

Dynamic ring-based forwarder selection to improve packet delivery in ultra-dense nanonetworks

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ABSTRACT

Nanotechnology is a revolutionary field of science and the design of nanometer-sized devices opens the door to a wide range of novel applications. Electromagnetic nanonetworks are networks of nanodevices communicating in the terahertz band. Nanonetworks can be ultra-dense, which makes the multi-hop communications inefficient, as a large number of forwarders are selected among nanonodes by most routing protocols. A large number of forwarders induce high traffic of exchanged packets in the network and thus lead to congestion. Forwarding data packets also consumes energy, whereas nanonodes are resource-constrained, which shortens the network lifetime. Therefore, we previously proposed to select forwarders in a ring close to the communication edge of each transmitter. The ring applies on top of existing routing protocols, optimizing them. However, the proposed ring had a fixed width, which was manually set and did not adapt to the local density, an important parameter in heterogeneous networks. In the current article we solve this problem by automatically selecting the ring width based on the local node density. Extensive simulations of our scheme applied to four routing protocols, using a dense nanonetwork simulator, show a dynamic ring that drastically reduces the number of forwarders used for transmission in the network, without sacrificing the packet delivery ratio and thus optimizing the network usage.

KEYWORDS

Routing, Congestion, Nanonetwork, Dense network, Scalability

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1 INTRODUCTION

Nanotechnology permits the design of integrated devices at the nanoscale and inspires novel applications that can connect to the Internet of Nano-Things (IoNT). The communications among nanodevices can be electromagnetic, molecular, acoustic or mechanical nanocommunications. This article focuses on electromagnetic nanonetworks, where nanonodes can radiate signals in the terahertz band (0.1–10 THz) using graphene antennas [9].

Electromagnetic nanonetworks are used in various fields. Applications in nanomedicine include health monitoring systems and Drug Delivery Systems (DDS). Health systems use nanosensors for monitoring different concentration levels of molecules in the blood and for detection of infectious intra-body agents. DDS use nanoactuators for delivering nanoparticles and drugs into the body [8]. Another application is Software-Defined Metamaterials (SDMs), where nanonetworks and metamaterials (artificial structures with un-natural properties) are combined, allowing the user to send commands to nanodevices to perform geometrically-altering actions on the metamaterial and tuning of its electromagnetic behavior [13]. Other applications include wireless robotic materials, industry, military and agriculture.

Nanonetworks are different than traditional networks, albeit sharing some characteristics with wireless sensor networks (WSN). First of all, a nanodevice has hardware limitations in its components: transceiver, memory, processor, power unit etc., and as such has a very small communication range and needs to execute very simple protocols (no matrix multiplication or long lists of neighbours to check for example). Also, because of energy scarcity, nanonodes cannot use carrier signals like traditional networks; a lightweight modulation was proposed, Time Spread On-Off Keying (TS-OOK), where bit 1 is sent as a 100 femtosecond-long ($= T_p$) pulse with energy, and bit 0 is defined as a silence without energy consumption [10]. On top of that, nanonetworks can be much denser than WSNs, e.g. thousands of nodes. This makes traditional routing schemes for WSNs not directly applicable in nanonetworks, for example Ad-hoc On-Demand Distance Vector Routing (AODV) has

been modified into a hierarchical version to make it efficient in nanonetworks [19]. To conclude, it is necessary to design new light-weight and highly scalable forwarding and routing protocols, with successful packet delivery and lower overhead.

In this context, we consider the following problem. A source node sends a message to all other network nodes (flooding) or to one destination node in a nanonetwork in a multi-hop fashion. In a dense network this generates an avalanche of forwarders, leading to collisions, congestion, useless energy consumption. We look for methods to reduce the number of forwarding nodes, while still achieving a successful message delivery to the intended destination(s).

