DCCORONA: Distributed Cluster-based Coordinate and Routing System for Nanonetworks

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***Abstract*—The miniaturization of devices at the nanoscale is expected to widely extend the Internet of Things (IoT) to the Internet of NanoThings (IoNT), opening the door to the emergence of several unprecedented applications in several fields (until now unimaginable). One of these applications, called Software-Defined Metamaterials (SDMs). SDMs enables the construction of unprecedented class of smart materials, which could change their electromagnetic behavior and could be reconfigured at runtime, utilizing embedded nanonetwork in their structure. Efficient energy-based data routing is a critical and challenging enabler of future SDMs applications, due to highly lossy conditions requiring a path redundancy, and the tiny storage capacity of nanodevices and inability to apply classical energy supply techniques. However, novel energy harvesting technologies have been proposed to replenish the energy supply of nanodevices, which could achieve an infinite lifetime, provided that the consumption processes and energy harvesting are jointly designed. The present study proposes a distributed cluster-based multi-hop point-to-point routing scheme for 2D dense homogeneous nanonetworks, targeting applications in SDMs. Extensive evaluation using nano-sim tool on NS-3 shows that the proposed scheme widely enhances the performances of the pioneering routing scheme proposed by Liaskos et al. in terms of energy efficiency and communication reliability.**

***Index Terms*—Terahertz band, nanonetwork, routing, energy harvesting, software-defined metamaterials, nano-sim**

I. Introduction

Recent advances in nanotechnology based on nanoscience knowledge have enabled the construction of a novel paradigm in a scale ranging from one to a few hundred nanometers, namely nanodevice [1]. The nanoscale's miniaturization is drawing broad interest from the scientific community because nanodevices have unprecedented functionalities and can detect and measure new types of events in the nanoscale [2]. Through communication, the nanodevices could accomplish more complex tasks by building nanonetworks, which in turn could interconnect with traditional communication networks via the Internet, thus defining a novel networking paradigm called the Internet of NanoThings (IoNT) [3]. One of the promising research direction that is envisioned to extend largely the applications of IoNT in the field of smart materials, is Software-Defined Metamaterials (SDMs) [4], [5]. Metamaterials are manufactured structures that seek to construct novel ElectroMagnetic (EM) objects with engineered and even unnatural functionalities (e.g., EM invisibility of objects, filtering and redirecting of sound and light, total absorption of radiation and so on [4], [5]). Despite their outstanding properties, metamaterials are specifically designed for a single application under preset conditions and cannot be reused. To overcome these limitations, Liaskos et al. proposed the concept of SDMs [4] that allows metamaterials to change their EM behavior at runtime, utilizing a network of nanocontrollers (sensors/actuators) embedded in their structure. In this study, we are interested in the point-to-point communication between the embedded nanocontrollers, which allows them to correlate and maintain the correct behavior of the SDMs [5].

The EM-based communication at Terahertz (THz) band (i.e., 0.1-10 THz) represents the most promising technique proposed for the data exchange between nanodevices. This band provides higher bandwidth and throughput, up to several Tb/s [6], [7], which can be used to design simple but efficient modulation and medium sharing schemes, such as Time Spreading On-Off Keying (TS-OOK) [8]. TS-OOK uses an EM pulse of duration Tp to transmit a bit of 1, and silence for a bit of 0, while the time between transmitting two consecutive bits is $Ts >> Tp$. Nevertheless, the THz band suffers from very high propagation loss, limiting the nanodevice communication range.

One of the open research issues in nanonetworks that is still in a very early stage is the design of point-to-point data routing schemes. In such networks, several unique challenges must be considered, making traditional schemes not directly suitable: i) a nanonetwork may contain thousands of nodes or even much more, implying a very low-cost architecture, as well as low hardware capabilities, ii) non-unique node address that requires synchronization and high packet exchange and iii) highly lossy conditions.

To the best of our knowledge, the present paper contributes the first distributed cluster-based multi-hop point-to-point routing scheme for 2D dense homogeneous nanonetworks. To date, all existing cluster-based routing schemes for nanonetworks aim to route data from nanodevices of the network to a specific nanodevice (data aggregation communication). Also, all these schemes target sparse heterogeneous nanonetworks that are composed of three types of nanodevices: nanonode, nanorouter and nanointerface [3], [9].

The proposed approach represents a lightweight routing scheme in terms of computing and storage requirement, as well as it aims to achieve energy efficiency by reducing the redundant retransmissions. Furthermore, the proposed routing scheme achieves a high successful packet delivery ratio, despite the expected frequent transmission failures and the network conditions that make node failures common, using reasonable path redundancy.

