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

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***Abstract*—Electromagnetic nanocommunication is a novel paradigm of communication among nanometer-sized devices in the terahertz band, which enables groundbreaking applications. In these multi-hop ultra-dense networks, the massively dense communications among nanodevices remain a challenge and most traditional routing protocols are inefficient. To reduce the number of forwarders and to scale up the routing protocols, we proposed in a previous work a scheme which selects a small set of efficient forwarders in a ring near the communication range at each hop. However, contrary to expectations, it appears in long multi-hops path, that the number of forwarders progressively increases with the distance from the source. In the current work, we improve this scheme by choosing the ring's shape carefully from a multi-hop perspective. We combine it with two routing protocols and implement them in a dense nanonetwork simulator. Extensive simulations of our scheme show that, compared to the initial approach, it notably reduces the number of forwarders while providing a guaranteed delivery to the intended destinations.**

***Index Terms*—Routing, Congestion, Nanonetwork, Dense network, Scalability**

I. INTRODUCTION

Nanotechnology enables the design of nanometer-sized devices with new functionalities leading to novel applications in many fields of science and to the Internet of Nano-Things (IoNT). Communication among nanodevices is a necessity for these applications. Promising communication paradigms are currently electromagnetic, molecular, acoustic and mechanical communications. This article focuses on electromagnetic (EM) nanonetworks where nanonodes collaborate using graphene antennas in the terahertz band (0.1–10 THz) [1].

The size restrictions of a nanodevice make it constrained in energy and memory and allow it to perform only simple tasks of sensing, basic actuation and data processing. To execute complex applications, a large number of nodes is required, forming a nanonetwork.

As applications, in-body nanonetworks are envisioned to revolutionize the medicine, where nanodevices detect, monitor or transport the drug to the appropriate cells in the human body [2]. Such applications require a large network in the scale of 10^3 to 10^9 nodes with very high node density $> 10^3$ nodes per cm^3 [3].

It follows that a nanonetwork can be an *ultra-dense network*, which we define as a network where nodes have high *node density* (or node degree), i.e. they may have hundreds or thousands of neighbours in their communication range. Most classical protocols are inefficient in dense networks (for example protocols relying on full neighbour knowledge), and our general goal is to adapt them to this context.

Due to channel characteristics and very low level of energy available, the communication ranges in the THz band are very short. To increase coverage, a multi-hop network is required. Along the routing path of packets from the source(s) to the destination(s), intermediate nodes called *forwarders* or *relays* re-transmit the received packets in order to reach the intended destination(s).

It is important to highlight that nanonetworks greatly differ from traditional wireless ad-hoc networks. Compared to wireless sensor networks (WSNs), a sensor at the nano-scale is even more resource-constrained, and a nanonetwork is much denser. Also, nanoantennas radiate in the THz band, and due to extremely small energy and processing capabilities, the modulation cannot use a carrier. Instead, a very simple pulse-based modulation must be used. In Time Spread On-Off Keying (TS-OOK), bit 1 is a 100 femtosecond-long ($= T_p$) pulse with energy, and bit 0 is a silence without energy [4].

Due to aforementioned peculiarities, nanonetworks require the design of new routing protocols taking into account that a constrained nanodevice cannot store nor process complete informations about its highly dense neighbourhood.

The end goal of this article is to scale up the routing protocols in dense networks by optimizing the selection of forwarders and thus reducing the routing cost and increasing the lifetime of a nanonetwork.

This article extends our previous work [5], where we proposed a ring-based forwarder selection scheme built above routing protocols in order to make them efficient in ultra-dense networks. Combined with this scheme, the routing protocol selects the forwarding nodes among the ring area near the communication range at each hop instead of the whole communication range. To define the ring, each node in the scheme uses two control packets sent with different powers (or communication ranges) only once, right before transmitting its very first data packet.

The contribution of this article is the following. We propose an improved scheme of the ring-based forwarder selection above [5], that we call the *expanded ring*, which restricts the forwarders to the *intersections* of rings of nodes. Secondly, we evaluate the scheme through simulations 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 rest of the article is organised as follows. Next section presents the related work. Afterwards, we present the details of the expanded ring and its evaluation using extensive simulations. Last section concludes the article.

II. Related work

Traditional routing protocols need to scale up to meet the requirements of ultra-dense resource-constrained nanonetworks. Nanodevices have limited capacity and cannot store or process information about its full neighbourhood or network.