To solve this problem, we previously proposed a ring-based forwarder selection in ultra-dense networks through an algorithm implemented above routing schemes [7]. This algorithm improves the routing by making it select the forwarders among ring neighbours only, and not among all neighbours. This is done by limiting the forwarding area to a ring at the border of the communication range, using two control packets sent to different communication ranges only once, right before the very first transmitted data packet. Note that there is no GPS-like module in nanonodes allowing them to compute distances between two nodes.

However, the limitation of the proposed ring is that it is static and manually set. A static ring width contains more forwarders in a dense environment compared to a non-dense environment. A large number of forwarders lead to congestion, while a small number of forwarders cause packet loss.

To overcome this limitation, we hereby propose an efficient extension of the ring-based forwarder selection. This scheme, *dynamic ring*, dynamically adapts the ring width to the local density. We evaluate it and show that it improves the routing by better selecting the forwarding nodes and by reducing their number while keeping a successful packet delivery.

The article is organised as follows: Section 2 presents the related work. Section 3 discusses the dynamic ring scheme. Section 4 evaluates the dynamic ring using extensive simulations. Section 5 draws some conclusions.

2 RELATED WORK

The routing schemes applicable to nanonetworks need to be simple, because constrained nanodevices cannot memorize nor process routing tables, neighbouring information or network knowledge. In this section we present some schemes aiming to reduce the number of forwarders, for a detailed view the reader is directed to [22].

2.1 Flooding schemes

In pure flooding, every node in the network forwards the data packet that it receives for the first time. This flooding is not scalable and results in redundant transmissions and broadcast storms in dense environments. In probabilistic flooding [17], nodes forward packets with a static probability and discard it otherwise. The probability should be carefully chosen depending on the scenario, in order to guarantee the message delivery with a minimal number of forwarders.

Backoff flooding [2] is a highly efficient flooding scheme, where the number of forwarders is notably reduced. Only nodes receiving

few copies of data packets (less than redundancy r) forward the packet. The count of data copies is done in a time window proportional to the number of neighbours, estimated using the node density estimator DEDeN [1].

In LSDD [3], nodes classify themselves as forwarders or non-forwarders (passive auditors) using packet-receive statistics (including success or failure on packet reception and integrity checks).

2.2 Unicast (or merely zone-cast) schemes

In RADAR routing [15], the nanonetwork is a circular area and a central entity emits radiation at an angle. Nanonodes found inside the angle of radiation are in the ON state, and all the other nodes are in the OFF state. RADAR consists in blind flooding inside the angle of radiation only. Nevertheless, a large angle can still cause a broadcast storm, and the destination node must be in ON state to receive the packet.

DEROUS [12] establishes a point-to-point communication in circular and radial paths. In the setup phase, a beacon node set at the center of a 2D circular area sends a packet, and nanonodes self classify as infrastructure (always retransmit) or user (never retransmit) using packet reception quality. During the routing, nanonodes that are between the source and destination become forwarders to finally form a circular or radial routing path. Thus, DEROUS limits the retransmissions to a circle area.

In CORONA routing [21], the network is a 2D rectangular area with *uniformly* distributed nanonodes and four anchor nodes placed at each corner. During the setup phase, anchors transmit their packets in sequence, allowing nanonodes to set their coordinates as hop counts from the anchors. During the routing phase, only nanonodes that are in a *rhombus area* between source and destination nodes forward the packet. Stateless Linear-path Routing (SLR) [20] extends CORONA to a 3D cubic space, and selects as forwarders only the nodes that are on a *line* between the source-destination pair.

All these protocols may benefit from further enhancements by limiting the number of forwarders at the MAC-level while still maintaining packet delivery to the destination(s). For this, we previously proposed the ring that is presented in the following.

2.3 Basic ring as a forwarder selection scheme

The basic ring-based forwarder selection algorithm [7] focuses on limiting the area of forwarding to the ring near the border of the communication range, as shown in Fig. 1. A node requires three conditions to be a forwarder: it has received the data packet for the first time, it is on the ring, and it is selected as forwarder by the routing protocol (on top of which the ring is implemented). Therefore, it is not the whole ring that transmits but only the forwarders that confirm the previous conditions.

