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Multi-Hop Counter Based Data Dissemination Protocol for Communicating Materials

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Abstract—The communicating material is a new paradigm of Internet of Things. It is designed to perform efficient product control and ensure an information continuum all along the product life cycle. Therefore, storage of life cycle information and data dissemination in communicating materials are very important issues. This paper provides a solution for storing data on the material by systematic dissemination through integrated ultra-small wireless sensors nodes via multi-hop counter based algorithm. The performance of our protocol is evaluated for non-localized and localized dissemination, then for not segmented and segmented data. Simulation results using Castalia/OMNeT++ show that our algorithm provides uniform dissemination for different limited density level and efficient localized storage.

Keywords—communicating materials; wireless sensor networks; data dissemination; data storage

I. INTRODUCTION

The communicating material is a new paradigm of industrial information system and it was presented and discussed for the first time in [1]. It enhances a classic material with the following capabilities: it can store data, communicate the information at any point of the product, and keep these previous properties after physical modification. This technology leads to an important change in intelligent product. Indeed, the material does not communicate using some tags or nodes in specific points, but becomes intrinsically and continuously communicating. To meet this vision, many ultra-small electronic devices (thousands) are scattered into the material of the product during its industrial manufacturing so as to be inseparable.

The first works focusing on communicating materials are presented in [2] [3]. It introduces a communicating material (e-textile) obtained by scattering a huge amount of RFID μ tags (1500 tags/m²) in a manufactured textile. The system involves RFID reader/writer which is connected to a relational database that contains all the product life cycle information. At each writing operation, the database is explored to select the relevant data items that must be stored in the material. A Data item is a fragment of a database table, describing a particular data and requiring several bytes to be stored in the μ tags when the textile passes under the writer module during the

manufacturing phases. Since the RFID are memory-constrained, the data item is splitted (segmented) and stored over several tags using specific protocol header which is also able to rebuild the initial information.

With such system, the 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 which limits the use of RFID technology in solid and large materials such as concrete and wood. Therefore, our current works propose to use wireless sensor networks (WSN) technology in such products. Ultra-small and micro (even nano [4]) sensor nodes are dispersed into the material (e.g. 100 nodes/m²). Due to the memory limitations of such devices, large data may be divided into smaller parts. In the rest of this article, this division process is called *segmentation* and the resulting parts are *segments*¹.

This paper presents a dissemination protocol to store relevant data items in wireless sensor nodes scattered into large scale products. Data items can be spread into the material through two different modes, which are *localized dissemination* (data are disseminated on a local part of the material) and *non-localized dissemination* (data are spread all over the material). These modes are used depending on the data context: some data may be linked to a specific location in the material (presence of a material defect) when some others may concern the whole material (origin, composition, ...).

For *localized dissemination*, the dissemination protocol should only ensure that data are located near the writing source (i.e. the master node in our study, as described later in section III.A.). If *non-localized dissemination* is used, the dissemination protocol should respect the following constraint: data must be readable everywhere on the material even after a shape transformation (e.g. cutting, sawing, and drilling). So, a given data item should be replicated in a uniform way.

¹ In our article, the term *segmentation* is not employed in its classic meaning, usually used for the transport layer of the OSI model.

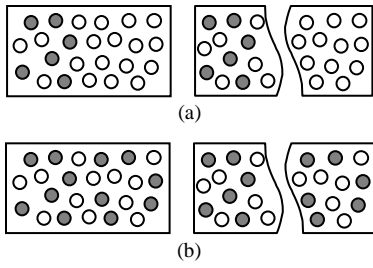


Fig. 1. Uniform dissemination for anticipation of material transformation.

As shown in figure 1(a), the information is not uniformly disseminated, so pieces of the material are empty and information can not be read after cutting as example. However, figure 1(b) shows a uniform replication so the information could be read in each piece.

Furthermore, to disseminate information, user sends data item coupled with limited importance level between 0 and 1 (1=highly critical data item, 0=ordinary data item). So, the number of nodes that have to store the data (i.e. storage density) depends on this level as shown in figures 2(a) and 2(b). Therefore, the dissemination algorithm has to keep the uniformity of data item replication in the material whatever the storage density and the importance level.

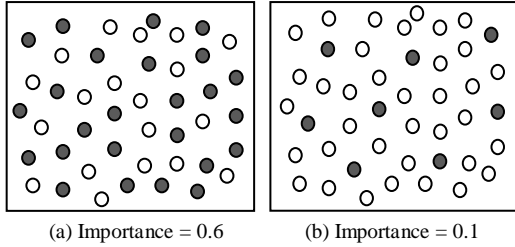


Fig. 2. Storage density according to the importance level.

