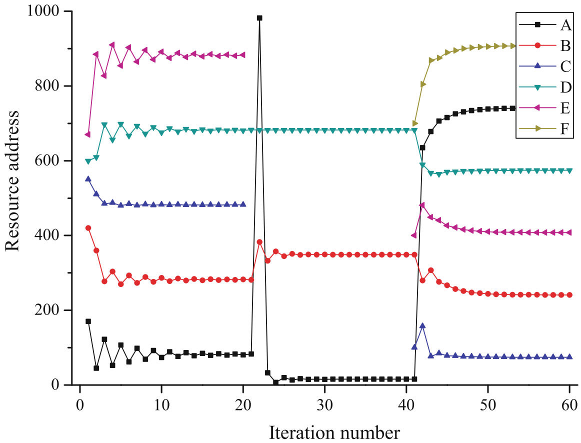


(a) Square topology (b) Variation of FI signal

Fig. 6. Square topology and the variation of address of FI signal



(a) Network topology change



(b) Variation of resource addresses

Fig. 7. Variation of resource addresses of VMRs according to addition and deletion of nodes

topology. Therefore, the amount of bandwidth allocated to each node becomes 50%, which is the same as that allocated to node B in the line topology. In Fig. 7, five nodes are connected to each other, forming a full-mesh star topology. Node C and node E are initially removed, followed by the addition of node C, node E, and node F. As shown in Fig. 7, as soon as the number of participant nodes in the network changes, the resource addresses of the VMRs become unevenly spaced, resulting in a bandwidth allocation that is no longer fair. This imbalance causes the neighboring nodes to adjust their resource addresses, and this eventually returns the system to a stable and fair state. We can verify that the proposed method exhibits self-adaptiveness and ensures fair bandwidth sharing under a dynamically changing network topology.

5 Conclusions

In this paper, we proposed a flocking-inspired resource allocation method that allocates bandwidth to VMRs in a mutually exclusive and fair manner. Each VMR determines the amount and address of the bandwidth resource iteratively and distributively without the aid of a centralized coordinator. The convergence property of the proposed method was analyzed. We verified the self-adaptiveness of the proposed method and evaluated the throughput performance in the cellular environment in consideration of two-way four-lane and three-way intersection road scenarios in the context of the IEEE 802.16j network. The results showed that the proposed method improves upon the conventional method by enabling the VMRs to share the bandwidth resource among the neighboring VMRs in a fair and mutually exclusively way, thereby alleviating the inter-VMR interference and enhancing the throughput performance.

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