Depending on the application, the routing protocol either delivers the data packets to a destination node or to many nodes (strict unicast or merely zone-cast routing), or even floods the whole network so that every node receives a certain message (flooding). In any case, nanodevices require low complexity routing schemes.

The traditional pure flooding makes every node in the network forward the packet it receives for the first time. Despite its simplicity, this protocol is costly as it leads to redundant transmissions and thus broadcast storms. Broadcast storms get worse in dense networks. Many works have been done in the context of nanonetworks to control the number of forwarders in the network, from which we can cite probabilistic flooding [6], Backoff flooding [7] and RADAR routing [8]. However, all these flooding schemes can still be improved and scaled up to meet the requirements of ultra-dense networks.

SLR (Stateless Linear-path Routing) [9] is an efficient zone-cast routing scheme that uses anchors and a coordinate system for nanonodes that can extend to a 3D environment. The node coordinates are represented as hop counts from the anchors. Thus, space is divided in zones, where all nodes in a zone share the same coordinates. Contrarily to IP networks where the forwarding router is chosen by the preceding router, a nanonode takes the forwarding decision for itself. Only nodes whose coordinates verify the line equation joining the source-destination pair are forwarders. Therefore, SLR limits the zone of forwarding to the path between the source and the destination and thus also reduces the number of forwarders in the network. On the other hand, all the nodes in the zone between the source and the destination are forwarders and there are still some redundant re-transmissions that can be eliminated.

III. Original and proposed ring schemes

A. Original ring scheme

The previous work [5] presents the ring algorithm in its basic form. Forwarders are only selected among those in the ring area near the communication range at each hop. The ring is implemented by the following: a node that receives a high-power control packet from a transmitter and does *not* receive a low-power control packet from the same transmitter is a candidate data packet forwarder for this transmitter, as shown in Fig. 1. The routing protocol further selects the actual forwarders among the candidate forwarders, as given by its own operation.

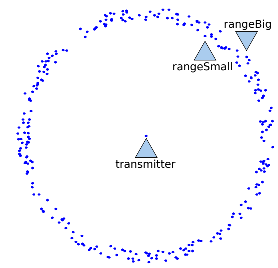

Fig. 1. Original ring algorithm: the transmitter is at the center of the communication range and only nodes in the ring area between rangeBig and rangeSmall are potential forwarders.

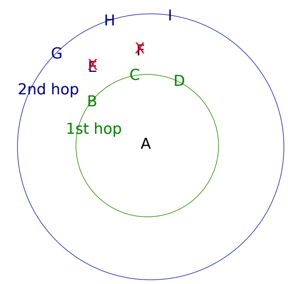

Fig. 2. Envisioned goal by the expanded ring: forwarders at the first hop are B, C, and D, and forwarders at the second hop are G, H, and I (and not E and F).

B. Expanded ring scheme

This paper proposes an enhancement of the original ring scheme, that we call *expanded ring*, whose improvement is visible in multi-hop communications. The expanded ring further reduces the number of forwarders by redefining the ring neighbours and limiting them to those laying at the *intersections of rings* (while the ring neighbours in the basic ring are found on any ring). Our aim is to have the initial source node as the center of concentric rings: the n-th ring includes n-hop transmitters, as illustrated in Fig. 2 for the first two hops.

Specifically, the expanded ring uses the same conditions as the basic ring, but with one modification: it is not sufficient anymore to be on the ring area of the node from which it received the packet the first time; the node must also be, for a specified time window w, in the ring of *all* the nodes having sent that packet (or a copy of it). Even if the modification is small, the effects are very different, and need to be evaluated.

To better understand our scheme, a simplified illustration, with five nodes, is shown in Fig. 3. A is the source node. B and C are 1st-hop neighbours of A and are forwarders as they are on the ring of A. D and E are 2nd-hop neighbours of A. E is on the rings of both B and C (always OnRing), while D is

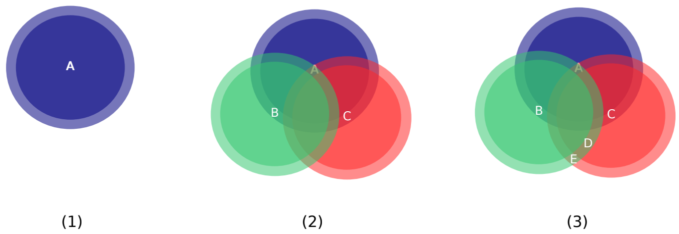

Fig. 3. Simplified illustration of the expanded ring behavior.