The proposed protocol is simulated by Castalia/OMNeT++ using a realistic collision model. It is evaluated by studying the uniformity of replication for non-localized and localized dissemination (i.e. information storage in the whole material and in limited area), and for segmented and not segmented data item for different importance levels.

The paper is organized as follow. Section 2 is dedicated to related works. Section 3 details the design of our algorithms for data dissemination in the communicating materials. Section 4 is dedicated to the presentation of simulation results and performance evaluation. Finally, section 5 concludes the paper.

II. RELATED WORK

In WSN, data dissemination protocols are usually used for network reprogramming, routing path discovery (e.g. DSR and AODV), fault tolerance, data mules, and mobile sink management [5]. In the past years, various algorithms have been proposed [6]. There are two main approaches: reactive and proactive which is divided into structured and unstructured distribution strategies as shown in figure 3. In the first one, nodes react to an event (e.g. the presence of mules and mobile sink) by disseminating data towards the nodes that are located close to the event positions. In proactive approach, however,

nodes distribute their data towards all or subset of nodes that have the role of storage unit, in anticipation of future event, nodes failure, mule collection, and others. Under structured dissemination, these storage nodes typically form a virtual structure (e.g. grid, line, and rail) within the WSN that make the data available to be retrieved later by mobile sink, as example, which should visit nodes belonging to this structure to collect data. However in unstructured dissemination, the data is replicated throughout the whole network.

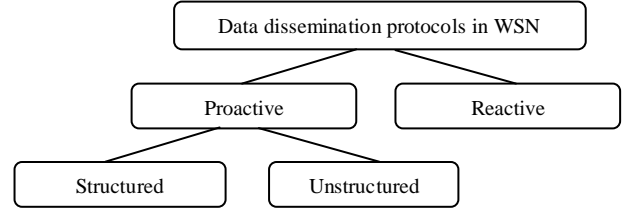


Fig. 3. Classification of data dissemination protocols in WSN.

The aim of this work is to fully disseminate and to uniformly replicate data in the whole communicating material, in order to ease the reading process in any point and to anticipate possible physical transformations. As a result, this section focuses on the protocols of the unstructured proactive dissemination.

Unstructured proactive dissemination protocols in WSN include a *broadcast mechanism* and a *storage strategy*, both are detailed in the following.

A. Broadcast mechanisms

Broadcast algorithms are usually referred to as flooding. Flooding is an important algorithm in WSN and is applied when a source node has to send information to subset or all nodes in the network. This is achieved by broadcasting a packet to the entire neighborhood. Each node that receives the packet rebroadcast it, if it has not been forwarded previously. In this way, the information traverses the whole network and reaches all the nodes which then decide to store it or not according to the storage strategy. Although flooding is a very simple and efficient for data dissemination, it has some deficiencies. The main problems are: duplication (i.e. a node is forced to get information twice from two different nodes), collision (i.e. the broadcast increase the contention), and resource blindness (i.e. nodes do not adopt energy saving mechanisms) [7]. As a consequence, various schemes for controlled flooding have been proposed including probabilistic-based also referred to as gossiping [8] [9], counter-based [10] [11], distance-based and location-based [12].

Distance and location based schemes exploit distance between nodes and their position information. Therefore, nodes need to be equipped with a Received Signal Strength Indicator (RSSI) or a Global Positioning System (GPS). Such additional functions could not be applied in communicating material since the nodes are embedded in the product with high density (i.e. nodes are very close).

Authors in [13] [14] show that counter-based scheme outperforms the probabilistic one in terms of reliability (i.e. the

percentage of nodes that are reached on average) and efficiency (i.e. the average amount of resources required for broadcasting a message). This mechanism can reduce the number of retransmitting nodes with a high arrival rate. Furthermore, it doesn't require hardware like a distance and location based scheme. For these reasons, the counter-based is adopted in our dissemination protocol as broadcast mechanism.