The remainder of this paper is organized as follows: Section II provides an overview of related works. Section III describes the proposed scheme. Section IV shows the simulation setup and assumptions and discusses the results. Finally, Conclusions are in Section V.

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II. Related Works

In the literature, there have been some proposals for designing flat and hierarchical routing schemes to allow nanodevices to communicate and achieve energy efficiency [10]. Liaskos et al. proposed an interesting flat point-to-point routing approach, Coordinate and Routing system for Nanonetworks (CORONA) [11]. Using CORONA, resource-constrained nanodevices can route data between the communicating node-pair with a stateless manner, i.e., without routing tables. Based on self-assigning geo-addresses, all nanodevices located between the communicating node-pair forward the received packets. In our prior work [12], we proposed three point-to-point routing schemes able to control and constrain the forwarding process of CORONA to achieve energy efficiency: $i)$ Energy-based probabilistic CORONA, the nanodevices located between the communicating node-pair forward the received packets according to an energy-based probability, $ii)$ Counter-based CORONA, this scheme proposed to avoid the die out problem of the previous approach by applying a counter-based mechanism, $iii)$ Hybrid CORONA, this scheme combines the two previous schemes to trade off between their pros and drawbacks. Liaskos et al. proposed another point-to-point routing deployed in a circular area, Deployable Routing System for Nanonetworks (DEROUS) [13]. In this scheme, a nanodevice is classified as forwarder or user depending on its packet reception statistics, where only forwarders are allowed to forward packets. However, all existing hierarchical approaches focused on data aggregation communication in Body Area NanoNetwork (BANN) applications [9], [14]–[16]. These networks are sparse, and due to their small size, the nanodevices are assumed to have unique identifiers. Furthermore, BANN-based works assume a set of relatively large powerful nanorouters control the resource-constrained nanodevices. Consequently, these schemes are too excessive for the smart material applications targeted by the present study. Due to the presence of such large nanodevices that could alter the structure and properties of a monitored material and also such applications require dense networks, thus low hardware capabilities and non-unique addressing [5].

III. Proposed Cluster-based Routing Scheme

This section presents the proposed self-addressing point-to-point distributed cluster-based multi-hop routing scheme for dense homogeneous nanonetworks. Generally, all existing cluster-based routing schemes in traditional networks or nanonetworks have the same main phases: $i)$ cluster establishment and $ii)$ cluster maintenance. However, the series of basic steps involved in such phases vary according to the conceptual rules of each scheme. Our scheme's steps are ordered and described as follows:

A. Self-addressing and Clusters Construction

As mentioned above, assigning a unique address for each node in such dense and constrained-resources networks is not a trivial process. Liaskos et al. proposed a lightweight computational and less overhead control packets system allowing self-assigning address [11]. In their work, after broadcasting four control packets, each nanodevice sets locally its not unique geo-address. Accordingly, the proposed approach constructs the clusters based on this observation, where nanodevices that share the same geo-address are affiliated to the same cluster. As illustrated in Fig. 2, the self-assigning system operates on a large set of nanodevices, which are uniformly deployed over a rectangular area with a layout that may be grid or random. The four nanodevices placed at the four vertices of this area have a clockwise or counter-clockwise order, so-called anchors. According to this order, the involved steps are done as follows:

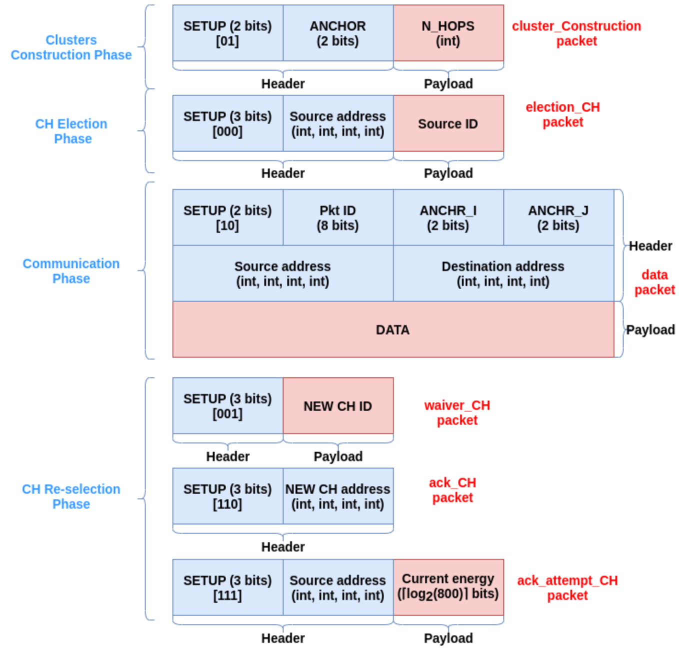

Fig. 1. Structure of all packets used in the proposed scheme.

