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Non-localized and localized data storage in large-scale communicating materials: Probabilistic and hop-counter approaches

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ABSTRACT

The rapid development of Internet of Things has triggered the multiplication of communication nodes based on Radio-Frequency Identification (RFID) and Wireless Sensor Networks (WSNs) in various domains such as building, city, industry, and transport. These communication nodes are attached to a thing or directly included in the material of the thing to form a communicating material. In communicating material, one of the desired objectives is to merge the logical data with its physical material, thus simplifying the monitoring of its life cycle, the maintenance operations, and the recycling process. In this context, the initial form of the communicating material can evolve during its lifecycle. It can be split, aggregated with other materials, or partially damaged. However, the entire information in the material should always be accessible after each change. Thus, the objective of this research is to develop specific algorithms for efficient dissemination of information in the material in order to limit information losses. Two dissemination algorithms hop-counter-based and probabilistic-based are proposed for storing data by using WSNs, and non-localized and localized storage is considered. Non-localized storage ensures that information can be retrieved from each piece of the material by using a uniform data replication process. Localized storage ensures that the information is stored in a limited region of the material. Castalia/OMNeT++ simulator is used to compare the performance of the proposed algorithms with other similar protocols such as DEEP, Supple, and RaWMS.

1. Introduction

Communicating material, a new paradigm of industrial information systems, was presented and discussed for the first time in [1]. It enhances a classic material by providing the following capabilities: (a) storage of data, (b) communication of information at any point of its surface, and (c) retention of properties (a) and (b) after physical modifications. This concept leads to an important change in the Internet of Things. During product manufacturing, thousands of ultra-small electronic devices are distributed in its material. Thus, the product does not communicate using certain tags or nodes at specific points, but communicates intrinsically and continuously.

The initial studies focusing on communicating materials are presented in [1–6]. In these studies, a communicating material called *e-textile* is obtained by scattering a large number of Radio Frequency Identification (RFID) μtags (1500 tags/m^2) in a manufactured textile. The system consists of an RFID reader/writer connected to a relational database that contains the entire product lifecycle information. For each writing operation, the database is examined to select the relevant data items (fragments of the database tables) that must be stored in the material. In order to achieve this objective, each data item is assigned an importance level between 0 and 1 that is computed via a multi-criteria decision-making algorithm [5]. For example, the importance value 1 indicates a highly critical data item and the value 0 indicates an ordinary one. Then, data items with the highest importance levels are stored in the μtags when the textile passes under the writer module during the manufacturing phase. The RFIDs are memory-constrained, and hence, the data item is split and stored over several tags by using a specific protocol header which can be used to rebuild the initial information. This division process is called segmentation and the resulting parts are *segments*.[1]

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[1] In our article, the term *segmentation* is not employed in its classic sense which is typically used for the transport layer of the OSI model.

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In such a system, data storage in the communicating material requires a reader/writer connection with each tag. If a tag is not connected during the dissemination phase, it will be isolated and left empty, thus limiting the use of RFID technology in solid and large-scale materials such as concrete in smart buildings, plane wings, and wood panels. Therefore, this study proposes the use of Wireless Sensor Networks (WSNs) in such products by dispersing micro sensor nodes in the material, as shown in Fig. 1. The insertion of WSNs into materials has been proposed by [7]; however, the objective of the insertion was self-measurement purposes. In our study *focusing on data management*, a dissemination algorithm for WSNs is used to store relevant data items in the material.

During the manufacturing process of a final product and its future use, the communicating material passes through various lifecycle steps, as shown in Fig. 2. In steps 1 and 2, the material undergoes shape transformation (e.g. cutting, sawing, and drilling) to construct the product. In the intermediate stage of the lifecycle (steps 3 and 4), the material could also undergo possible physical transformations (e.g. breakage, piece addition/elimination) which lead to information loss if data is not replicated in the entire material. Therefore, the information should be stored in a uniform manner, and it should be present in each piece of the material. Further, by ensuring uniform distribution, the data item can be retrieved later by the user without visiting many nodes in the material, thus conserving its energy resources.