B. Storage strategies

Storage strategies in unstructured proactive dissemination protocols are developed in the literature according to the target application. In [15] [16], the information is replicated in each node for network reprogramming. If a node does not receive the new version of binary code, its software is not updated and is isolated. Authors in [17] [18] [19] propose storage strategies to improve network resilience against the risk of nodes failures. The storage nodes are selected according to some critical parameters such as connectivity, available memory and remaining energy. DEEP [20] adopts another storing strategy for an effective data collection by mobile sink with uncontrolled trajectory. Every node that receives a data stores it with a probability p according to the number of information that must be replicated in each node. In [21], authors use a hop-counter mechanism to replicate data for mobile sink collection. Hop-counter is a process in which a data is repeatedly forwarded from a node to one of its chosen neighbors, the information is stored at the node in which the counter stops.

C. Synthesis and proposed solution

The main approach of broadcast and storage approaches for data dissemination protocols in WSN could be summarized in two categories as shown in table 1.

TABLE I. BROADCAST AND STORAGE APPROACHES

	Broadcast mechanism	Storage strategy
Probabilistic approach	Probabilistic-based	Probabilistic-storage
Counter approach	<u>Counter-based</u>	<u>Hop-counter</u>

The above storing strategies use the physical nodes parameters (e.g. memory and energy), network topology, and neighborhood awareness to replicate data throughout the WSN. They don't assume the properties and the characteristic of the disseminated data itself. This problem is the key contribution of our work, in which a dynamic information-based dissemination protocol is proposed and applied on the communicating material framework.

In this current paper, the data importance level is processed. The item with a high level must be replicated more than the lower one. The dissemination protocol has to ensure the uniformity of replication for each level. Thus, a variant of hop-

counter storage approach is developed to disseminate data item in the material coupled with counter-based flooding.

The rest of the paper details the proposed data dissemination protocol, and then presents a simulation based analysis of the uniformity performances of the replication mechanism for different importance level of data item.

III. DATA DISSEMINATION PROTOCOL

This section presents the different strategies and algorithms of our data dissemination protocol. Firstly, the concept of master node is defined, then the counter-based forwarding scheme is described, and finally the non-localized and localized dissemination algorithms are presented.

A. Master Node

When the user has to disseminate information, he connects to the communicating material through a selected node in its transmission range which is named in this paper "master node". Master node is responsible for requests diffusion, collecting response messages from all nodes, and disseminating data items. Some constraint can be used for the master selection such as the highest residual energy level.

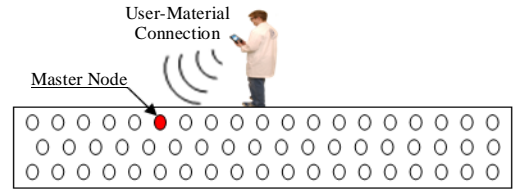


Fig. 4. Master node selection during the user-material connection.

B. Counter-based scheme

Our dissemination protocol adopts the counter-based forwarding scheme. When node receives a new packet, it fixes a random waiting delay before making the forwarding decision. During this delay, the sensor counts the number of retransmissions of the same packet by neighbor nodes. After the waiting delay has elapsed, the packet is only forwarded if the number of retransmissions is smaller than a predetermined threshold. As a result, the forwarding ratio depends on the nodes density, in low density areas this ratio will be high, whereas in high density areas it will be low. Different method could be used for threshold selection such as those described in [22] [23]. In [22], a node sets the value of the counter threshold according to the number of its neighbor nodes. Similarly, in [23], a node sets it according to the distance from the broadcasting node to itself. Authors in [24] show that a threshold between 4 to 6 retransmissions is preferable from the viewpoint of the trade-off between reliability and efficiency. As the communicating material has high density embedded sensor nodes (e.g. 100 nodes/m²), a threshold of 4 is used for the counter-based scheme of our dissemination algorithms.

C. Non-localized dissemination

This section presents an algorithm for disseminating data items in the entire material. To replicate data item, a counter "Hop" is defined which indicates the number of hops to do

before storing the data. The master node starts broadcasting the packet with a counter value according to the importance level of the information. Different functions can be used to determine the hop value using the importance as parameters. In this paper, a simple function is adopted which provide a counter value for each interval subset of importance level as shown in equation 1 (e.g. Hop=1 if $0.85 < \text{importance} \leq 0.9$).

$$\forall x \in [0,1], H(x) = \begin{cases} 0 & \text{if } 0.9 < x \leq 1 \\ 1 & \text{if } 0.85 < x \leq 0.9 \\ 2 & \text{if } 0.8 < x \leq 0.85 \\ \vdots & \\ 20 & \text{if } 0 \leq x \leq 0.1 \end{cases} \quad (1)$$

The packet is broadcasted from one node to all its neighbors, and at each hop the counter is decremented ($\text{Hop} \leftarrow \text{Hop} - 1$) until it reaches zero. In this case, the node must store the data, then resets Hop to its initial value (Initial_Hop), and rebroadcasts the packet within its neighborhood. This process continues until the edges of material are reached.

