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Lightweight, self-tuning data dissemination for dense nanonetworks

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ABSTRACT

A nanonetwork comprises a high number of autonomous nodes with wireless connectivity, assembled at micro-to-nanoscale. In general, manufacturing and cost considerations imply that nanonetworking approaches should have minimal complexity, ideally without sacrifices in network coverage. The present paper studies a networking approach fit for static, dense topologies comprising numerous, identical, computationally-constrained nodes. These attributes are especially important in the context of recently proposed applications of nanonetworks. The presented networking approach assumes that each node is equipped with 10 bits of reclaimable storage to accommodate four integer counters, and a trivial set of integer operations on them. These modest resources are used for logging packet reception statistics. Nanonodes with good reception serve as retransmitters within the network. This classification process is based on the Misra–Gries algorithm, used for detecting frequent items into sequential streams. Evaluation via extensive simulations in various 2D and 3D topologies yields high network coverage, achieved with less resources than related approaches.

1. Introduction

Recent advances in nanotechnology enable the creation of nano-sized power units, antennas, communication modules and CPUs, promoting the advent of nanonetworking [1]. Swarms of autonomous, wireless nodes that can sense and act on their environment will introduce radical changes in everyday life and the industry [2]. Presently, however, manufacturing autonomous nodes at nanoscale implies extremely limited hardware capabilities [1]. Furthermore, interesting applications of nanonetworks may require thousands to millions of nodes [2–4], posing cost issues as well. Thus, nanonode architectures must be as simplistic as possible, while fulfilling efficiently their application-specific goal. Given that the networking module is but a part of the nanonode architecture, it should require even fewer resources in terms of complexity, without compromising the connectivity of the nanonetwork.

The present study proposes a nanonetworking model fit for static, dense networks with numerous nodes. An important assumption is that the nodes are unique in all hardware and geometry aspects. Such networks can be used for the nano-scale monitoring of mission-critical materials, e.g. embedded within nuclear reactors [5]. Another important application is in the context of the recently proposed Software-Defined Materials (SDMs) [4]. SDMs allow for programmatic control over the electromagnetic (EM) behavior of an object. Their functionality stems from metamaterials, a class of artificial materials with a well-defined, periodic structure. SDMs equip a standard metamaterial with a network of nanonodes, which can receive

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external commands and alter the internal structure of the metamaterial accordingly. Thus, the EM properties of an object as a whole can be controlled programmatically as well.

The nano-scale allows for very high concentrations of nodes per volume, compared to macro-scale networks. The handling of dense nanonetworks yields three main challenges. *Firstly*, the scalability in terms of manufacturing and node communication is a major issue. For example, certain SDMs may require 10–100 nodes per mm^3 [4]. Therefore, the manufacturing cost per node should be minimal, implying a very simple hardware architecture. On the other hand, overly simplified architectures may not even support simple communication protocols, yielding connectivity issues as the number of nodes increases [6]. *Secondly*, the networking paradigm should offer high coverage per packet, with as few retransmissions as possible. Minimal packet retransmissions favor energy-efficiency and packet delivery time, since redundant transmissions and communication errors are minimized. *Thirdly*, the communication channel model within dense nanonetworks has a unique attribute: the nodes themselves act as non-trivial obstacles to the propagating EM wave [7].

The present paper contributes a networking scheme that addresses these challenges as follows. *Firstly*, a flood-based communication paradigm is adopted. Thus, the node architecture is simplified, since no medium access or routing protocol is required. This results into manufacturing cost benefits, and highly scalable node communication offered by the flood paradigm [8]. *Secondly*, packet retransmissions are reduced significantly with regard to related approaches. The methodology is based on the real-time classification of the nodes into few retransmitters ("infrastructure" nodes) and many passive auditors ("user" nodes), depending on their packet reception statistics. Internally, each node maps incoming packets to reception outcomes (e.g., successful or failed). The formed sequence is processed by a novel variant of the Misra–Gries algorithm [9], which detects the most frequent outcome types. The output of the algorithm deduces the classification result. This process has an extremely small computational footprint, while requiring trivial, integer processing capabilities only. *Thirdly*, the proposed scheme is evaluated in a state-of-the-art simulator that employs 3D ray-tracing to approximate the EM propagation between all node pairs within the nanonetwork [10]. Statistical channel models are shown to diverge significantly from the ray-tracing results in the studied dense topologies.