The ring is bounded by two communication ranges corresponding to two control packets sent at different transmit powers. These two control packets are sent *only once*, before the first data packet to be forwarded by a node. Control packets may be retransmitted if the network topology changes. Nodes that receive the high power control packet and do not receive the low power control packet are considered to be on the ring and become candidate forwarders.

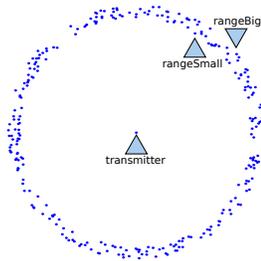


Figure 1: Basic ring algorithm: the transmitter is at the center of the communication range and only nodes in the ring area between *rangeBig* and *rangeSmall* are potential forwarders.

The only assumption made in this scheme is that a nanonode can send packets at different transmit powers.

This scheme is similar to greedy forwarding schemes [5, 11] using distance-from-neighbours metric, which is unavailable in our (resource-constrained) dense nanonetwork context.

3 DYNAMIC RING SCHEME

This paper proposes an enhancement of the ring algorithm, called the *dynamic ring*, which makes nodes configure the ring width automatically, based on a desired number of local ring neighbours and the local density. It is presented in the following.

The basic ring algorithm uses a static ring width for all forwarding nodes in the network, with the region of the ring lying between two ranges: *rangeBig* and *rangeSmall*. The dynamic ring scheme aims to *automatically* set the ring width for every forwarder. In the new scheme, *rangeBig* is kept fixed and equal to the communication range to make the forwarding progress faster, while *rangeSmall* varies and makes the ring thinner or thicker. The challenge is to find the appropriate *rangeSmall* value. This value is inferred from the desired number of ring neighbours per hop, denoted by N .

Finding the *optimal* number of 1-hop neighbours is an NP complete problem. A recent research [14] finds the distributed minimum of multipoint relays (MPRs) selection in dense mesh networks. However, the network is not dense (up to 150 nodes) compared to our scenario (of 10 000 nodes), and the method requires powerful hardware for mesh nodes and a sufficiently stable network, therefore, this method cannot be applied in our context. The optimal value also depends on the routing protocol used and the desired redundancy. Finding the optimal value for various applications is out of the scope of this article. For now, we consider that the network user tests and finds a low but sufficiently high value of ring neighbours N to guarantee delivery.

An efficient dynamic ring scheme executed by nodes takes into account the network's high density and the nanodevice's hardware constraints. In the following, two classical acknowledgment methods are presented briefly and are shown not to be efficient in nanonetworks, followed by a dynamic ring method that is demonstrated to work in nanonetworks in Section 4.

First method: dynamic ring with implicit acknowledgment. In this method, a forwarding node starts with any value for *rangeSmall*,

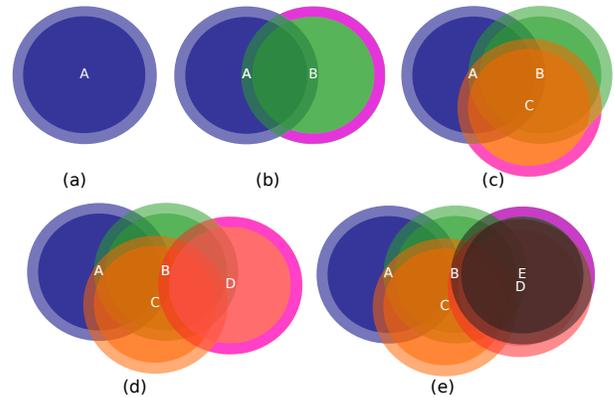


Figure 2: Drawbacks of dynamic ring with implicit ack: only the pink areas include new forwarders that will send the data packets counted as acknowledgments.

and updates it based on the number of acknowledgments received compared to the required number N of forwarders. The considered (implicit) acknowledgments are the copies received by a forwarding node from nodes in its next-hop forwarding ring. If the number of forwarders is N , then the ring width is fine; elsewhere, if the latter is smaller then the ring needs to be thicker, and vice-versa.