Our dissemination algorithm is broadcast based. With such communication model, the packet is further processed by nodes that have already received the same one. Furthermore, user can disseminate many segments or other data items. So, each packet is identified in the network layer (Packet ID) and then the nodes are limited to accept once the same message. If a node receives again a message with the same ID, it will be dropped. Figure 5 shows the flowchart of this process.

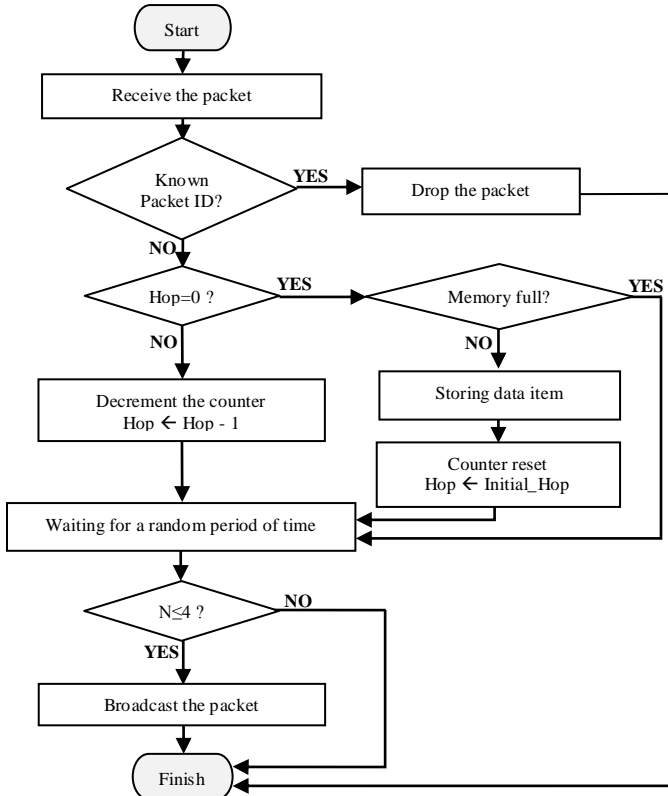


Fig. 5. Flowchart of non-localized data dissemination process.

D. Localized dissemination

This section aims to store the product life cycle information in limited area in the communicating material as shown in figure 6.

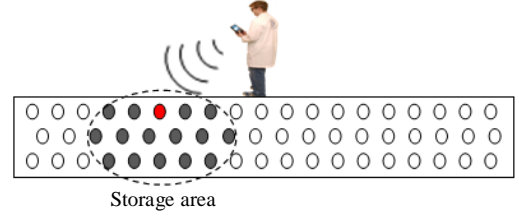


Fig. 6. Localized information storage in the communicating material.

For localized dissemination, the user sends the packet to a master node that is located in the target area with a Hop value according to the desired size (e.g. Hop=20 for large storage area). A node that receives the packet stores the information, decrements Hop ($\text{Hop} \leftarrow \text{Hop} - 1$), and rebroadcasts it to all its neighbors. This process continues until the end of the counter. The nodes that receive a packet with Hop=0, stores the data item and drop it. Figure 7 shows the flowchart of this process.

