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On the improvement of wireless mesh sensor network performance under hidden terminal problems

David Rodenas-Herraiz [a], Antonio-Javier Garcia-Sanchez [b,*], Felipe Garcia-Sanchez [b], Joan Garcia-Haro [b]

[a] *Computer Laboratory, University of Cambridge, William Gates Building, 15 JJ Thompson Avenue, Cambridge CB3 0FD, United Kingdom*

[b] *Department of Information Technologies and Communications, Universidad Politecnica de Cartagena (UPCT), Campus Muralla del Mar, Cartagena E-30202, Spain*

HIGHLIGHTS

- WMSN approaches offer new perspectives to conventional WSN-based applications.
- Among WMSN proposals, the ASES mode guarantees the most relevant mesh capabilities.
- ASES has no mechanisms to mitigate the negative effects of hidden terminals (HT).
- Under ASES rules, we propose an optimization model and a multi-channel time-slotted algorithm to alleviate the HT problem.
- An intensive performance evaluation study is discussed to validate our proposals.

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ABSTRACT

Wireless Mesh Sensor Networks (WMSNs) have recently received a great deal of attention in the scientific and developers communities due to the significant advances of this technology in the wireless communication field. The main reason was that competing WMSN approaches that emerged in the last few years provide mesh capabilities (*e.g.*, robustness, scalability, multi-hop mesh routing, or energy efficiency, among others) to conventional WSN-based applications, encouraging researchers and end users to adopt new perspectives and solutions. Unfortunately, each one of these approaches lacks some (or many) of the aforementioned mesh capabilities, not assuring, a priori, the feasibility and, especially, the long-term stability of WMSN applications. The IEEE 802.15.5 standard and, in particular, its Asynchronous Energy Saving (ASES) mode was conceived to fill this gap since it integrates, in a single solution, most of these capabilities, guaranteeing, among other benefits, a long network lifetime. However, the ASES mode has no built-in mechanisms to mitigate the negative effects of hidden terminals, which sharply degrades the network performance. This fact leads us to conclude that any current WMSN approach is non-exempt of some problem, which prevents the definitive boost of this technology in the consumer market. Under these circumstances, our contribution to the WMSN field in this paper is a twofold proposal addressed to alleviating the hidden terminal problems in a scenario running under the most relevant design premises of ASES mode. Therefore, we first formulate a multi-objective optimization and then solve it by using Goal Programming. Both mathematical techniques are applied to obtain the best solution that simultaneously minimizes the aggregate message collision time due to hidden terminals and maximizes the network lifetime. Secondly, we propose the design of a *MULti-channel TIme-scheduled algorithm for the HIdden Terminal problem avoidance* (MULTI-HIT) which appropriately exploits the available bandwidth and accomplishes a straightforward coordination between any sender–receiver pair. Finally, the analysis and simulation experiments are presented and their results carefully discussed, demonstrating the effectiveness of both proposals in the WMSN arena.

* Corresponding author. Tel.: +34 968 326 538; fax: +34 968 325 973.
E-mail addresses: dr424@cam.ac.uk (D. Rodenas-Herraiz), antoniojavier.garcia@upct.es (A.-J. Garcia-Sanchez), felipe.garcia@upct.es (F. Garcia-Sanchez), joang.haro@upct.es (J. Garcia-Haro).

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1. Introduction

Wireless Mesh Sensor Networks (WMSNs) comprise a technological field that has arisen as the natural evolution from the conventional Wireless Sensor Networks (WSNs), composed of only a few nodes, to large-scale networks in which sources and destinations are interconnected through different paths of intermediate nodes forming a mesh layout [1]. To this end, new *mesh capabilities* such as multi-hop mesh routing, scalability, robustness, reliability, self-organization or energy efficiency must be satisfied [2]. In this sense, advances in WMSNs over the next few years will be addressed to the design, development and integration of all these capabilities into a single standard mesh solution which, in turn, will ensure a strong boost of this technology in a wide range of areas, such as automation and control (home and industrial), environmental surveillance, precision agriculture, traffic monitoring, or health services [1].

Concerning the mesh capabilities mentioned above, we pay special attention to energy efficiency since it is considered as one of the major issues in WMSN nodes usually fed by conventional (chemical) batteries. This is because many of the network nodes must accomplish a twofold functionality: (i) acquire and dispatch physical information of the surrounding area and (ii) relay appropriately the data from other different source nodes. Under these circumstances, the Asynchronous Energy Saving (ASES) mechanism defined by the IEEE 802.15.5 standard is an operational mode conceived to reduce the power consumption of the WMSN nodes. To achieve this purpose, ASES integrates, in a single solution, an efficient duty-cycle strategy for saving energy along with most of the above mesh capabilities. This fact makes IEEE 802.15.5 standard and its ASES mechanism advantageous with respect to other WMSN approaches [2], such as Zigbee Pro [3], the International Engineering Task Force (IETF) with its solution IPv6 over Low power Wireless Personal Area Networks (6LoWPAN) [4], WirelessHART [5] or ISA SP100.11a [6].