This evident method has two drawbacks. The first one is that N , a unique value for all nodes, applies sometimes to *partial* rings only. These partial rings do not contain "old forwarders", i.e. nodes that have already seen the same data packet before. For instance, in Fig. 2 (a), A is the first transmitter and its whole ring, including B, forwards. In Fig. 2 (b), showing the second hop, only the yet uncovered region of the ring of B, i.e. the pink region at right that has not yet received the data packet, will forward and will be counted as acknowledgments. Thus, the ring of B is much smaller than the ring of A, yet the value N erroneously applies for both of them. Subsequent images in the same Fig. 2 illustrate that, as the number of hops increases, the ring (the pink areas), that represent new forwarders at each hop and that are counted as acknowledgments, have smaller and smaller surfaces and number of nodes.

The second drawback is that a nanonode might not be able to count the number of acknowledgments that is in the order of hundreds, given the high local density and the hardware constraints. The resource constraints of a nanonode in energy, memory and data processing require the node to use large backoffs before transmission window at the MAC level to avoid further collisions.

Second method: dynamic ring with explicit acknowledgment. To solve the misleading number of acknowledgments given by the previous method, the explicit acknowledgment method makes a ring neighbour (either forwarder or not), after receiving its data packet, generate a new control packet to be received by the transmitter for the acknowledgment counts. Still, this method suffers from another misleading ring neighbours count (instead of forwarders count), where ring neighbours with already seen data packets are ignored. Indeed, as shown in Fig. 3 (a), A is the first transmitter and B and C are ring neighbours of A so they send their corresponding acknowledgments to it; again in Fig. 3 (b), B is the second transmitter and

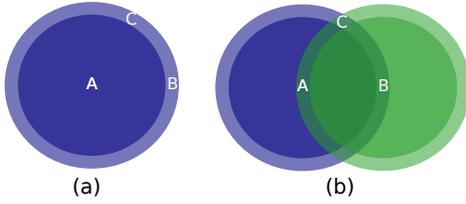


Figure 3: High traffic problem in dynamic ring width with explicit ack.

A and C need to send their corresponding acknowledgments to it, although A has already seen the data. Another problem with this method is the high traffic caused by the additional control packet, which a nanonode cannot handle, which in turn might generate numerous collisions.

Third and selected method: dynamic ring using node density estimation. The previous two methods have issues, hence they cannot be used to dynamically adjust the ring width. Here, we present the third method, the dynamic ring with DEDeN, which is the method we select for the dynamic ring.

This method takes as input the number N denoting the required ring neighbours per hop. During network initialization, nodes perform the *local density* estimation using a density estimator. One such estimator is Density Estimator for Dense Networks (DEDeN) [1]. In a nutshell, when a node receives $n = 100$ packets with an answering probability of $p = 10\%$, then it can infer that it has around $n/p = 1000$ neighbours. The higher p , the higher the estimation confidence, but the higher the number of packets exchanged. Formally, a node successively sends probe packets with increasing probabilities p , waits for responses, and when the number of responses fulfill some confidence condition, provided by the user, it estimates the number of its neighbours using the simple formula n/p .

We recall that *rangeBig* is the communication range. Instead, *rangeSmall* corresponds to the desired number of ring neighbours. Hence, the ratio of ring neighbours N to the neighbours L (= local density above) should be equal to the ratio of the ring to the communication circle:

$$N/L = \text{RingArea}/\text{circleArea} \quad (1)$$

$$N/L = \pi(\text{rangeBig}^2 - \text{rangeSmall}^2)/(\pi\text{rangeBig}^2) \quad (2)$$

hence

$$\text{rangeSmall} = \sqrt{-N * \text{rangeBig}^2 / L + \text{rangeBig}^2} \quad (3)$$

The ring computation is presented in Algo. 1. The *rangeSmall* value is set directly using a formula. It works also for heterogeneous networks (node densities are different in different parts of the network) and for different propagation models (e.g. unit disc and shadowing models). However, if the topology changes with time, the local density changes too, and thus *rangeSmall* needs to be recomputed during runtime.