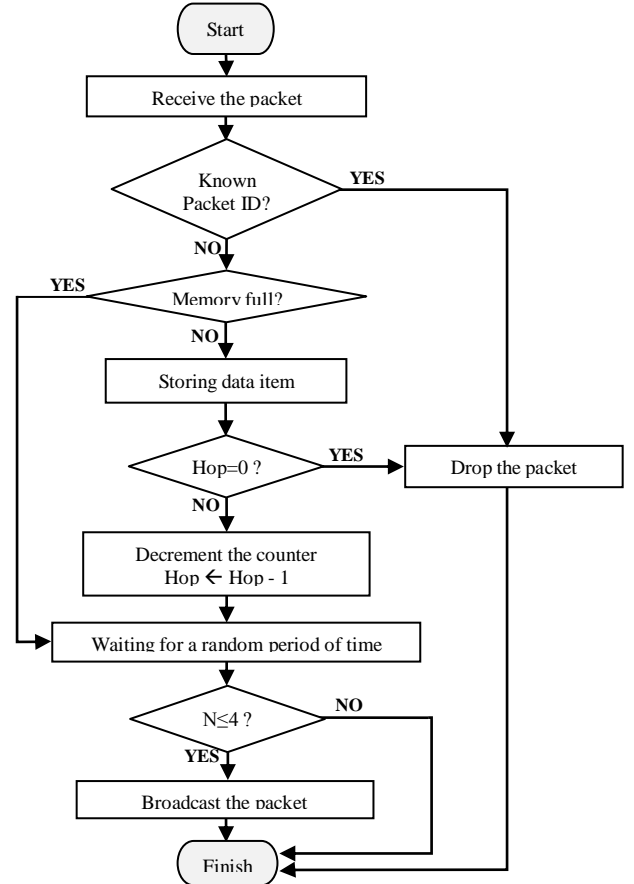


Fig. 7. Flowchart of localized data dissemination process.

IV. SIMULATION AND PERFORMANCE EVALUATION

In this section, the simulation setup is described firstly. Then, the simulation results are discussed.

A. Simulation setup

The performance of our solution is evaluated through simulation. Castalia/OMNET++ simulator is used to implement our dissemination algorithms. Currently, many wireless sensor network simulators are available as COOJA and TOSSIM but Castalia provides realistic wireless channel and radio models, and realistic node behavior especially relating to access of the radio [25]. In particular, Castalia has been configured to support communicating material application. A specific radio module is developed which is consistent with CC2420 components but allow more reduced transmission range. Thus, a thousand of scattered nodes in small material size could be simulated.

The simulated communicating material consists of 2500 nodes. The nodes positions are all uniformly distributed within a 5m x 5m square (100 nodes/m²) and the transmission power -90 dbm is used which ensures that only the adjacent nodes hear each other. The chosen simulation parameters are summarized in table 2.

TABLE II. SIMULATION PARAMETERS

Material size	5m x 5m
Number of nodes	2500
Nodes density	100 nodes/m ²
Nodes distribution	Grid 50x50
Location of master node	Center of the material
MAC layer	TMAC
Transmission power	-90 dbm
Radio	CC2420 (Frequency= 20 MHz, Modulation= PSK, Throughput= 250 kbps)
Radio Collision Model	Additive interference model

B. Simulation results

1) *Non-localized dissemination*: Figure 8 shows the simulation results of the broadcast and storage mechanism of not segmented data item for different hop counter.

