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A flocking-inspired algorithm for fair resource allocation in vehicle-mounted mobile relays

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A R T I C L E I N F O

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A B S T R A C T

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 analyze the convergence of the proposed flocking-inspired algorithm and verify its self-adaptiveness under the dynamically changing network topology. Further, we construct a cellular simulation environment in consideration of two-way four-lane and three-way intersection road scenarios and then evaluate the throughput performance of the proposed method in the context of the IEEE 802.16j relay network. The results show that the proposed flocking-inspired resource allocation method adaptively alleviates the inter-VMR and BS-VMR interferences, and enhances the throughput performance beyond that of a conventional method.

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) (Hamza et al., 2013). To resolve this problem, relay stations (RSs) that can be deployed in existing cellular networks have been introduced to next-generation mobile networks (Yang et al., 2009). 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 (Chandra et al., 2011; Park and Bahk, 2009; Nagarajan, 2013). 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 Heo et al. (2011) 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 Kim and Kim (2009), 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. In Yaacoub et al. (2014), two-hop relay-based LTE radio resource management in high speed train systems was investigated to avoid the radio signal propagation losses and maintain a stable high speed wireless link between the relay and the mobiles stations (MS) inside the train car. A path-prediction handover algorithm was proposed in Ann and Kim (2009), which resolves the frequent-hand-over problem due to the high speed of mobile users in a relay-deployed network by using data information between the VMR and the BS. In Saleh et al. (2010), 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.

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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 (Camara, 2015; Chien et al., 2015; Zheng and Sicker, 2013; Konak et al., 2013; Antoniou et al., 2013), 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 (Reynolds, 1987; Cucker and Smale, 2007). 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.

In this paper, we apply the flocking model to the resource allocation of VMRs, to obtain a mutually exclusive and fair resource allocation among them VMRs and to enhance the throughput performance in the context of the IEEE 802.16j relay network. The rest of this paper is organized as follows; Section 2 explains the flocking algorithm that is based on the Cucker-Smale model. In Section 3, we explain the operational procedure of the proposed fair resource allocation method and analyze its convergence. Section 4 shows the convergence of the proposed method and provides the simulation results for given road scenarios. And last, the conclusion is summarized in Section 5.

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:

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

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

for $1 \le i \le N$ 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 (Cucker and Smale, 2007). Generally, $\psi(\cdot)$ is a non-negative function of the distance between two agents. Some examples for $\psi(\cdot)$ are as follows:

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

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

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

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:

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

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

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 and convergence analysis

3.1. 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

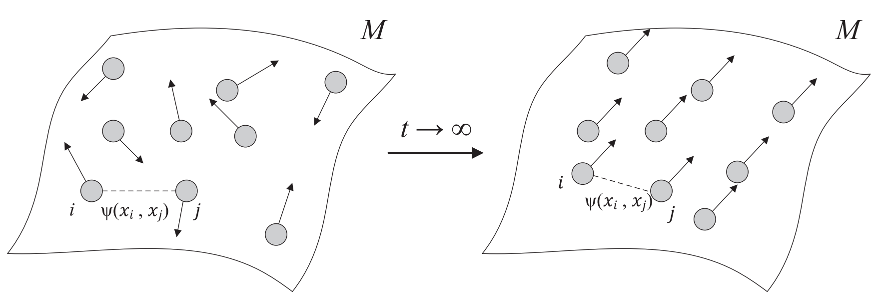

Fig. 1. Flocking behavior.