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Clustering and sensing with decentralized detection in vehicular ad hoc networks☆

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ABSTRACT

In the near future, vehicles will be more and more advanced sensing platforms: for instance, at least one smartphone (with several on-board sensors) is likely to be inside each vehicle. Smartphone-based inter-vehicle communications thus support the creation of vehicular sensor networks (VSNs). In this paper, we analyze the performance of clustered VSNs, where (hierarchical) decentralized detection schemes are used to estimate the status of an observed spatially constant phenomenon of interest. Clustering makes processing efficient and the architecture scalable. Our approach consists of the creation, during a *downlink* phase, of a clustered VSN topology through fast broadcast of control messages, started from a remote sink (e.g., in the cloud), through a novel clustering protocol, denoted as cluster-head election irresponsible forwarding (CEIF). This clustered VSN topology is then exploited, during an *uplink* phase, to collect sensed data from the vehicles and perform distributed detection. The performance of the proposed scheme is investigated considering mostly IEEE 802.11b (smartphone-based) as well as IEEE 802.11p (inter-vehicle) communications in both highway-like and urban-like scenarios. Our results highlight the existing trade-off between decision delay and energy efficiency. The proposed VSN-based distributed detection schemes have to cope with the "ephemeral" nature of clusters. Therefore, proper cluster maintenance strategies are needed to prolong the cluster lifetime and, as a consequence, the maximum amount of data which can be collected before clusters break. This leads to the concept of decentralized detection "on the move."

1. Introduction

In the last decade, commercial vehicles have witnessed an exponential growth of their sensing, computational, and communication capabilities. This huge improvement is enabling the implementation of a large number of innovative services and applications, including: safety, traffic management, smart navigation, environmental monitoring, etc. By exploiting their sensing and communication capabilities, the vehicles can cooperate to create so-called vehicular sensor networks (VSNs) [1]. VSNs have peculiar characteristics at various levels, from communication, networking, and data processing perspectives.

From a communication perspective, the vehicles continuously gather, process, and share location-relevant sensor data (e.g., road conditions, pollution, etc.). Information collection and dissemination can be performed using inter-vehicular

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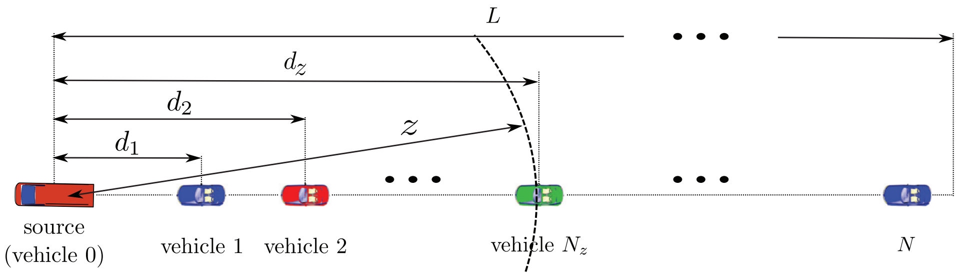

Fig. 1. Pictorial description of a linear VSN.

communications [2] and/or relying on the presence of roadside infrastructure [3]. Moreover, each vehicle is likely to contain at least a smartphone, which is itself a powerful sensing platform. In this context, cluster-based networking is an attractive solution to reduce network congestion and to simplify routing and data aggregation/dissemination [4].

An interesting approach to cluster-based vehicular communications can be found in [5], where communications are typically broadcast but, when possible, short-lived clusters are created in order to constitute a backbone, that can be used to support unicast communications. One of the strongest motivations for the design of cluster-based vehicular networks is provided by [6], where the authors show that, according to realistic mobility models, vehicular ad-hoc networks (VANETs) naturally evolve to clustered configurations. The advantages of clustering have also been exploited in the realm of decentralized detection [7], e.g., to determine optimum clustering and medium access control configurations. In particular, in [8] the authors provide a general framework for the computation of the probability of decision error when a spatially constant binary phenomenon is detected through a (possibly) multi-level sensor network.

The goal of this work is to present a decentralized detection scheme for data acquisition in clustered VSNs, which fits well with the requirements of on-demand detection applications. In particular, the proposed scheme might be used to determine, in a timely manner, if in a given city area (e.g., several blocks) there has been a critical situation (e.g., road congestion). A possible application of interest is the dissemination of this information to prevent other vehicles from running into this congested area (e.g., adaptive cruise control for congestion avoidance [9,10]). The proposed sensing and detection scheme foresees a two-phase communication mechanism. First of all, a *downlink phase* is triggered by a remote sink, with data collection duties, in order to form a clustered topology, constituted by ephemeral clusters (i.e., with limited lifetime) with associated cluster heads (CHs). The downlink phase is carried out through an innovative protocol, denoted as cluster-head election irresponsible forwarding (CEIF), which significantly improves the multihop probabilistic broadcast protocol, denoted as CIF, originally proposed in [11]. The so-formed clustered VSN is then used, during the (second) *uplink phase*, for data aggregation and/or local per-cluster fusion carried out at the CHs. The proposed scheme has been preliminarily presented in [12], where the basics of (i) the clustering protocol and (ii) the decentralized detection mechanism have been outlined together with preliminary results. While in [12] only static (steady-state) network conditions are considered, in this paper the performance of CEIF is analyzed by considering realistic dynamic ("on the move") conditions, in both highway-like and urban-like mobility scenarios. In particular, the performance of the proposed VSN clustered decentralized detection scheme is investigated considering mostly IEEE 802.11b communications between smartphones, as well as IEEE 802.11p between vehicles. Moreover, we also propose a novel reclustering procedure to be activated after ephemerals clusters break.

The rest of this paper is structured as follows. In Sections 2 and 3, preliminaries on the system and communication models, respectively, are provided. In Section 4, the decentralized detection mechanism is described. In Section 5, the performance of the proposed scheme is analyzed in a static scenario, i.e., under average steady-state conditions. In Section 6, we analyze the impact of mobility on the system performance in highway-like scenarios, from both clustering and sensing points of view. In Section 7, the system performance is investigated in a realistic urban-like scenario. Finally, concluding remarks are given in Section 8.

2. System model

Fig. 1 shows the linear network topology of reference for a VSN: N nodes are placed in a one-dimensional scenario. This is representative of a highway-like scenario—in Section 7, an urban-like scenario will be considered. Each node is uniquely identified by an index $i \in \{1, 2, \dots, N\}$. The source node, denoted as node 0, is placed at the left end of the network. In order to derive the proposed clustering protocol (i.e., CEIF), we first consider steady-state conditions, i.e., a static network where nodes are positioned according to a one-dimensional Poisson point process with parameter ρ_s, where ρ_s is the linear vehicle spatial density (dimension: [veh/m])—the validity of this assumption is confirmed by empirical traffic data [13]. In Section 6, we will relax this assumption by analyzing more realistic VSNs with mobile nodes.

Each vehicle has a fixed transmission range, denoted as z (dimension: [m]), which depends on the transmit power and on the propagation model. In particular, the latter is assumed to be deterministic and the following models will be considered: Friis and Two Ray Ground [14]. Each vehicle is equipped with a global positioning system (GPS) receiver—namely, each on-board smartphone. As a consequence, each vehicle knows its own position at any given time—this is realistic in most vehicular conditions (but galleries). The maximum network length of the linear VSN is denoted as L (dimension: [m]), so that the number N of vehicles in $[0, L]$ can