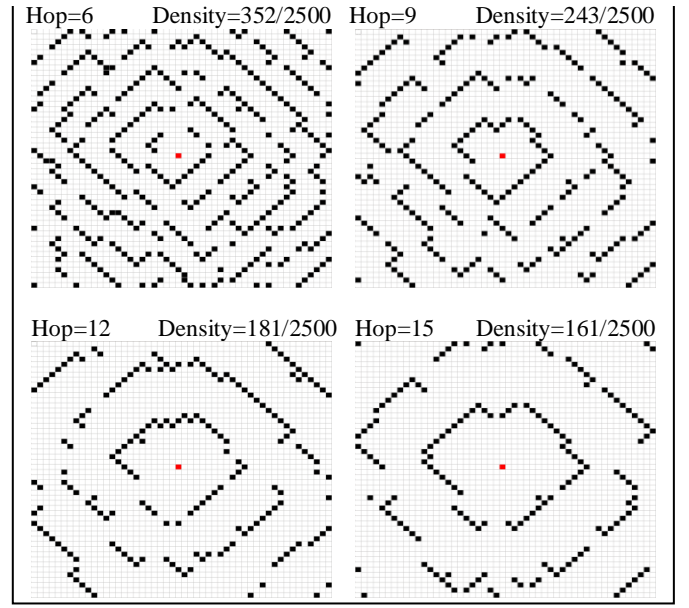
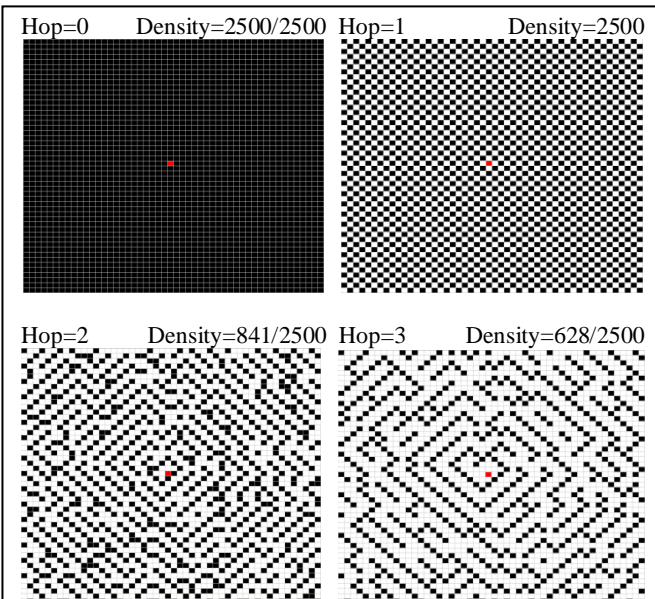
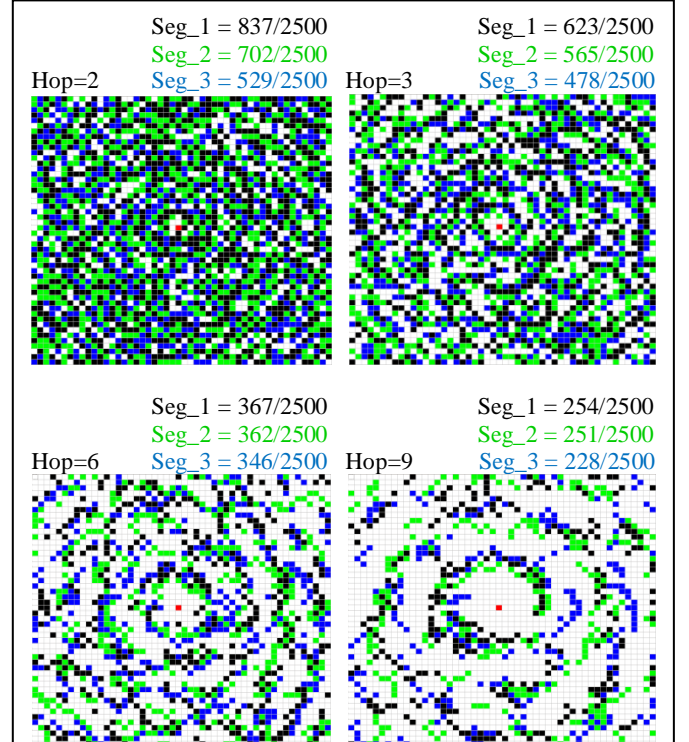


Fig. 8. Simulation results of not segmented data item.

Simulation results of the dissemination of segmented data item for different hop counter are shown in figure 9. Black, green, and blue colors present the nodes that have stored first, second, and third segments, respectively. The three segments are disseminated with the same counter value.



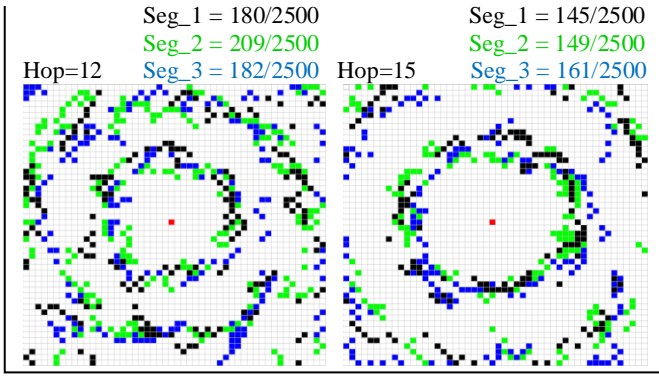


Fig. 9. Simulation results of segmented data item.

In figure 10, the dissemination results of two data items on the communicating material with different hop counter (different importance level) are presented.

