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Energy and spectrum-aware MAC protocol for perpetual wireless nanosensor networks in the Terahertz Band

Pu Wang [a,*,1], Josep Miquel Jornet [b,1], M.G. Abbas Malik [c,1], Nadine Akkari [c,1], Ian F. Akyildiz [c,d,1]

[a] Department of Electrical Engineering and Computer Science, Wichita State University, Wichita, KS 67260-0083, USA
[b] Department of Electrical Engineering, University at Buffalo, The State University of New York, Buffalo, NY 14260, USA
[c] Faculty of Computing and Information Technology, King Abdulaziz University, Jeddah, Saudi Arabia
[d] Broadband Wireless Networking Laboratory, School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA30332, USA

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ABSTRACT

Wireless NanoSensor Networks (WNSNs), i.e., networks of nanoscale devices with unprecedented sensing capabilities, are the enabling technology of long-awaited applications such as advanced health monitoring systems or surveillance networks for chemical and biological attack prevention. The peculiarities of the Terahertz Band, which is the envisioned frequency band for communication among nano-devices, and the extreme energy limitations of nanosensors, which require the use of nanoscale energy harvesting systems, introduce major challenges in the design of MAC protocols for WNSNs. This paper aims to design energy and spectrum-aware MAC protocols for WNSNs with the objective to achieve fair, throughput and lifetime optimal channel access by jointly optimizing the energy harvesting and consumption processes in nanosensors. Towards this end, the critical packet transmission ratio (CTR) is derived, which is the maximum allowable ratio between the transmission time and the energy harvesting time, below which a nanosensor can harvest more energy than the consumed one, thus achieving perpetual data transmission. Based on the CTR, first, a novel symbol-compression scheduling algorithm, built on a recently proposed pulse-based physical layer technique, is introduced. The symbol-compression solution utilizes the unique elasticity of the inter-symbol spacing of the pulse-based physical layer to allow a large number of nanosensors to transmit their packets in parallel without inducing collisions. In addition, a packet-level timeline scheduling algorithm, built on a theoretical bandwidth-adaptive capacity-optimal physical layer, is proposed with an objective to achieve balanced single-user throughput with infinite network lifetime. The simulation results show that the proposed simple scheduling algorithms can enable nanosensors to transmit with extremely high speed perpetually without replacing the batteries.

1. Introduction

Nanotechnology is providing a new set of tools to the engineering community to create nanoscale components with very specific functionalities, such as computing, data storing, sensing and actuation. Advanced nano-devices can be created by integrating several of these nano-components in a single entity. An early application of these nano-devices is in the field of nanosensing. Nanosensors take advantage of the unique properties of novel nanomaterials to detect new types of events at the nanoscale. WNSNs, i.e., networks of nanosensors, will enable advanced applications of nanotechnology in the biomedical field (e.g., intrabody health monitoring and drug delivery systems), in environmental research (e.g., agriculture plague and air

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[*] Corresponding author.

E-mail addresses: pu.wang@wichita.edu (P. Wang), jmjornet@buffalo.edu (J.M. Jornet), mgmalik@kau.edu.sa (M.G. Abbas Malik), nakkari@kau.edu.sa (N. Akkari), ian@ece.gatech.edu (I.F. Akyildiz).

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pollution control), and in defense and military technology (e.g., surveillance against new types of biological and chemical attacks at the nanoscale).

The peculiarities of nanosensors introduce many challenges in the realization of WNSNs. On the one hand, the miniaturization of classical antennas to meet the size requirements of nanosensors would impose the use of very high operating frequencies (hundreds of Terahertz), which would limit the feasibility of WNSNs. To overcome this limitation, the use of graphene-based nano-antennas and nano-transceivers has been recently proposed [10,23,17,25]. As a result, nanosensors are expected to communicate in the Terahertz Band (0.1–10 THz). The Terahertz Band suffers from a very high propagation loss, which drastically limits the communication range of nanosensors due to their expectedly very limited power and energy. At the same time, though, it provides a very large bandwidth, which can be used to develop simple but yet efficient modulation and medium sharing schemes.