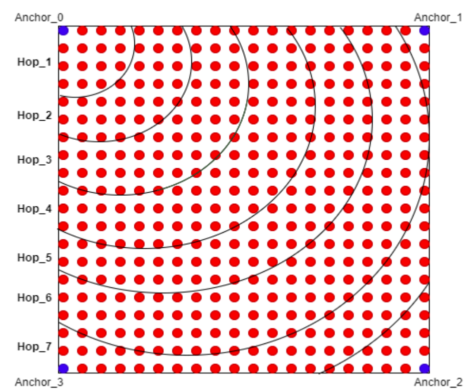

Fig. 2. Illustration of the self-assigning addresses.

1) Each anchor sequentially, after a safe time-out generates a $cluster\_Construction$ packet (see Fig. 1) by setting the ANCHOR field to its index and the N_HOPS field to 1, and then broadcasts it.
2) Upon reception of a packet, each node X realizes via the $SETUPflag$ that the given packet is for the self-assigning address purpose. Consequently, this node sets its hop-count distance to the given $anchor_i$ (X_i) to the minimum N_HOPS value over the incoming packets.
3) Then, node X increments the N_HOPS field's value and forwards the packet. As shown in Fig. 2, the arcs represent the hop-count distance between each nanodevice and the $anchor_0$.

At the end, each node knows its address that is composed of four attributes; each one corresponds to the hop-count distance between this node and one of the four anchors. Nodes located in the same area share the same address; thus, they are affiliated to the same cluster (see Fig. 3). The number of nodes located in the same area depends on $i)$ the nanodevice transmission power and $ii)$ the network layout.

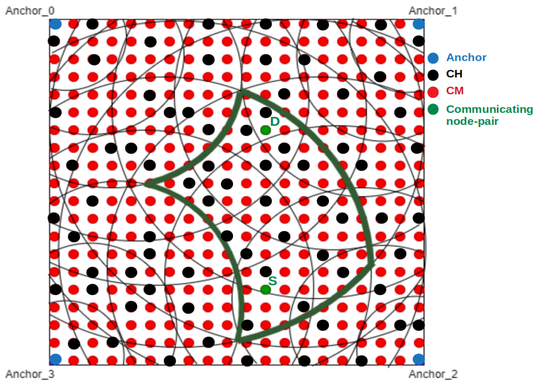

Fig. 3. Illustration of the node affiliation and routing process.

B. Cluster Head Election

At the end of the self-assigning address and the self-cluster affiliation, and since we are still in the network construction phase, all nanodevices have fully charged batteries. Therefore, the election of the cluster head (CH) for each cluster in the first cycle is based on a randomly generated ID, where the nanodevice that generated the largest ID in the cluster is elected as CH. The involved steps of the CH election process are done as follows:

1) Each nanodevice generates a random value (ID).
2) Each node generates and broadcasts an $election\_CH$ packet (see Fig. 1) after a random time-out.
3) Upon reception of an $election\_CH$ packet, the receiving node applies the Algorithm 1.

Algorithm 1: Cluster Head Election

```
Input: MyAdr, MyID /* the node's address and ID,
    respectively                                    */
Output: CH, SuccNode /* the node's state and the ID of its
    successor in a virtual circle, respectively     */
Local: CH, SuccNode
/* Initialisation                                   */
CH ← true;
SuccNode ← -1;
/* Election                                         */
Upon receiving election_CH do
begin
    if election_CH.SrcAdr == MyAdr then
        if MyID < election_CH.SrcID then
            CH ← false;
            if SuccNode > election_CH.SrcID or SuccNode < MyID then
                SuccNode ← election_CH.SrcID;
            end
        else if CH == true then
            if SuccNode > election_CH.SrcID then
                SuccNode ← election_CH.SrcID;
            end
        end
    end
end
```

At the end of this process, for each cluster:

1) A cluster head has been elected for the first election cycle.
2) Each nanodevice knows its state (Cluster Head (CH) or Cluster Member (CM)) for the first cycle.
3) The nanodevices (CH and CMs) are arranged in a virtual circle.
4) Each CM knows its successor in that circle, which is the nanodevice that generated the smallest ID greater than its ID. While CH's successor is the nanodevice that generated the smallest ID.