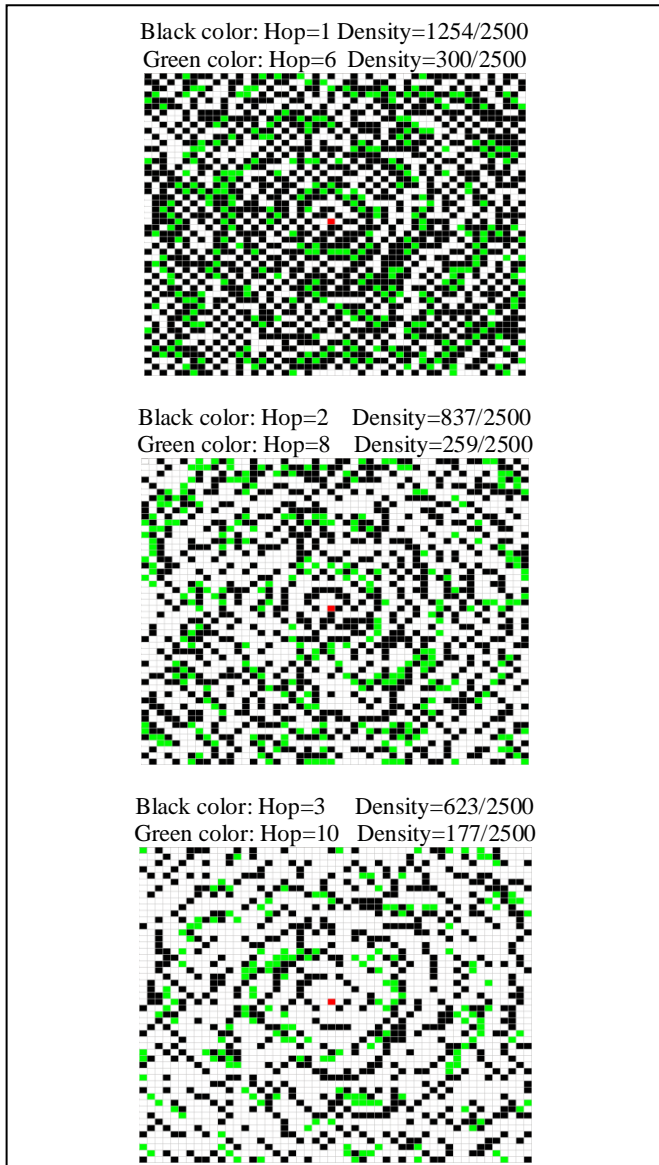


Fig. 10. Simulation results of two data items with different hop counter.

2) *Localized dissemination*: Figure 11 shows the simulation results of the broadcast and storage mechanisms of localized data item dissemination for different size of area in the communicating material.

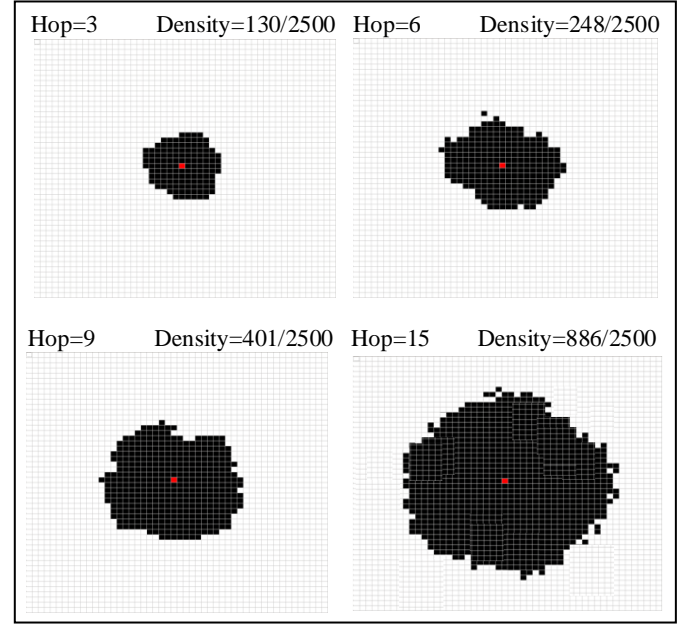


Fig. 11. Simulation results of localized data item dissemination.

C. Discussion and performance evaluation

The impacts of the hop counter variation on the uniformity performance of the proposed data dissemination algorithms have been investigated, through Castalia simulation. On the basis of the obtained results, the following observation can be carried out.

Figure 8 shows the high reliability of the counter-based flooding scheme as all nodes store the information for Hop=0. The information is uniformly replicated in the communicating material when a low counter value is used, for example Hop=1 and Hop=3 (critical data item). If the number is increased to relatively high values such as Hop=15, more large areas are obtained which are empty of data.

To study the uniformity performance, the simulated material is divided into small pieces of 50 cm x 50 cm as shown in figure 12. Each piece has 25 sensor nodes as uniform distribution (grid 50x50) is used. Then, the number of nodes that have stored the data item in each piece is counted.