On the other hand, the very limited amount of energy that nano-batteries can hold and the unfeasibility to manually recharge or replace them, have motivated the development of novel nanoscale energy harvesting systems [27,6,4]. Nanoscale power generators convert vibrational, fluidic, electromagnetic or acoustic energy into electrical energy. When using energy harvesting systems, the energy of nanosensors does not just decrease with time, but has both positive and negative fluctuations. Therefore, rather than minimizing the energy consumption, a communication system should optimize the use of the energy in the nano-battery by capturing its temporal fluctuations. Ultimately, WNSNs can achieve perpetual operation if the energy consumption process and the energy harvesting process are jointly optimized.

Due to the transmission at very high speed in the Terahertz Band and the expectedly very high number of nanosensors in WNSNs willing to simultaneously communicate, novel Medium Access Control (MAC) protocols are needed to regulate the access to the channel and to coordinate and synchronize the transmissions among nanodevices. Classical MAC protocols cannot directly be used in WNSNs because they do not capture (i) the limited processing capabilities of nanosensors, which requires the development of ultra-low-complexity protocols [2]; (ii) the peculiarities of the Terahertz Band [12], i.e., very large distant-dependent bandwidth (bandwidth is not a problem anymore, but synchronization is) and very high propagation loss (very limited transmission range); and, (iii) temporal energy fluctuations of nanosensors due to the behavior of power nano-generators [9]. Therefore, there is a need to revise the traditional assumptions in MAC design and propose new solutions tailored to this paradigm.

In this paper, we propose an energy and spectrum aware MAC protocol to achieve perpetual WNSNs. First, we propose to take advantage of the hierarchical network architecture of WNSNs and shift the complexity of the MAC protocol towards more resourceful nano-controllers. In our solution, the nano-controller regulates the access to the channel of the nanosensors, by following a Time Division Multiple Access (TDMA) approach. To guarantee a fair, throughput and lifetime optimal access to the channel, the nano-controller takes into account the data requirements and energy constraints of the different nanosensors willing to communicate. Moreover, this is done for two different possible physical layers, namely, a more practical physical layer based on a recent proposed pulse-based scheme for nanoscale communications, and a theoretical bandwidth-adaptive capacity-optimal physical layer. The system model and an overview of the proposed solution are explained in Section 3 and Section 4, respectively.

As the essential building block of the proposed MAC solution, the throughput-and-lifetime optimal schedule has to be designed, which aims to find an optimal transmission order for the nanosensors so that the network throughput is maximized, while maintaining the infinite network lifetime. Towards this end, we first derive an important system design parameter, namely, the critical packet transmission ratio (CTR). The CTR is the maximum allowable ratio between the transmission time and the energy harvesting time, below which the nanosensor node can harvest more energy than the consumed one, thus achieving perpetual data transmission. Thanks to the peculiarities of the Terahertz Band and the nanoscale energy harvesting process, it is revealed that the CTR exhibits a unique distance-dependent nature so that nanosensors at different locations possess different CTR. The definition and the details on the computation of the CTR are explained in Section 5.

Based on the CTR, a novel symbol-compression based MAC solution, built on the pulse-based physical layer, is introduced. The symbol-compression solution utilizes the unique elasticity of the inter-symbol spacing to allow multiple nanosensors to transmit their packets in parallel without inducing any transmission collisions. Based on this symbol-compression solution, a sub-optimal symbol-compression scheduling algorithm is proposed, which can assign each nanosensor with different sets of transmission slots in such a way that all nanosensors achieve their near-maximum single-user throughput, simultaneously, while maintaining their transmission ratios below the CTR for energy balancing. Different from the pulse-based physical layer, we reveal that there exist three unique properties of the capacity-optimal physical layer, namely, (i) non-overlapped packet transmissions, (ii) nonexistence of throughput-and-lifetime optimal schedules, and (iii) the single-user throughput unbalance. Then, based on these properties, a packet-level timeline scheduling algorithm is proposed to achieve the balanced single-user throughput with the infinite network lifetime. The algorithms are presented in Section 6.

The remainder of this paper is organized as follows. In Section 2, we review the recent literature related to MAC protocols for WNSNs. In Section 3, we describe the nanosensor model and network model used in our analysis. In Section 4, we provide an overview of the proposed energy and spectrum-aware MAC protocol. In Section 5, we analytically obtain the energy harvesting rate and the energy consumption rate for the two proposed physical layers, and compute the CTR. We present the optimal throughput