ARTICLE IN PRESS

Nano Communication Networks ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at ScienceDirect

Nano Communication Networks

journal homepage: www.elsevier.com/locate/nanocomnet

Nature inspired node density estimation for molecular nanonetworks

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ARTICLE INFO

Article history:
Received 3 December 2016
Available online xxxx

Keywords:
Density estimation
Molecular communication
Nanonetworks

ABSTRACT

The problem of estimating the node density in ad hoc networks is a significant one for protocol design. In molecular nanonetworks, the node density estimation problem poses additional challenges due to the limited processing and communication capabilities of the network nodes which necessitate the design of simple to implement distributed solutions, and the diffusion based communication channel which is different from traditional electromagnetic networks. In this work, inspired by the quorum sensing process, we propose and analyze a new node density estimation scheme based on synchronous transmission of all network nodes and measurement of the received molecular concentration. We show that when the synchronous transmission is performed in infinite space, a linear parametric model of the node density can be derived which can be used for estimation purposes. When, however, the transmission is performed over a finite space the model becomes time varying. To overcome the difficulties associated with the time varying nature we propose the use of periodic transmission which for large enough values of the period transforms the linear model into a static one. An online parameter identification technique is then introduced to estimate the node density using the derived linear static parametric models. The utilization of the node density estimates to adaptively regulate probabilistic flooding in network structures relevant to nanonetworks is then considered. The random geometric graph model and uniform grid structures are used to demonstrate how the node estimates can be used to dictate the desired rebroadcast probabilities, through analysis and simulations.

1. Introduction

The node density is an important network parameter which greatly affects network properties such as congestion [1], network capacity [2], routing efficiency and delay [3] and power consumption [4]. It is thus an important problem to design node density estimation schemes.

Density analysis is more challenging in infrastructure-less networks like MANETs, VANETs and molecular Nanonetworks [5] as the nodes are mobile in nature and the node density is thus a time varying parameter. A number of estimation schemes have been proposed in literature for MANETs, based on beacon message exchange, and the Received Signal Strength, and for VANETs based on the flow rate and speed information [6,5]. In [4] for example, the authors discuss a power control method for MANET clustering based on the network density, where nodes exchange packets to estimate the number of neighbors in a cluster and the distance to the farthest neighbor. According to the acquired information each node adjusts its transmission power to the minimum sufficient level. Another technique which was proposed for general wireless ad hoc networks and is based on the received power is [7]. The authors discuss a cooperative technique where each node shares its received power information with its own neighbors and hence a better estimation of the density is achieved. In [8] a density estimation scheme based on neighbor information is proposed for VANETs. The probe vehicle is assumed to find the number of its neighbors via exchanging "HELLO" packets, the distance between vehicles is assumed to have an exponential pattern and based on this assumption the equations to calculate the local density in the cases of One-Hop-Neighbor, Two-Hop-Neighbor and Cluster information are derived. In [6], the authors propose a node density estimation scheme for VANETs, by using distributed methods for system size estimation in P2P networks, a method which does not require high deployment and maintenance costs compared to infrastructure based solutions. This method relies on exchanging small messages between nodes which have position information to estimate the size, a result which is then divided by the area of the road to find the number of nodes per unit area. The work in [5] on

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http://dx.doi.org/10.1016/j.nancom.2017.02.003
1878-7789/

the other hand proposes a solution to predict node density without the overhead and congestion which could be caused by exchanging beacon messages. The authors run simulations to provide nodes with two equations, one to relate the received signal strength to the number of nodes transmitting simultaneously and the second is to relate node density to the number of nodes transmitting simultaneously. The results of the simulation-based technique suggest that it is robust to different traffic flow conditions. In [9] the speed of the vehicle is used as an indication of the network density in order to develop an adaptive probabilistic broadcasting scheme. Low vehicle density implies high vehicle speed while high density is indicated by low vehicle speed. In the case of broadcasting, high densities cause the broadcast storm problem [10] which can be mitigated by broadcast suppression. There are several ways to do the latter. In [11] they have been categorized into probabilistic methods, area based methods and neighbor knowledge methods. Probabilistic broadcasting has been addressed extensively in the literature [12,9,13–15], in order to find a technique with which the optimum rebroadcast probability can be calculated. It has been pointed out in [9] that the critical probability after which high reachability is achieved is significantly affected by the density of the network. Thus, node density estimation is important when employing probabilistic broadcasting.