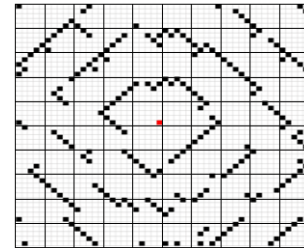


Fig. 12. Division of the material into pieces of 50 cm x 50 cm.

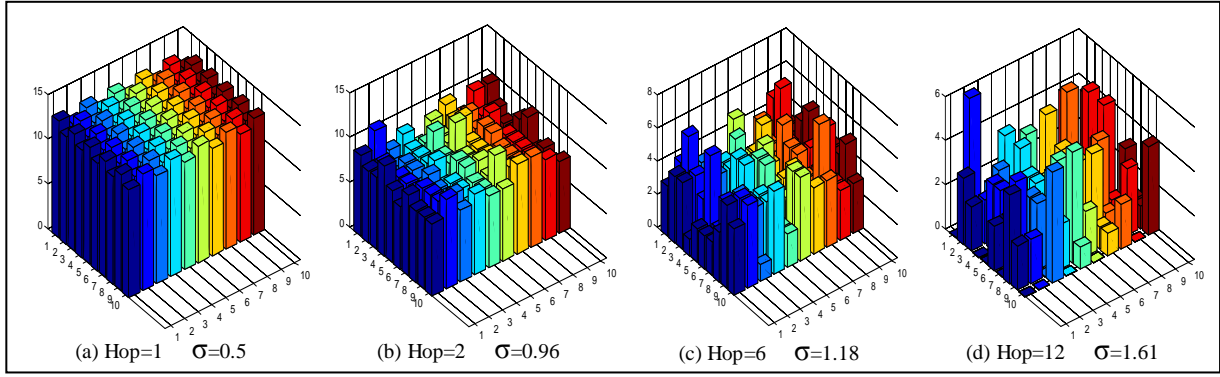


Fig. 13. Uniformity evaluation through Bar3 Matlab function.

Figure 13 shows the difference between the densities of storage of each piece for various hop counters. Figures 13(a) and 13(b) show that the uniformity of storage is the same throughout the material for a relatively small number of hops (i.e. standard deviation $\sigma < 1$). However, the uniformity decreases with large counter value. For hop=12 in figure 13(d) as example, there are pieces that have a high storage density, others are poorly filled and the rest of pieces are completely empty which could lead to data loss during material transformation.

Figure 9 shows that all the disseminated segments have the same density in the material as the proposed algorithm tries to make exactly the same replicas of all broadcasted packets. However such as the not segmented data item, if the number of hops is relatively increased, there are more empty area. Furthermore, if large size segments are used and then are disseminated with a low number of hops (e.g. Hop=0), the first broadcasted item will be stored in all available memories of nodes and prevent the rest of segments to be replicated.

For dissemination with two different importance levels, the data items are replicated according to their counter value as shown in figure 10. The item of the highest importance is more stored than other, which leads also to the deficiency problem of memory space.

A solution of these problems could rely on a dynamic self-organization of the data item storage, in which node autonomously decides to replicate or not. The replication process may adapt controlled storing approach as neighborhood negotiation to be aware if the data has already been stored by other nodes [19], or applying data compression techniques such as those described in [26] [27]. Compression algorithms are suited for reduced storage and limited resources of ultra-small nodes (e.g. in [26] compression ratios up to 70% on environmental datasets).

As for the proposed localized storage algorithm, it can be concluded that the simple hop-by-hop replication mechanism guarantees efficient data item storage by all nodes in the target area of the material. The storage area is increased according to the counter value as shown in figure 11, Hop=15 providing the largest one. However, there is no deterministic method to measure the area size. It depends on distribution, memories, and transmission range of sensor nodes.

V. CONCLUSION

In this paper, a data dissemination protocol is proposed to store information in communicating materials through scattered ultra-small wireless sensor nodes. A counter-based flooding approach and hop counter strategy are used to distribute the packets to whole network and to control the replication rate according to the importance level of the user information. A solution for localized data storage in a desired area of the material is also proposed. The performances of our solution are evaluated through computer simulation. Simulation results show that our algorithm provides uniform replication for limited number of hops. If a high counter value is used on the dissemination phase, more large empty areas are obtained which can lead to data loss during physical material transformation. However, simulation results show an efficient localized storage. Our future works will be focused on improving the uniformity of non-localized dissemination and data replication mechanisms in the communicating material for high importance levels of user information using probabilistic approach as storage strategy.

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