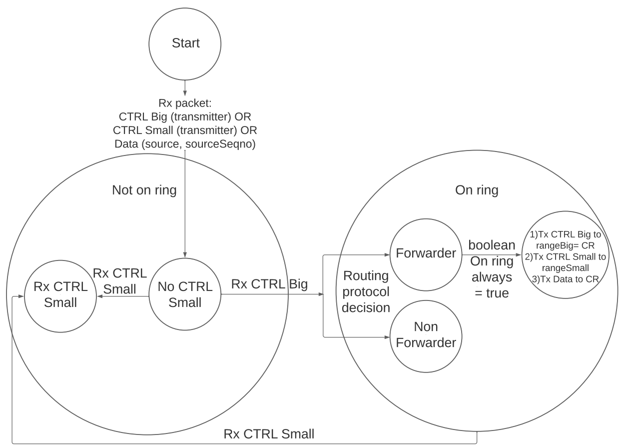

Fig. 4. State diagram of expanded ring.

on the ring of B but *not* of C. In the basic scheme both nodes D and E are forwarders; in the expanded scheme only E is a forwarder.

The implementation of this scheme is fully presented in Algo. 1. The modifications compared to the basic scheme are at lines 3–7 and 21–23.

The state diagram is presented in Fig. 4. A node can be on the ring or not, and if on the ring then it can be a forwarder or not, depending on the routing protocol operation.

IV. Evaluation of the Scheme

This section compares three versions: the proposed scheme, original ring, and no ring, each of them on top of two routing protocols: pure flooding and SLR.

A. Available simulation software

Several simulators of electromagnetic nanonetworks have been proposed for electromagnetic nanonetworks [10], such as Nano-Sim [11] and TeraSim [12] which are heavy and in practice can simulate networks of up to around one thousand nodes, and thus are not suitable for our study. In contrast, BitSimulator [13] is highly scalable: it can simulate nanonetworks with hundreds of thousands of nodes on a classical computer, and focuses on both network and transport layers. It is accompanied by VisualTracer, a very useful visualizer of 2D nanonetworks, shown in next figures. It is free software[1].

[1] BitSimulator is available at http://eugen.dedu.free.fr/bitsimulator

Algorithm 1: Expanded ring algorithm.

Data:
$rangeBig$ = defaultCommunicationRange
amIonRingMap = [transmitterID, ctrlBig, ctrlSmall]
needToSendControl = true
sourceRingMap = [sourceID, hopCount, isOnTransmitterRing]
Result: Perform expanded ring restriction of forwarders

1 **Upon packet reception (type, sourceID, seqNo, transmitterID)**
2 **if** *type is DATA* **then**
3 isOnTransmitterRing = ctrlBig[transmitterID] AND !ctrlSmall[transmitterID];
4 **if** *sourceRingMap[sourceID] does not exist* **then**
5 insert [sourceID, hopCount, isOnTransmitterRing] in sourceRingMap
6 **if** *!isOnTransmitterRing AND hopCount(packet) < hopCount[sourceID]* **then**
7 isOnTransmitterRing[sourceID] = false;
8 **if** *call amIOnRing AND routing protocol selects me as forwarder* **then**
9 call forwardDataPackets
10 **else if** *type is CONTROL-BIG* **then**
11 ctrlBig[transmitterID] = true
12 **else if** *type is CONTROL-SMALL* **then**
13 ctrlSmall[transmitterID] = true

14 **bool function amIOnRing**
`// I am on the ring if the following conditions are met:`
`// - I received a ctrlBig packet from this transmitter`
`// - did NOT receive a ctrlSmall packet from this same transmitter`
15 return ctrlBig[transmitterID] = true AND ctrlSmall[transmitterID] = false;

16 **function forwardDataPacket**
17 **if** *needToSendControl* **then**
18 send ControlBig with rangeBig
19 send ControlSmall with rangeSmall
20 needToSendControl = false
21 schedule send data packet event in t

22 **Upon scheduled send data packet event**
23 **if** *isOnTransmitterRing[sourceID]* **then**
24 send data

Therefore, we use BitSimulator to evaluate our improved scheme.

