Computer Networks 57 (2013) 3389–3409

Contents lists available at ScienceDirect

Computer Networks

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

# Energy efficient and reliable data delivery in urban sensing applications: A performance analysis

Eleonora Borgia [a,*], Giuseppe Anastasi [b], Marco Conti [a]

[a] Institute of Informatics and Telematics, National Research Council (CNR), Italy
[b] Department of Information Engineering, University of Pisa, Italy

ARTICLE INFO

*Article history:*
Received 26 October 2012
Received in revised form 26 June 2013
Accepted 8 July 2013
Available online 11 August 2013

*Keywords:*
Urban sensing
Wireless sensor networks
Mobile sinks
Reliable data delivery
Erasure coding
Analytical model and implementation

ABSTRACT

Urban sensing is an emerging application field for Wireless Sensor Networks (WSNs), where a number of static sensors is sparsely deployed in an urban area to collect environmental information. Data sensed by each sensor are, then, opportunistically transmitted to Mobile Nodes (MNs) that happen to be in contact. In the considered scenario, communications between MNs and sensors require paradigms with a minimal synchronization between devices, extremely fast and energy efficient, especially at the sensor side. To deal with the above issues, in [1] we proposed a hybrid protocol for data delivery from sensors to MNs, named Hybrid Adaptive Interleaved Data Protocol (HI). By combining Erasure Coding (EC) with an Automatic Repeat reQuest (ARQ) scheme, the proposed protocol maximizes the reliability of communications while minimizing the energy consumed by sensors. In this paper, we present an in-depth analysis of the HI performance. We provide an analytical evaluation by defining a flexible model to derive the probability of data delivery and exploiting it to investigate the performance over a wide range of parameters. Moreover, we perform an experimental study to evaluate the HI effectiveness on real sensor platforms. Specifically, we analyze the impact of resource constraints imposed by sensors on data delivery and provide a careful characterization of its actual consumption of resources.



## 1. Introduction

Wireless Sensor Networks (WSNs) play a crucial role in the realization of the Future Internet, which will be truly pervasive, ubiquitous and content-centric with data generated automatically by applications/devices or by users [2,3]. In this scenario, WSNs are a powerful technology to automatically generate content, gather and process the data generated and, thus, to increase the awareness of a certain environment or phenomenon. Their applicability spans over a large variety of domains [4–6]. Relevant applications include, among others, environmental monitoring, surveillance, event detection, intelligent agriculture, health monitoring.

Traditionally, a WSN consists of static and resource-constrained sensor nodes, densely deployed in the sensing area, so that sensed data can be relayed through multi-hop communication and collected by a sink node [7–12]. More recently, there has been an increased interest in the research community to introduce mobile elements in WSNs, to increase their performance [13–15]. Mobile elements can be either regular sensor nodes or special nodes that are exploited to support the data-collection process. In the former case, sensor nodes can be mounted, for instance, on vehicles (e.g., taxis or buses) and exploited for pollution monitoring or surveillance of urban areas [16]. In the latter case, sensor nodes are still static, however, the WSN is enhanced with special mobile data-collector nodes. These special mobile nodes can be either mobile

* Corresponding author. Address: Via G. Moruzzi 1, 56124 Pisa, Italy. Tel.: +39 050 315 2407; fax: +39 050 315 2593.

*E-mail addresses:* eleonora.borgia@iit.cnr.it (E. Borgia), giuseppe.anastasi@iet.unipi.it (G. Anastasi), marco.conti@iit.cnr.it (M. Conti).

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http://dx.doi.org/10.1016/j.comnet.2013.07.025

elements specifically introduced in the sensing field for data collection (e.g., mobile robots), or mobile elements that already exist in the environment and can, thus, be exploited to collect data from sensor nodes. In the latter case, they are also known as Mobile Nodes (MNs), data mules or message ferries [17].