The remainder of this paper is organized as follows. Related studies are given in Section 2. The system model and application context are given in Section 3. Section 4 details the proposed networking scheme. Evaluation via simulations takes place in Section 5. The conclusion is given in Section 6.

2. Related work

Nanonetworking is presently studied from two different angles. The first approach proposes biological or bio-inspired communication modules. For example, the nodes may encode a single piece of information on several biological molecules (e.g., RNA) and diffuse them to their environment, or may exchange data upon collision only, mimicking the operation of viruses [2,11]. The second approach, which is assumed in the present study, considers wireless EM communication [1]. Related studies have so far focused on defining operational physical (PHY) layer specifications and Medium Access Control (MAC) protocols. We will first provide a brief overview of the PHY layer of nanocommunications, highlighting its challenges and the assumptions of the present work. Then, we will focus on MAC approaches which are related to the present work.

PHY layer. Related studies focus on specifying the channel model, nanoantenna geometry, and the power supply module. Concerning the channel model and nanoantennas, studies support that the most promising operating spectrum is the Terahertz Band (0.1–10.0 THz) [12]. The miniaturization of the antennas at nanoscale, while keeping the operating frequency tractably high (THz) can be achieved with the use of graphene. More particularly, the propagation speed of EM waves in carbon plasmonic nano-antennas can be orders of magnitude lower than in classical materials, yielding antennas 100–1000 smaller than conventional ones for the same wavelength [2]. Recent studies have shown that the communication range of a single node may be increased with the use of the 0.1–0.54 THz window [13]. The authors showed that, when using this window, the free-space propagation loss becomes the dominating factor in channel characteristics, minimizing molecular absorption and achieving the largest transmission distance. Particularly, the 100 GHz is very promising, assuming standard atmospheric conditions, since it corresponds to a local minimum in terms of molecular absorption, while still offering high data rates [14]. However, it has been recently shown that even small objects, such as aerosol particles, affect the channel model substantially, introducing additional EM scattering [7]. Nonetheless, the nanonodes themselves have not been considered in any channel model so far, despite being themselves substantial EM scatterers, especially in dense topologies. Regarding modulation and encoding, Jornet et al. [15] proposed the use of Rate Division Time Spread On–Off Keying (RD TS-OOK). Nanonodes transmit a logical "1" as a *femto*sec-long pulse and a logical "0" as silence. Any two nodes choose a unique inter-pulse time interval via a handshake protocol, in order to minimize collisions. In absence of handshaking collisions are possible, considering the wide spectrum of a *femto*sec pulse. Finally, the nanonode power supply is perhaps the most challenging module. Jornet et al. propose an *energy scavenging* unit based on piezoelectric nanogenerators, which can store 800 pJ of energy in 50 s, occupying an area of 1000 μm^2 [1]. Given that a 25 byte-long packet consumes 200 pJ (RD TS-OOK) [1], a maximum of 1 packet per 12.5 s can be sustained via energy-scavenging, which can pose a problem even for simple handshake-based communication protocols. Similar results are reported by the solution of Mohrehkesh et al., with a harvesting module that can store 20 pJ with an average rate of 0.5 pJ/s, and a drain of 2–10 pJ per transmitted packet [16]. Thus, 1 packet exchange per 10 s can be sustained as well. Wang et al. also report a solution that can store up to 9 nJ with an average rate of 63 pJ/s [17].