We implemented our ring schemes in the simulator on top of two already-implemented routing protocols: pure flooding and SLR.

B. Scenarios

The parameters used are shown in in Table I. The simulated nanonetwork is a square area of $36\,\text{mm}^2$. 10 000 nodes are randomly placed in three equally sized horizontal bands with different densities: 5500 nodes in the upper band, 3000 nodes in the middle band, and 1500 nodes in the bottom band, yielding a *heterogeneous* network.

The communication range of a nanonode is $CR = 1000\,\mu$m and includes 906 neighbours in average. It results in a network

TABLE I
SIMULATION PARAMETERS.

Parameter	Value
Size of simulated area	6 mm * 6 mm
Number of nodes	10 000
Communication range	1000 μm
RangeBig	1000 μm
RangeSmall	830 μm
Data packet size	1003 bit
Control packet sizes	101, 102 bit
Time window w	200 ns

width of x/CR = 6 mm / 1 mm = 6 hops horizontally and vertically in the network, appropriate for multi-hop communications.

The simulator uses a more realistic propagation model, known as *shadowing*. In absence of collisions, nodes up to a distance d from the emitter, with $d < CR$, receive all the packets correctly. Nodes between d and CR receive them with a probability progressively decreasing from 1 to 0, and nodes beyond CR do not receive any packet.

Compared to our previous work, on basic ring [5], the evaluation in the current article uses an heterogeneous network (in terms of node density) and the shadowing propagation model that also significantly impacts results.

The ring is delimited by two ranges: rangeBig (of high-power control packet) is set to default communication range to increase the forwarding progress, and rangeSmall (of low-power control packet) is chosen empirically to guarantee successful packet delivery. In both old and new protocols we used the same values. We recall that the control packets are sent only once per node, before the very first forwarded data packet, so their cost fades away after 50 data packets. The data packet is a random sequence of 1003 bits of "1"s and "0"s. The high and low-power control packets are also random sequences, of 101 and 102 bits, respectively (these specific values are chosen simply to be spotted easily in the output log files of simulations). To avoid endless loops (see Algo. 1), nodes forward data packets they received the first time, by recording only its source ID and its sequence number. Additionally, a backoff before transmission is used before forwarding any packet in order to reduce collisions.

The scenario includes a source node at the top of the network that transmits a CBR flow of 50 data packets. The destination is either the whole network (for pure flooding) or a destination node, at the bottom-right of the network (for SLR protocol). SLR anchors are at the top-left and bottom-left corners of the network.

The expanded ring is implemented in both pure flooding and SLR. We compare three schemes for both protocols: no ring, original ring, and expanded ring. For each of the six cases, the simulation is done for 10 different RNG seeds, used for the backoff time before transmission. This results in 60 simulations with 50 data packets each.

The evaluation metrics are the number of forwarders and the delivery ratio. Indeed, the goal of the ring schemes is to reduce the number of forwarders while ensuring a 100% packet delivery to the destination(s).

TABLE II
EVALUATION RESULTS WITH 10 000 NODES AVERAGED FOR 10 RUNS AND 50 PACKETS EACH.

	No ring	Original ring	Expanded ring
Pure flooding:			
Forwarders per packet	10 000	2747.3	1111.6
Receivers per packet	10 000	10 000	10 000
SLR:			
Forwarders per packet	901.6	213.2	123.8
Destination reached	100%	100%	98.8%

Table II shows the average numbers of forwarders and receivers per data packet for each case (three schemes and two protocols), and will be analysed later.

In order to reproduce the simulation results we provide a separate web site[2].

C. Results

We remind that in the original ring, the forwarding nodes are required to be on the ring of the first packet received. In contrast, the expanded ring restricts the forwarding nodes to nodes which are on the ring of *all* the packets received in a given time window w.

1) Results for pure flooding: Pure flooding, as previously defined in Section II, is the basic broadcasting scheme where nodes forward a data packet once, as they receive it for the first time. Its performance degrades in dense environments, because redundant transmissions cause collisions and may lead to broadcast storms. The proposed expanded ring adds a restriction to the forwarders: a forwarder has to receive the data packet for the first time (as in pure flooding), but it also has to remain on the ring of all the packets for a given time window w.