C. Routing Process

On top of the addressing mentioned above, the proposed scheme allows to route packets from the source node S with coordinates (S_1, S_2, S_3, S_4) to the destination node D with coordinates (D_1, D_2, D_3, D_4), without the need of using routing tables. It is done using only the information incorporated in the packet and node-local information. As mentioned in [11], in a 2D rectangular area, two anchors distances are sufficient to accurately located each node in this area. Accordingly, before to broadcast a data packet (see Fig. 1), the node S chooses the two anchors ($ANCHOR\_I$ and $ANCHOR\_J$), that minimize the distance to node D, given by [11]:

$$(ANCHOR\_I, ANCHOR\_J) = \{(I, J) \\ / \; min(|S_I - D_I|), min(|S_J - D_J|), J = (I + 1)\%4\} \quad (1)$$

Upon receiving a data packet at each neighbor nanodevice, the packet is checked whether it has been treated to avoid route loops. A treated packet is a packet that has already been forwarded or discarded from this nanodevice. If this packet has never been treated, each nanodevice forwards this packet according to its state, as summarized in Fig. 4. Otherwise, the packet is simply discarded.
Each CH:

1) Checks whether it is located between the communicating node-pair using the following criterion (i.e., all CHs located in the green arc-shaped area in Fig. 3):

$$(CH_I \in [S_I, D_I]) \, and \, (CH_J \in [S_J, D_J]) \quad (2)$$

2) If it is the case, it simply forwards the received packet. Otherwise, the packet is discarded.

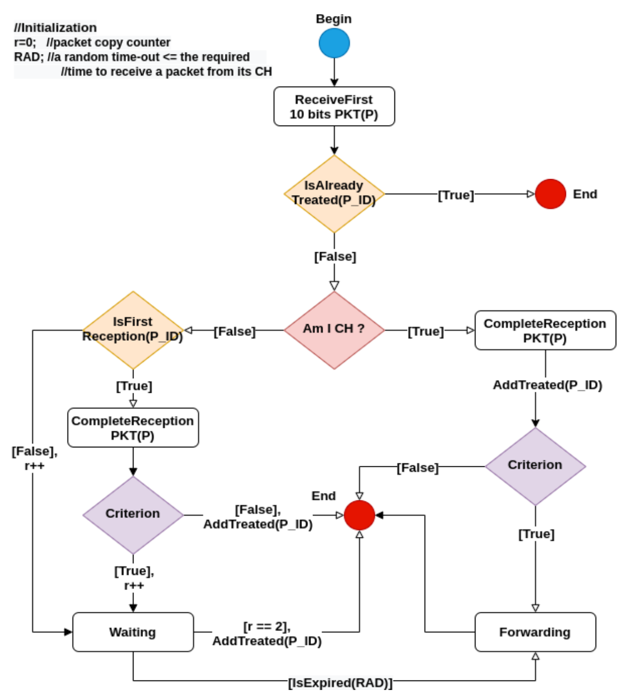

Fig. 4. Block scheme of the proposed routing scheme.

Relying only on CHs to forward packets, significantly reducing redundant retransmissions. However, it offers no guarantee that the network connectivity is satisfied, i.e., every two CHs affiliated to two neighbor clusters can communicate directly. To avoid this drawback, so-called the die out problem [17], the CMs located between the communicating node-pair participate in the forwarding process by applying a counter-based forwarding mechanism. Thus, each CM decides whether to forward a packet or not by counting the number of this packets copies received during a random delay (RAD). If the RAD expires and the given CM does not receive the intended redundant copies (R) of the packet, the CM forwards it. Otherwise, this packet is discarded. We choose R = 2 to assure the minimum number of forwarding in a cluster, by supposing that the first copy of a packet is from a neighbor cluster, while the second copy is from the given cluster. Since nanodevices are equipped with restricted memories and the communication delay is an important metric in SDM applications, the proposed scheme offers a trade-off between these challenges by exploiting the peculiarities of the used modulation technique, TS-OOK; a packet is received bit by bit. Accordingly, without the need to wait receiving all the packet, CM needs to receive only the first 10 bits of each packet ($SETUP$ and Pkt_ID fields), to verify if this is the first reception of this packet. If it is not the case, the corresponding counter copy (r) of this packet is incremented.

D. Maintenance Phase

A cluster heads re-selection phase is needed, to give current CHs more time for harvesting energy, and to avoid temporary loss of network connectivity. As Algorithm 1 organizes each cluster's nanodevices in a virtual circle and each nanodevice knows its successor, the current CH for each cluster selects the next CH in a round-robin manner. As summarized in Fig. 5, the involved steps, according to the nanodevice state, are done as follows:

For each CH:

1) After each communication process, CH checks whether it has enough energy for future communication.
2) If it is not the case, CH broadcasts a $waiver\_CH$ packet (see Fig. 1) containing the ID of its successor.
3) Upon reception of an ack_CH or $ack\_attempt\_CH$ packet (see Fig. 1), this CH changes its state from CH to CM.