Algorithm 1: Dynamic ring width with DEDeN.

Data:
 N = desired number of ring neighbours
 L = number of neighbours = local density
rangeBig = defaultCommunicationRange
controlSeqNo = 0
countAckMap = [sourceID, seqNo, *rangeSmall*]
amIOnRingMap = [transmitterID, ctrlBigSeqNo, ctrlSmallSeqNo]
needToSendControl = true
Result: Find appropriate ring width for forwarders

- 1 **Upon packet reception (type, sourceID, seqNo, transmitterID)**
- 2 **if type is DATA then**
- 3 **if dataSeqNoMap[sourceID] does not exist**
- 4 **OR dataSeqNoMap[sourceID] < seqNo then**
- 5 dataSeqNoMap[sourceID] = seqNo
- 6 **if call amIOnRing**
- 7 **AND routing protocol selects me as forwarder then**
- 8 | call forwardDataPackets
- 9 **end**
- 10 **end**
- 11 **else if type is CONTROL-BIG then**
- 12 ctrlBigSeqNo[transmitterID] = seqNo
- 13 **else if type is CONTROL-SMALL then**
- 14 ctrlSmallSeqNo[transmitterID] = seqNo
- // Reason of CONTROL-BIG and CONTROL-SMALL seqno: we cannot rely on any packet, e.g. among ctrl1, ctrl2, data, ctrl3, ctrl4, the node can receive any of them, e.g. ctrl1 and ctrl4 only
- 15 **bool function amIOnRing**
- // I am on the ring if the following conditions are met:
- // - I rx ctrlBig from this TX
- // and did NOT rx ctrlSmall from this same TX
- // OR
- // - I rx ctrlBig from this TX with higher seqno
- // than ctrlSmall
- 16 return ctrlBigSeqNo[transmitterID] exists
- 17 AND (ctrlSmallSeqNo[transmitterID] does not exist
- 18 OR ctrlBigSeqNo[transmitterID] > ctrlSmallSeqNo[transmitterID]);
- 19 **function forwardDataPacket**
- // N/L = RingArea/circleArea
- 20 *rangeSmall* = $\sqrt{-N * \text{rangeBig}^2 / L + \text{rangeBig}^2}$
- 21 **if needToSendControl then**
- 22 send ControlBig with *rangeBig*
- 23 send ControlSmall with *rangeSmall*
- 24 needToSendControl = false
- 25 **end**
- 26 send data
- 27 **if countAckMap[sourceID,seqNo] not found in countAckMap then**
- 28 insert [sourceID, seqNo, *rangeSmall*] in countAckMap
- // key is sourceID or seqNo
- // use the same *rangeSmall*
- // for all packets from the same source
- // or for only one packet seqno
- 29 **end**

Table 1: Simulation parameters.

Parameter	Value
Size of simulated area	6 mm * 6 mm
Number of nodes	10 000
Communication range	1 000 μ m
RangeBig	1 000 μ m
RangeSmall	variable
Data packet size	1 003 bit
Control packet sizes	101, 102 bit

4 EVALUATION OF THE SCHEME

This section presents how the dynamic ring with DEDeN is applied to four routing protocols: pure flooding, probabilistic flooding, back-off flooding and SLR, and how they compare to traditional routing protocols.

4.1 Available simulation software

Nano-Sim [16] and TeraSim [6] are *ns3* plug-ins with heavy footprint, lacking scalability (usable up to around one thousand nodes) and thus cannot be used in our context of dense networks.

On the contrary, BitSimulator [4] can simulate hundreds of thousands of nodes that, additionally, can be visualized. Its scalability is confirmed in a study comparing these three electromagnetic nanonetwork simulators [18]. VisualTracer is the visualization tool of a 2D nanonetwork, and will be used in the following evaluation figures. All results in BitSimulator are fully reproducible, due to the use of random seeds RNG for different runs. Therefore, we use BitSimulator in this article.