Table II shows that the number of forwarders per packet decreases from 10 000 (without ring) to 2747.3 (with original ring) and to 1111.6 (with expanded ring), i.e. the expanded ring reduces the number of forwarders by 88.8% compared to traditional pure flooding and by 59.5% compared to original ring. Moreover, despite this large decrease in the number of forwarders, both ring schemes allow for the correct distribution of all data packets (100% destination reached).

Fig. 5 visually shows that the forwarders are better positioned at the border of communication ranges and at the intersections of rings of other nodes in expanded ring than without ring. The expanded ring clearly shows concentric rings around the source node, as envisioned in goal Figure. 2. Those ring are still imperfect as a consequence of the different backoffs before transmission used by transmitters, but are an acceptable trade-off.

2) Results with SLR: As previously described, SLR is a unicast routing scheme for a source-destination zone pair, specifically designed for nanonetworks. A forwarder in the SLR with expanded ring must fulfill the following conditions:

[2]http://eugen.dedu.free.fr/bitsimulator/iwcmc22

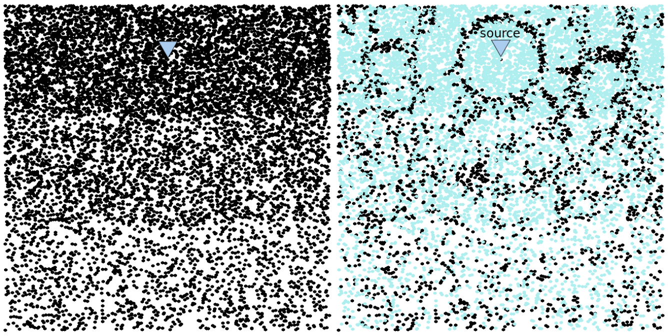

Fig. 5. Pure flooding without ring (left) and with (right) the expanded ring for the first packet of the first run (forwarders are in black, receivers are in light blue).

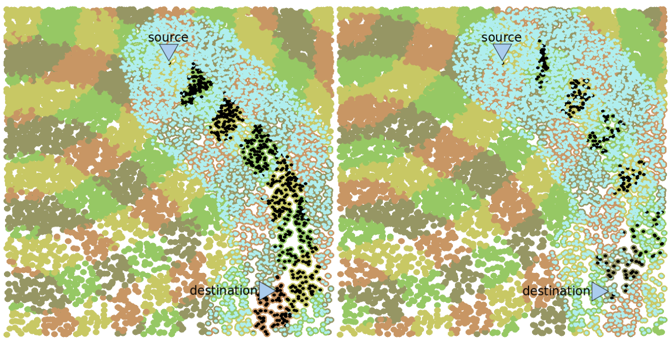

Fig. 6. SLR without (left) and with (right) the expanded ring for the first packet for the first run (forwarders are in black, receivers are in light blue).

it receives the data packet for the first time, it is on the path between the source and destination (as required by SLR), and it is on the intersections of rings of nodes for the specified time window w.

A very good reduction rate of 86% is seen in Table II for the number of forwarders per packet, going from 901 without ring to 123 for expanded ring. The expanded ring also improves the original ring by reducing the number of forwarders by 41.9% from 213.2 to 123.8. The delivery rate to the destination node for the expanded ring stays very high: 98.8%.

Fig. 6 shows much fewer forwarders for expanded ring (right) compared to without ring (left) along the path between the source and the destination nodes.

To summarize, the expanded ring scheme is better at selecting forwarders in multi-hop scenarios. When configured with an optimal ring width value, it greatly reduces the number of forwarders compared to traditional protocols (88% and 86% in the simulations).

V. Conclusion and future work

This article presents the expanded ring, that is a multi-hop optimization for the routing schemes in electromagnetic nanonetworks. An early work presented the original ring scheme, as a forwarder selection method from the ring area using two control packets. The expanded ring scheme presented in the current article improves the original ring scheme by redefining nodes on the ring to only those which are on the intersections of rings.

We implemented the expanded ring in a highly scalable nanonetwork simulator, for two routing protocols (pure flooding and a destination-oriented protocol) and with a suitable propagation model. The expanded ring shows an improvement of the routing protocols over many hops using the main metrics: the number and placement of forwarders, and the packet delivery rate. Forwarders are fewer and generally selected at the border of the communication ranges, which increases the forwarding progress. The packet delivery is successful.

Future work includes analysing the ring width value of the expanded ring, and thus understanding the effect of local forwarders on the packet delivery rate.

Acknowledgments

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