For each next CH (current CH's successor):

1) Upon reception of a $waiver\_CH$ packet, CM deduces that it is likely the next CH since the embedded ID is its own.
2) If this CM has enough energy for future communication, it replies by broadcasting an ack_CH packet, as well as it changes its state from CM to CH. Otherwise, it does nothing.

For each other CM:

1) Upon reception of a $waiver\_CH$ packet, CM deduces that it is not the next CH.
2) CM waits for a random time-out before attempting to be the next CH by broadcasting an $ack\_attempt\_CH$ packet containing its current energy level.
3) If this CM receives an ack_CH or $ack\_attempt\_CH$ packet that contains an energy level greater than its energy level, this CM cancels the attempt to be the CH for the next cycle.

IV. Performance Evaluation

In this section, through extensive simulations on the nano-sim tool [18], we evaluate the routing efficiency of the proposed routing scheme, compared to CORONA routing scheme [11] and our prior proposed routing schemes [12]. In Section IV-A, we present the evaluating metrics, while in Section IV-B, we show the simulation setup and assumptions. Finally, in Section IV-C, we discuss the obtained results.

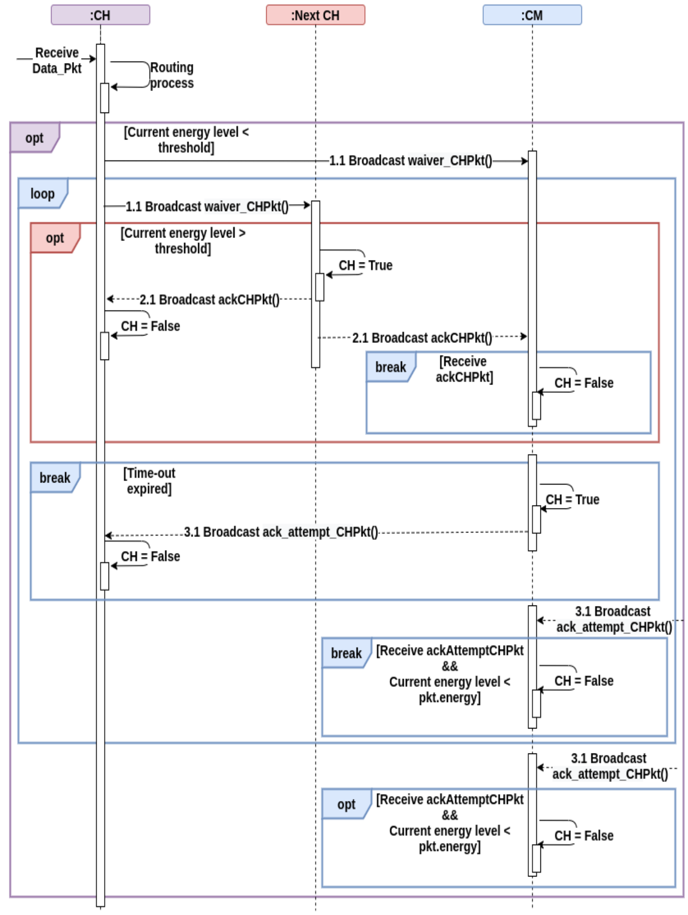

Fig. 5. Sequence diagram of the cluster head re-selection phase.

A. Evaluating Metrics

In this study, we use the same evaluation metrics used in [12]: Packet Delivery Ratio (PDR), Average Ratio of Forwarders (ARF) and Average Residual Energy (ARE). We compute the Average End-to-End Delay (AE2ED) using Equation 3.

$$AE2ED = \frac{\sum dt_i}{NbrPkt} \tag{3}$$

where i and $NbrPkt$ are the IDs of packets successfully delivered to the destination nodes by all compared routing schemes and the total number of these packets, respectively. While dt_i is the time required to route each packet i from the source to the destination.

B. Simulation Setup and Assumptions

Since the present study targets applications in SDMs, we simulate the embedded nanocontrollers by 1600 identical energy harvesting nanonodes deployed uniformly within a 2D rectangular grid. The spacing X between nanonodes varies according to the corresponding performance scenario. The energy is harvested from air-vibrations, which can be accurately modeled as an exponential process, with the vibration frequency set to 50 Hz [19]. The maximum storage capacity of a nanonode is set to 800 pJ, while for communication range is set to 1 cm, the energy consumed in transmitting and receiving a TS-OOK pulse are set to 1 pJ and 0.1 pJ, receptively [19]. The summary of the nanonetwork settings and communication-related parameters are summarized in Table 2, based on the highlighted results found in [20]. It worth noting that each value in Figures 6-9, represents

TABLE I
SIMULATION PARAMETERS.