4.2 Scenarios

The simulation parameters are shown in Table 1. The scenario is a heterogeneous nanonetwork of 10 000 nodes distributed over three horizontal bands, each with a homogeneous density (5500, 3000, and 1500 respectively), in a 2D square area of 36 mm². This highly dense scenario corresponds to applications in software-defined metamaterials and in in-body communication, for example.

Nodes have omnidirectional nanoantennas with a default communication range $CR = 1000 \mu\text{m}$ and can change the range using a different transmission power (for control packets). The network dimensions along with the communication range result in $x/CR = 6 \text{ mm} / 1 \text{ mm} = 6$ hops in each dimension, which are enough for the routing protocol evaluations. The computed average number of neighbours per node is 906. For more realistic results, the propagation model used is the shadowing, with a 100% packet reception rate at distance $[0, d]$ from the transmitting node, a decreasing packet reception rate from 100% to 0% in the interval $]d, CR]$, and a zero packet reception rate at distance $> CR$, where d is configurable.

RangeBig is set to the default communication range (to increase the forwarding progress), and rangeSmall value is dynamically chosen by nodes depending on the local density, according to Eq. 2.

The packet payload are random sequences of "1"s and "0"s. The data packet size is 1003 bits and the two control packets sizes are 101 and 102 bits. These values are distinctive so that they can be spotted easily in the output log files.

A source node in the top of the network generates a CBR flow of 50 packets. The source either floods the whole network, or transmits to one destination node (found in the bottom). Since a node sends controls only once before the very first forwarded data packet, the cost of the control packets fades out over 50 data packets.

The dynamic ring proposed algorithm is implemented in three flooding schemes: pure flooding, probabilistic flooding and backoff flooding, and one destination-oriented scheme: Stateless Linear-path Routing (SLR). For backoff flooding, the maximum number of data copies received in a time window must not exceed 2 packets in order for the node to forward (*redundancy* = 2). For probabilistic flooding, the probability value is set to the minimum probability p that gives 100% delivery in each scenario.

The dynamic ring scheme starts with the DEDeN initialization phase in order for nodes to know their local density and compute their rangeSmall values. We recall that DEDeN initialization can be repeated when the network changes its topology. The CBR flow starts after the DEDeN and SLR initialization phases, to not interfere with them.

To desynchronise node forwarding in ultra-dense networks and to reduce collisions, nodes choose a random backoff before forwarding, from a fixed window in pure flooding, probabilistic flooding and SLR, and from a dynamic window in backoff flooding.

To avoid forwarding loops, nodes forward packets they receive for the first time only. Node temporarily record the source ID and the data packet sequence number, so that they do not re-forward copies of the same data packet, as detailed in Algo. 1.

The evaluation uses the 4 routing protocols above with 2 variants each (without the ring and with dynamic ring), and for 10 different random number generator seeds for the backoff time before transmission. This results in 80 simulations with 50 data packets each.

Our ring scheme aims to reduce the number of forwarders by placing them at the border of the communication, while keeping a 100% successful packet delivery to all the nodes (in flooding schemes) or the destination node (in unicast schemes). Thus, the evaluation metrics are the number of forwarders and the delivery ratio. A good network performance means a successful packet delivery to the destination with minimum resources (forwarders). The cumulative number of forwarders per packet along with the cumulative number of receivers per packet are averaged over the 10 runs and the 50 packets.

4.3 Dynamic ring with DEDeN

We recall that in the dynamic ring, the ring is set at the start (at the first data packet) as in the original ring. Afterwards, the dynamic ring uses density information from DEDeN density estimator to automatically adapt the ring width (rangeSmall) in order to include N ring neighbours in the ring per hop. In the particular case where the local density is smaller than N , the rangeSmall value is set to zero and all neighbours become ring neighbours. For the following simulations, we use $N = 60$ for all the routing protocols. This value includes non-forwarders and forwarders; non-forwarders are not only nodes that previously forwarded a copy of the data packet, but also nodes that are not chosen by the routing scheme to forward.