Robots are often sophisticated mobile entities (e.g., Unmanned Aerial Vehicles) that are able to make complex decisions in order to move close to sensor nodes to collect the data. On the other hand, the mobility patterns of MNs cannot be controlled and it is, typically, independent from the WSN operations. Hence, sensor nodes must adapt their behavior when a MN happens to be within their transmission range. Despite these limitations, WSN with MNs represents a cost effective solution for data collection in sensor networks, especially when sensor nodes are sparsely deployed in the environment and, thus, they cannot communicate directly. MNs move in the environment for their own business (e.g., city buses) and are exploited to collect the sensed data from the sensor nodes, without the need to deploy new and costly elements such as mobile robots. Sparse WSNs require a much lower number of nodes than traditional (dense) WSNs. This reduces not only the cost of the WSN, but also contention and collisions. Finally, since MNs can traverse the network to collect data, the energy consumption can be spread more uniformly in the network as well as reduced, therefore contributing to make the environment more sustainable and greener [18]. As a result, the network lifetime can be significantly improved [19,20]. For the above reasons, in this paper we focus on data collection in sparse WSN with MNs.

Sparse sensor networks are particularly appealing for urban applications [21,22]. In this case, a low number of static sensors can be placed in a few strategic points of a city to collect physical information about the environment, e.g., the level of pollutants or allergens in the air. Data generated by sensors can be collected by MNs, which can be either vehicles (e.g., bikes, cars, buses or shuttles) or people carrying a smartphone. MNs can either use the collected information for their own purposes, make them available to other MNs that happen to be in contact with them, or send them to remote user or sink node, through a long-range communication facilities (e.g., GPRS/UMTS).

In such a scenario, data delivery presents several issues. One of them is the limited contact time available to sensors for communicating with MNs. This is especially true when MNs are vehicles moving at a high speed. A different aspect is related to the variable quality of wireless communication. The wireless channel is known to be noisy, especially in urban scenarios where there might be several sources of interferences. Since MNs are mobile, the message loss rate is highly time-varying, and significantly affected by the physical distance between sensors and MNs [21]. As a consequence, communication protocols targeted to data delivery in such a scenario should be reliable, and should also have a limited overhead in order to exploit the short and limited contacts to the full extent. In this context, approaches based on Erasure Coding (EC) have shown to be effective [23]. To deal with all the above issues, the Hybrid Adaptive Interleaved Data Protocol (HI), a hybrid communication protocol for reliable data delivery from sensors to MNs, has been proposed [1]. HI efficiently combines EC with an ARQ scheme such that: (i) reliability of communications is significantly enhanced and (ii) energy consumption at the sensor node is drastically reduced. The simulation analysis carried out in [1] has demonstrated that the proposed hybrid communication protocol outperforms a pure ARQ scheme based on acknowledgments and selective retransmissions, especially when many MNs are simultaneously in contact with the sensor. However, being based on simulation experiments only, the analysis in [1] is not exhaustive because it does neither study the general properties of the hybrid communication protocol, nor its effectiveness when implemented on real resource-constrained sensor nodes. For example, it does not consider that most real sensor platforms currently in use have scarce memory, thus the maximum *stretch factor* (i.e., ratio between the number of redundant and original messages), which has been used to study the potential of EC, may not be feasible.

This paper extends the analysis in [1] along the following two directions: (i) it provides an analytical evaluation of the data delivery process to study the sensitiveness of the protocol performance to the parameters' setting and (ii) it analyzes the effect of resource limitations imposed by real sensor devices. Concerning point (i), the major contribution is the development of an analytical model that characterizes the behavior of the overall data delivery process. The proposed model provides a much more flexible (and quick) tool than simulation models. In fact, the complexity of simulation models, due to the high number of events that need to be handle, does not allow to study in detail the system behavior over a large number of parameters. The analytical model is first validated against simulation results to assess its accuracy, and then used to investigate the general properties of the HI protocol.

Regarding point (ii), the major contribution is to analyze the real effectiveness of the proposed hybrid delivery protocol when implemented on real sensor nodes. Indeed, some performance indices are difficult (if not impossible) to measure through analytical or simulation models. An example is the actual consumption of resources, such as percentage of memory or additional energy used for encoding/decoding. Such quantities, which obviously depend on the specific sensor platform considered, must be necessarily assessed by means of an implementation on real sensor nodes. Therefore, to complete the performance analysis of the HI protocol, in this work we also provide a comprehensive analysis on the use of resources by an experimental analysis.

The obtained results show that, when using the HI protocol, the MN is able to decode the original bundle with high probability, even with low values of stretch factor and duty cycle, or with different mobility patterns followed by the MN. These results are further confirmed by the experimental analysis that shows that HI is a feasible solution, despite the very limited storage and processing resources of commercially available sensor platforms, and it introduces a very low energy consumption. In addition, HI is also very appealing for urban sensing scenarios, where more than one MN can be simultaneously in contact with a static sensor at once.