Parameter	Value
Frequency	0.1 THz
Pulse duration	100 fs
β: TS-OOK time spread ratio	100
SNR	-100 dBm
Communicating range	1 cm
Nanonetwork size	1600 (40x40)
t_{cycle}: harvesting cycle time	20 ms
Packet payload size	100 $bits$
Scenario 1	
Packet inter-arrival time (ms)	50, 100, 150, 200, 250, 300, 350
X: spacing (cm)	0.125
Scenario 2	
Packet inter-arrival time (ms)	300
X: spacing (cm)	0.166, 0.142, 0.125, 0.111, 0.1

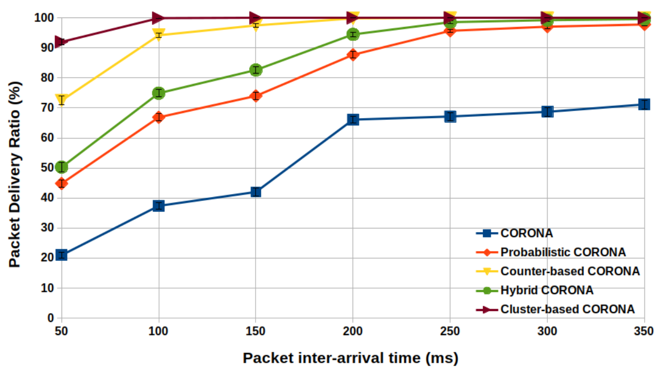

Fig. 6. PDR of the compared schemes, versus the packet inter-arrival time.

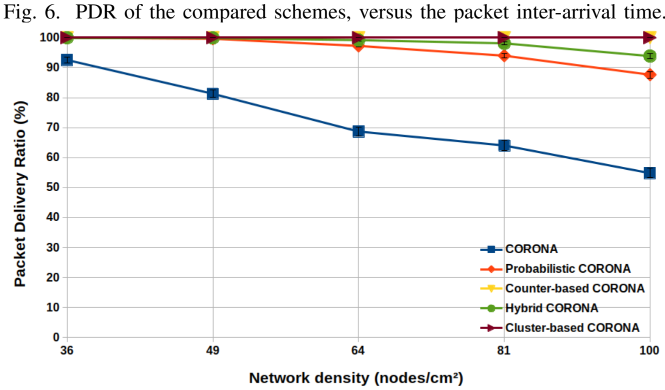

Fig. 7. PDR of the compared schemes, versus the nanonetwork density.

the average value of 50 values obtained by repeating simulation run 50 times. In each simulation, 100 packets are generated, with an inter-arrival time that depends on the corresponding performance scenario. The communicating node-pair are selected randomly. The error bars indicate the 95% confidence intervals which indicates that the obtained results are credible.

C. Results and Analysis

1) Packet Delivery Ratio: The packet delivery ratio is presented over increasing the packet inter-arrival time and the nanonetwork density in Fig. 6 and Fig. 7, respectively. Fig. 6 shows that the

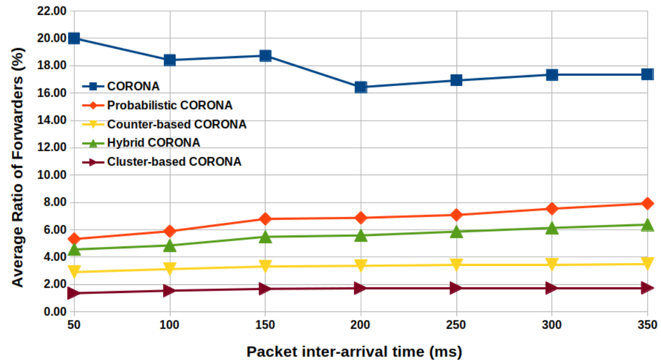

Fig. 8. ARF of the compared schemes, versus the packet inter-arrival time.

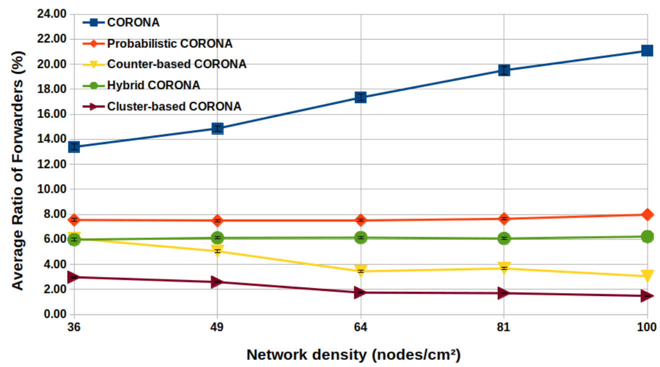

Fig. 9. ARF of the compared schemes, versus the nanonetwork density.