Table 2: Evaluation results in a 10 000 node network averaged for 10 runs and 50 packets each.

	Without ring	With dynamic ring
Pure flooding:		
forwarders per packet	10 000	1 949.2
receivers per packet	10 000	10 000
Probabilistic flooding: $p = 6\%$		
forwarders per packet	601.59	273.512
receivers per packet	9 999.9	9 999.47
Backoff flooding:		
forwarders per packet	79.934	52.242
receivers per packet	9 999.97	9 999.55
SLR:		
forwarders per packet	901.688	129.116
Destination reached	100%	100%

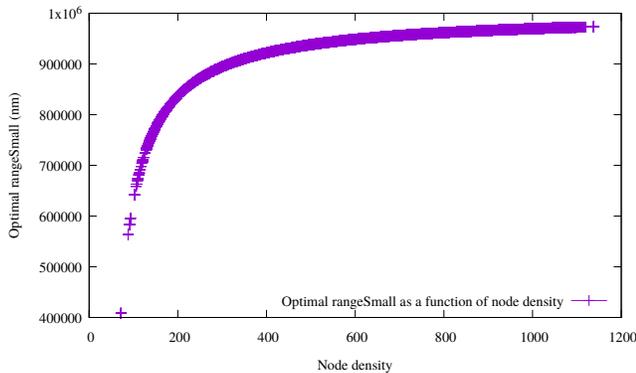
**Figure 4: The dynamic ring with DEDeN in pure flooding assigning different rangeSmall values for nodes depending on their density.**

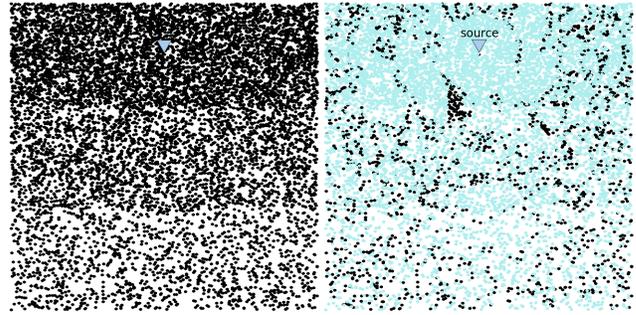
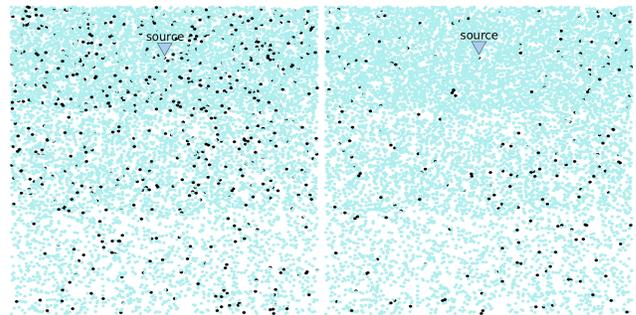
Table 2 shows the final comparison of the average values of the 10 runs with 50 packets each for all the different combinations of the routing schemes. We provide a separate web site¹ to reproduce results along with the simulations description.

Effect of the dynamic ring on pure flooding. Fig. 4 confirms that the dynamic ring assigns indeed ring widths (rangeSmall) to nodes, depending on their local density. The higher the density, the higher the rangeSmall value is, and the thinner the ring width is. When the local density is very high, the rangeSmall value approaches the communication range (10^6 nm). However, when the density ≈ 120 (that is double the number of ring neighbours), the rangeSmall value is approximately half the communication range.

Table 2 also confirms the expectations: the number of senders per packet is reduced by 80%, from 10 000 to 1949.2, with 100% delivery rate. Fig. 5 shows the placement of the forwarders on rings.