However, ASES mode is not free from problems, one of the main ones being, in our opinion, that it prevents the definitive penetration of this solution in the consumer market: the hidden terminal (HT) effect. The HT phenomena occur when two (or more) sender nodes which are unable to sense each other transmit simultaneously, provoking message collisions at one or several common receiver nodes. This event leads to retransmitting the message/-s that suffered a collision, which greatly increases the energy devoted to transmitting/receiving a message successfully. Furthermore, if further collisions by HT also affect the retransmissions, it may occur that messages are finally discarded; therefore not reaching the receiver. This situation, extended to the overall WMSN, results in a dramatic increase in the number of messages lost, which may entail a strong deterioration of the network operation. Thereby, the inability of plain ASES to mitigate the HT effects together with the fact that the remaining WMSN solutions only satisfy an incomplete set of mesh capabilities is the reason that has motivated this work. In this paper, we propose a novel analytical model and a multi-channel time-slotted algorithm. Both proposals are aimed at alleviating the HT problems in a WMSN running under the most relevant premises of ASES mode, which assures, among other issues, a longer lifetime operation.

Therefore, as a *first contribution* of this research work, we introduce a multi-objective (MO) optimization problem [7], which allows us to formulate multiple objectives in a single problem definition, in order to later apply the mathematical tool denoted as *Goal Programming* (GP) [8,9] to simultaneously satisfy the objectives pursued. Prior to the definition of the MO problem objectives, we have to decide the most appropriate constraints that approximate the work here proposed to the real network operation. To this end, we derive the mathematical equations of the achieved throughput per link (total bitrate between a pair of nodes) and the energy consumption associated to each node. Furthermore, the hidden terminals effect along with some design premises of the ASES mode is also modeled in the formulation of the constraints. As objectives of the MO problem, we select: (i) the aggregate message collision time, denoted as the total ineffective time lost by collisions produced by HT problems, and (ii) the network lifetime, defined as the minimum node lifetime for any node belonging to the network. Interestingly, the simultaneous optimization of both objectives ensures a suitable throughput per link due to the decrease in the number of messages lost by collisions and, in turn, extends the network lifetime.

Among all the existing MO optimization techniques, we decided on *Goal Programming* to solve the problem formulated. Unlike more conventional optimization approaches (*i.e.*, single-objective, sequential-objectives or other MO techniques) [7], GP offers an adjustable model to real network operation conditions, combining, on the one hand, simplicity of formulation expressing constrains usually as linear/non-linear programming, and, on the other hand, flexibility to compute the optimal solution thanks to simultaneously optimizing the deviations (underachieve/overachieve) of estimations (called *goals*) about real (domain-driven applications) conditions. These deviations become the objectives of the optimization problem. In order to obtain the best performance of the WMSN, we numerically estimated the goals for the aggregate message collision time and network lifetime metrics which are consistent with the operation of some real scenarios related to agriculture applications where our group has wide experience [10,11]. The numerical results obtained by GP clearly satisfy the deviations of these goals, thus setting an optimal design in order to reach an efficient and complete sensing monitoring during, at least, the period specified by the end users for the WMSN applications under consideration. To the best of the authors' knowledge, this is the first work in the scientific literature that provides a solution based on Goal Programming in order to improve the WMSNs performance under hidden terminal interference.

As a *second contribution* of this paper, we present the design of a *MULti-channel TIme-scheduled algorithm for the HIdden Terminal problem avoidance*, which we call MULTI-HIT. This new algorithm, based on the design principles of the ASES mode operation, is conceived to mitigate the HT problems in a WMSN. To this end, we first take into consideration the studies in [12–14], which allow us to learn about the strong points and limitations of the different techniques that cope with the HT effects in WSNs and WMSNs. These techniques are classified into four main categories, namely, time-slot scheduling mechanisms, channel multiplexing protocols, directional antenna techniques and, CDMA-based proposals. Among them, we propose a solution which follows some of the rules related to channel multiplexing [15] and time-slot scheduling [16,17] techniques, and does not require additional and costly hardware, as it is the case of proposals that employ CDMA-based or directional antenna methodologies. On the contrary, MULTI-HIT implements a straightforward schedule for the nodes transmission/reception tasks while making an efficient use of the multiple frequency channels available in the 2.4 GHz ISM band. The final result is a clear reduction in the energy and computing/memory resources required in comparison with solutions based on CDMA or directional antennas.

The MULTI-HIT scheme is also evaluated by means of computer simulation, comparing its performance results with the ones obtained by (i) the optimization study and (ii) a recent approach denoted as *Quorum-based energy-efficient Medium Access Control protocol* (Queen-MAC) [12]. This scheme has already been validated by the scientific community and also combines channel multiplexing and time scheduling techniques, thus sharing common features with our MULTI-HIT proposal. Therefore, it seems appropriate to judge Queen-MAC against MULTI-HIT, though, as will be