time taken between generating two consecutive packets positively affects the PDR of existing routing schemes. The increasing of packet inter-arrival time leads to increasing the packet delivery ratio performance for each scheme. This is expected because the long time between generating two consecutive packets gives nanodevices ample time to harvest energy, numerous nanodevices are available, which increases the probability of successful delivery of the following packet. In contrast, thanks to the used routing strategy, where only a specific set of nanodevices are involved in the forwarding process, the proposed scheme can deal with the shortage of energy resources and offers the highest PDR. Fig. 7 shows that the increase of the nanonetwork density does not affect the proposed scheme's packet delivery ratio performance. In contrast, the performances of existing routing schemes, especially CORONA routing scheme, are negatively affected. The higher the nanonetwork density, the more likely collisions and faster packet queue overflow, leading to reduce successfully PDR.

2) Average Ratio of Forwarders: We studied the average ratio of forwarders in two cases: $i)$ increasing the packet inter-arrival time from 50 to 350 ms and $ii)$ varying the nanonetwork density from 36 nodes to 100 nodes per cm^2. Fig. 8 shows that the proposed scheme has the best performance and it keeps the same participation rate of nodes in the retransmission process even when the packet inter-arrival time increases. Only CHs and some CMs between communicating nodes are involved. By contrast, CORONA routing scheme shows the worst performance, where the nodes' participation rate in the retransmission process increases as packet inter-arrival time increases. The longer packet inter-arrival time, the more time is available for the nodes to replenish their energy, i.e., a high number of nodes may have enough energy to forward packets, leading to a high number of

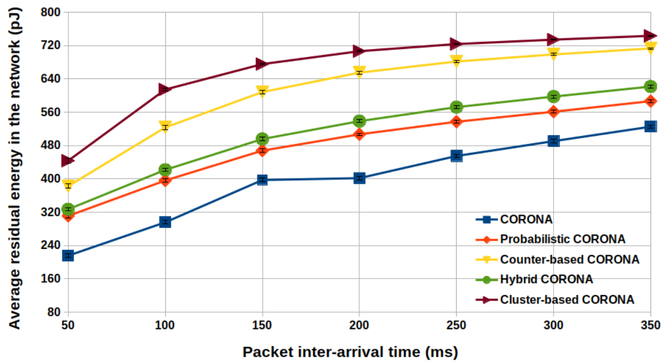

Fig. 10. ARE of the compared schemes, versus the packet inter-arrival time.

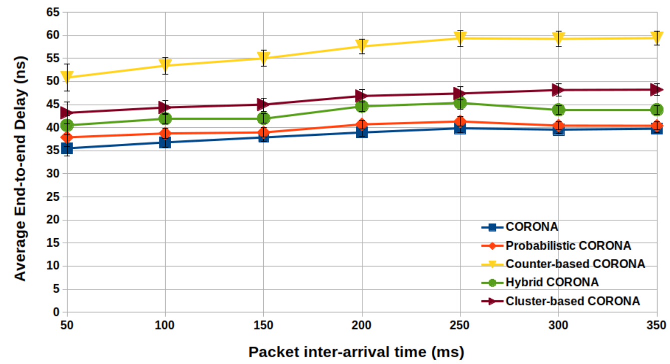

Fig. 12. AE2ED of the compared schemes, versus the packet inter-arrival time.

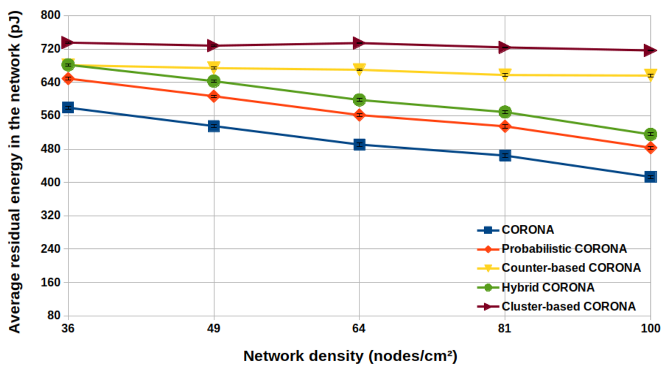

Fig. 11. ARE of the compared schemes, versus the nanonetwork density.