Molecular nanonetworks is a recent network paradigm which comprises of a large number of highly mobile nodes in the scale of micrometers, known as nanonodes. Molecular Communication (MC) is a means of communication where information is carried in chemical signals using molecules [16]. Nanonetworks employing molecular communication pose a number of design challenges due to their high density and the diffusion based propagation model and many issues in protocol design remain largely unexplored [17]. Since nanonetworks are not expected to have large processing capabilities due to the small size of the network nodes a key requirement is the simplicity of implementation. In our recent work in [18] we have demonstrated that probabilistic flooding is a good candidate solution for information dissemination in nanonetworks and that for optimal performance node density estimations are required. However, MC represents a propagation model which is different than that of electromagnetic waves propagation and does not suffer from multipath fading. Therefore, the above mentioned techniques are not suitable for density estimation when MC is employed. In this work we propose a distributed and simple to implement method for node density estimation. The method is inspired from the quorum sensing process and relies on synchronous transmission of the network nodes. The method is analogous to using the signal strength for density estimation in traditional electromagnetic networks. However, in molecular communications the propagation model is different and the resulting analysis which is presented here is thus different. As mentioned above, the method relies on synchronous transmission of the network nodes which in case of infinite space leads to a linear static parametric model which allows for node estimation [18]. However, in this paper we build on our work in [18] to show that when the space is finite the linear model is time varying and not static which makes the estimation prone to errors since the initial transmission time is difficult to determine. We overcome this problem by employing periodic broadcasting and averaging over the period of rebroadcasting. This allows for the parametric model to be almost static with the constant of proportionality being affected by the frequency of rebroadcasting and the area in which rebroadcasting takes place. We show these relationships in both two dimensional and three dimensional structures. The linear static parametric models are then used as a baseline to design estimates of the node density using online parameter identification techniques. The estimation algorithms are shown analytically to converge to the true parameter value. In addition a discussion is offered regarding the implementation feasibility of such an algorithm using latest developments in the field of synthetic biology.

Furthermore, we consider probabilistic broadcasting as an application where node density estimation is crucial. Information dissemination in nanonetworks must be performed using simple distributed techniques which suit the low computational and power capabilities of nanonodes [19]. Probabilistic broadcasting is a suitable candidate for high density networks like nanonetworks as it alleviates the broadcast problem [10]. In this paper, we provide design guidelines for probabilistic flooding in network structures which are relevant to the molecular nanonetwork paradigm. We consider the problem of adaptively regulating the rebroadcast probability using the obtained node estimates in random geometric graphs and in uniform grid networks. In random geometric graphs, which are meaningful due to the random movement of the molecular nodes and the MC paradigm, we show how recent analytical findings [20] can be used to determine the desired rebroadcast probability. In addition, in uniform grid networks which are meaningful in metamaterial nanonetworks [21] with molecular communication capability [22], we show using simulations that the high reachability requirement is critically affected by the node density and not the network size and desired rebroadcast probabilities are suggested for different cases in 2 and 3 dimensional structures.

The paper is organized as follows, in Section 2 a review of the Quorum sensing process is provided, in Section 3 the linear static parametric models are derived which are used as a baseline to design the online estimation scheme in Section 4. In Section 5 design guidelines are provided as to how the node estimates can be used to adaptively regulate probabilistic flooding in molecular nanonetworks and finally in Section 6 we offer our conclusion and future research directions.

2. Quorum sensing

Quorum sensing is a biological means of communication in bacteria. Based on the diffusion and reception of information molecules known as autoinducers bacteria can monitor, control and synchronize their group behavior. Studies have shown that the change in bacterial behavior is closely related to the population density of bacteria in the environment [23,24]. For instance, V. fischeri bacteria, which is responsible for the bioluminescence in squids, only emit light when its population exceeds a certain threshold. Many other physiological processes are controlled using QS, such as motility, antibiotics production and secretion of virulence.

Quorum sensing is the system with which bacteria can communicate to synchronize and sense their density population in order to perform cooperative behaviors and hence have a multicellular-organism-like action [25]. When using quorum sensing, bacteria diffuse a type of information molecules, known as autoinducers, into the extracellular environment. The reception of autoinducers by other bacteria stimulates the production of more molecules of the same kind. Thus, high concentration of these molecules indicates high density population of bacteria. Bacteria keep monitoring the level of the signaling molecules concentration. When the concentration of autoinducers exceeds a certain limit, sensed by the community of bacteria within the environment, the group behavior of bacteria changes [24]. Also, the rate of production of autoinducers increases dramatically when the concentration of these particles exceeds a certain limit [26]. In some cases more than one type of autoinducers are used to enable inter species communication as in V. harveyi bacteria [25]. Quorum sensing is crucial when taking a group action that would fail if taken by an individual bacterium. For instance, when attacking