WSNs in communicating material exhibit certain specific characteristics: high node density and ultra-small nodes (micro-nodes) with extremely limited memory, energy, and computation abilities. Further, replacement of nodes or batteries is impossible because the nodes are embedded in the material. Hence, the data dissemination in such networks and environment must be judicious. The amount of data transmitted in the network should be reduced as much as possible to maximize the material lifetime (i.e. communication is the main activity responsible for energy consumption in WSNs [8–10]). Thus, any data dissemination mechanism developed for nodes with such limited resources must be simple and incur low communication overhead.

Another factor in the storage in communicating materials is the data importance level, as discussed in [5]. In order to disseminate information, the user sends a data item coupled with an importance level having a value between 0 and 1, which affects the storage density (i.e. the data replication rate). The number of storage nodes should depend on this level. For instance, the number of storage nodes for an importance level of 1 should be larger than that for lower levels of importance. Thus, the key research challenge of this study is to determine a mechanism for storage of the data item among limited-resource WSNs; thus, the data item will be present in each piece of the material (uniform storage), irrespective of the importance level. A failure in this process may result in data loss during material transformation in its lifecycle.

Considerable research has been conducted in data dissemination in WSNs [11]; however, few studies have considered the challenges mentioned earlier in this manuscript. In general, dissemination algorithms can be categorized as *reactive* or *proactive*. In the reactive approach [12–15], nodes react to an event by sending data towards the nodes that are located close to the event positions. However, in the proactive approach, nodes anticipate future events and distribute their data towards all the nodes or a subset of nodes that have the role of a storage unit. This proactive approach is composed of *structured* and *unstructured* algorithms. In structured dissemination [16–18], the storage nodes typically form a virtual structure (e.g. grid, line, and rail) within the WSN, which makes the data available for retrieval at a later point of time (e.g. by sinks visiting the storage nodes to collect data). However, in unstructured dissemination [19,20], the data is replicated throughout the entire network. In this case, the manner in which data dissemination is performed will determine whether the information is uniformly stored. *In this study, we focus on unstructured proactive data dissemination strategies and selection of uniform distributed storage nodes in WSNs*.

In this study, we have developed two unstructured proactive dissemination algorithms for the storage of data items in large-scale communicating materials. Both algorithms use a counter-based broadcasting scheme for spreading the message to all nodes of the material. However, the algorithms have different storage strategies. The first algorithm uses probabilistic-based storage and the second algorithm uses hop-counter-based storage.

– *Probabilistic-based storage*: Every node that receives data stores it with a probability *P* which is equal to the importance level.
– *Hop-counter-based storage*: The message is broadcast from one node to all its neighbours, and, at each hop, the counter is decremented. When the counter is zero, the node must store the data, reset the counter to its initial value, and rebroadcast the message.

As shown in Fig. 3, various storage modes are proposed for these dissemination algorithms: *non-localized storage* and *localized storage*. In the non-localized mode, the data is replicated in a uniform manner, and thus, it will be readable everywhere on the material, even after a shape transformation. The storage density varies in the material according to the data importance level. However, in the localized mode, the storage region size should depend on this importance. The storage region is larger for higher values of importance than for lower values.

These algorithms are simulated with Castalia/OMNeT++ using a realistic collision model and compared with other unstructured proactive data dissemination schemes such as DEEP, Supple, and RaWMS. They are evaluated by studying the uniformity performance for various importance levels, the communication overhead ratio, and the efficiency of the localized storage.

The remainder of the manuscript is organized as follows: In Section 2, related work is discussed. The design of the dissemination algorithms for data storage in communicating materials is described in Section 3. Simulation results and performance evaluation are discussed in Section 4. Finally, the conclusion is presented in Section 5.

2. Related work

Unstructured proactive dissemination protocols have been proposed in literature in order to overcome the challenge of node failures and mobile collector sink management. The goal of replication is to copy data at other nodes within the WSN in order to increase resilience and improve

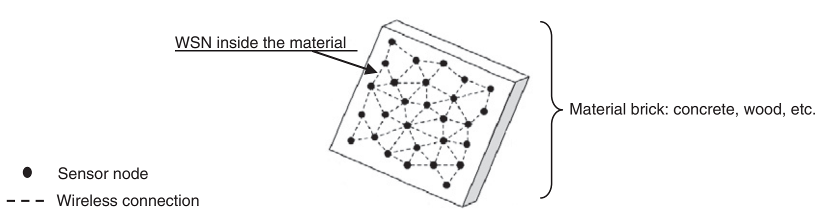

Fig. 1. Large-scale communicating material using WSN.