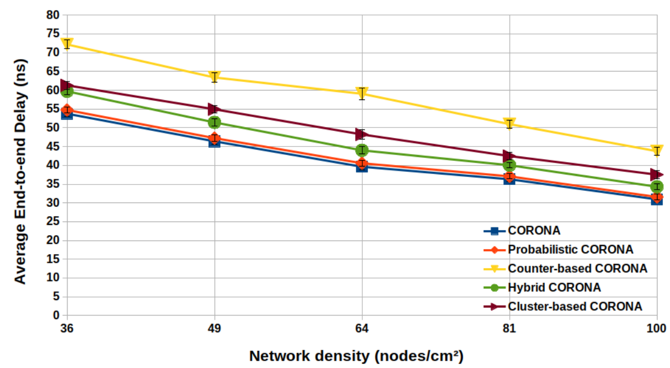

Fig. 13. AE2ED of the compared schemes, versus the nanonetwork density.

nodes participating in the retransmission process since the CORONA scheme allows all nodes that have enough energy and located within the communicating nodes to forward. Fig. 9 shows that for the proposed scheme, the increase of the nanonetworks density leads to the decrease of the participating nodes in the retransmission process. It is due to the size of clusters which increases and the number of clusters decreases, while only the CHs with a certain set of CMs located between the communicating node-pair are allowed to forward. However, since CORONA routing scheme suffers from the increase of collisions due to the increasing nanonetwork density as shown in Fig. 7, thus in high nanonetwork density, CORONA requires high redundant packet transmissions to successfully deliver packets.

3) Average Residual Energy: We studied the average residual energy in the nanonetwork in two cases: i) increasing the packet inter-arrival time from 50 to 350 ms and ii) varying the nanonetwork density from 36 nodes to 100 nodes per cm^2. Fig.10 shows that the residual energy in the whole nanonetwork is proportional to the time between generating two consecutive packets. As a long packet inter-arrival time gives nanodevices more time to harvest energy and vice versa. It can be seen that the proposed scheme keeps the highest residual energy, due to the constrained rate of participating nodes in the retransmission process, as shown in Fig. 8. In Fig. 11, it can be observed that the proposed scheme offers the best performance and its performance is not affected by the increase of the nanonetworks density. Because regardless of the nanonetwork density, the proposed scheme keeps the same participating rate of nodes in the retransmission process, as shown in Fig. 9.

4) Average End-to-End Delay: We studied the average end-to-end delay of packets that are successfully delivered by all compared schemes in two cases: i) increasing the packet inter-arrival time from 50 to 350 ms and ii) varying the nanonetwork density from 36 nodes to 100 nodes per cm^2. Fig. 12 shows that for all schemes the increase of packet inter-arrival time leads to a slight increase in this metric. Because as shown in Fig. 6, the increase of packet inter-arrival time, allows to successfully deliver new packets. Where the latter have relatively long delays since they are routed through long paths. CORONA routing scheme shows the best performance, due to its redundant path mechanism, where each node within the communicating nodes directly forwards the received packet, thus the shortest path could be among these paths. By contrast, the proposed routing scheme has a longer delay than CORONA's delay, because there is no constraint in terms of delay on the selection of nodes which can forward the packet. Thus, there is no guarantee in this scheme for the packets to be forwarded over the shortest path. Fig. 13 shows that when the nanonetwork density increases the average end-to-end delay decreases (for all considered schemes).This makes sense because the increase of nanonetwork density reduces the hop-count distance between communicating nodes, thus limiting the length of paths traversed by each packet from the source node to the destination node.

V. Conclusion

In this paper, we proposed an energy-based distributed cluster-based routing scheme for 2D dense homogeneous nanonetworks. We compared its performance to four other approaches (CORONA, Probabilistic CORONA, Counter-based CORONA and hybrid CORONA) with respect to the following four metrics: Packet Delivery Ratio (PDR), Average Ratio of Forwarders (ARF), Average Residual Energy (ARE), and Average End-to-End Delay (AE2ED). For each metric we considered two scenarios: i) the packet inter-arrival time varied from 50 to 350 ms and $ii)$ the number of nodes in the network is varied from 36 nodes to 100 nodes per cm^2. The simulation results show that the performance of the proposed scheme is not affected when the nanonetwork density increases which means that this scheme is scalable. By contrast, the other four schemes' performance is negatively affected when the nanonetwork density increases. By comparison to the best state-of-the-art approach (Counter-based CORONA), the proposed scheme improves the ARF, ARE, and AE2ED by 50.89%, 8.21% and 15.55%, respectively. Moreover, although the energy shortage, the proposed scheme improves the PDR, ARF, ARE, and AE2ED by 4.23%, 47.69%, 8.64% and 18.07%, respectively, when compared to Counter-based CORONA.

In order to further improve the latency, we plan to enhance the selection process of forwarders (CHs and CMs) by incorporating delay constraints and packet direction prediction. Therefore only nodes located on the straight path connecting a communicating node-pair are involved in the forwarding process. Furthermore, we intend to propose a simulator that could simulate the pulse-based communication in the THz band, to apply the duty cycle mechanism on the proposed scheme by exploiting the peculiarities of TS-OOK, as current nano-sim simulator does not support this feature.

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