Effect of the dynamic ring on probabilistic flooding. Table 2 shows that the probabilistic dynamic ring is efficient in reducing the number of forwarders per packet by 54% from 601 to 273, while the

¹<http://eugen.dedu.free.fr/bitsimulator/nanocom22>

**Figure 5: Pure flooding without (left) and with the dynamic ring with DEDeN (right); forwarders in black, receivers in blue, first packet of the first run only.****Figure 6: Probabilistic flooding without (left) and with the dynamic ring with DEDeN (right); forwarders in black, receivers in blue, first packet of the first run only.**

delivery rate is of 99.9%. Fig. 6 shows the difference in the placement of forwarders from random (left) to on rings (right).

Effect of the dynamic ring on backoff flooding. The dynamic ring improves backoff flooding as seen in Table 2, where the number of relay nodes per packet decreases by 34% (from 79.9 to 52.2), with almost all nodes receiving the packet (99.99%). Fig. 7 shows fewer and better placed forwarders with the dynamic ring (right) compared to no ring (left). This is an exceptional result, given that backoff flooding is already a highly efficient flooding.

Effect of the dynamic ring on SLR. Table 2 shows that the number of forwarders is reduced by 85%, from 901 (without the ring) to 129 (with the dynamic ring), while keeping 100% successful packet delivery. Fig. 8 visually shows this reduction and the optimized placement of forwarders on border of ranges.

To conclude, the dynamic ring allows to optimize all the presented routing protocols by choosing a ring width value. The dynamic ring selects forwarders on border of communication ranges in rings and significantly reduces the number of forwarders per packet while keeping 100% delivery rate to the destination(s).

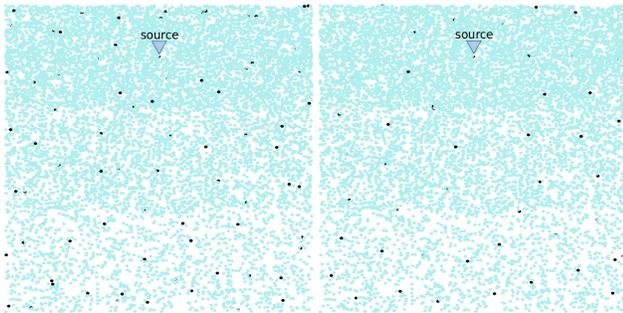


Figure 7: Backoff flooding without (left) and with the dynamic ring with DEDeN (right); forwarders in black, receivers in blue, first packet of the first run only.

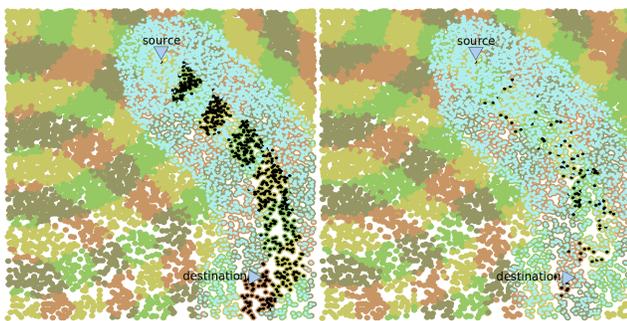


Figure 8: SLR without (left) and with the dynamic ring with DEDeN (right); forwarders in black, receivers in blue, first packet of the first run only.

5 CONCLUSION AND FUTURE WORK

This article presents an optimization for the routing schemes in electromagnetic nanonetworks, using an improved method of the ring: the dynamic ring. The original ring uses two control packets that delimit a fixed ring area, and forwarders are chosen only from this area. Classical acknowledgment methods, that count the number of acknowledgments from the ring to update its width, are proved not to work in the context of electromagnetic nanonetworks.

The dynamic ring scheme with a density estimator automatically selects a ring width value for each node. The scheme is implemented in a nanonetwork simulator above four routing protocols: three flooding schemes and one destination-oriented scheme. The results are compared using two metrics: the number and placement of forwarders and the packet delivery rate. They show that the scheme generally selects forwarding nodes found at the border of communication ranges and reduces the number of forwarders per packet, while maintaining a successful packet delivery.

Future work includes studying the optimal number of ring neighbours in the dynamic ring and understanding the effect of local number of forwarders on the delivery rate.

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