CORONA: A Coordinate and Routing system for Nanonetworks

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ABSTRACT

The present paper introduces a joint coordinate and routing system (CORONA) which can be deployed dynamically on an ad-hoc nanonetwork. User-selected nodes are used as anchor-points at the setup phase. All nodes then measure their distances from these anchors, obtaining a sense of geolocation. At operation phase, the routing employs an optimal subset of anchors, selected by the sender of a packet. CORONA requires minimal setup overhead and simple integer-based calculations only. Once deployed, it operates efficiently, yielding a very low packet retransmission and interference rate, promoting energy-efficiency and medium multiplexity.

Keywords

Wireless Networking, Nanoscale.

1. INTRODUCTION

Advances in nanotechnology enable the development of tiny machines from nanoscale components, namely nanomachines. Composed of a power supply, a memory, an antenna and a CPU module, nanomachines are entirely autonomous nodes which are able to perform simple operations and communicate in short distances. Currently, miniature graphene based antennas [1] are introduced giving nanomachines the ability to achieve high transmission rates over very short distances when operating in the most promising operating spectrum of Terahertz Band [2],[3]. Such networks are expected to be widely deployed in a variety of fields, such as biomedicine, industry, environment and the military [1]. Communication among nanomachines is evolving in the direction of ad-hoc networks due to their characteristics: the ability to be reconfigurable and shelf-organized. However, the severe restrictions of nano-nodes [4] in terms of computational power, memory and energy combined with the expected high number of nano-nodes per network give rise to different protocol and networking design issues [5, 6]. The key challenge in nano- architectures and protocols is to maintain simplicity without compromising the connectivity and lifetime of the nanonetwork.

Early nanonetworking approaches were flood-based, where upon the first reception of a packet, each of the nodes rebroadcast it blindly, thus all reachable nodes receive the packet [7]. While this maximizes the network coverage, unconditional broadcast schemes are expected to result in serious redundancy and collision the so-called "broadcast storm" problem, due to high density of nodes in nano-networks. The Dynamic Infrastructure (DIF) [6, 8], approach has been introduced to mitigate transmissions without compromising the high network coverage. The key idea in DIF is that only nodes with good reception quality can act as retransmitters, while the remaining nodes revert to receiving-only mode. The classification of nodes is based on packet reception statistics, running locally to each node, called the maturity process. According to it, a nanonode can deduce whether it is best to "mature" into "infrastructure", taking part in packet retransmission. While the DIF approach achieves significant gains in energy efficacy, similar to flood approach, every single node in the topology overhears transmitted packets in the network even when it is not necessary. Most of the nanonetworks applications are expected to be data-centric in the sense that data is requested based on certain attributes. For instance, consider a wireless temperature sensing nanonetwork, if a user-node requests for temperature equal or greater to a value, then nanonodes that satisfy this condition have to respond. It can be easily seen that since reply-messages have to be driven to a specific node to the user-node, it would be wiser to use unicast routing rather than broadcast.

The present work proposes a new data-centric routing scheme with respect to the restrictions and the characteristics of nanonetworks. That assumes no neighborhood status information and a nano-CPU able to perform simple integer calculations only. A reply-packet is delivered by utilizing only the address information in message, preventing its broadcast to the network. The addresses are composed of a set of four location-attribute values, which characterize the local range of area where the specific node belongs to. According to the proposed addressing process each node sets locally its own address, rather than being pre-assigned. In large nanonetworks such an approach is expected to reduce the painful assignment of addressing quite significantly.

The remainder of this paper is organized as follows. Related studies are given in Section 2. Section 3 details the concept and introduces the proposed CORONA scheme. Evaluation via simulations take place in Section 4. Finally, the conclusion is given in Section 5.

2. RELATED WORK

The nano networking has become a topic of research interest in different fields. In general, two main trends can be distinguished: the biological or bio-inspired communication modules and the wireless electromagnetic (EM) communication. The first relies on biology as a source of inspiration and exploits biological molecules as information carries. For example, the information is encoded on several biological molecules (e.g. RNA), which are diffused to the environment [1, 9]. The latter trend, which is assumed in the present work, relies on radiative transfer theory, where wireless communication is based on electromagnetic (EM) waves. Related research efforts so far have been focused on the physical and the Medium Access Control (MAC) definition. The driving factor of research is the energy efficiency of the proposed schemes.

At physical layer, early studies show that electromagnetic communication in the Terahertz Band ($0.1 - 10.0$ THz) is the most promising approach [2]. The development of an antenna at nano-scale, while keeping its operating frequency at this promising operating spectrum, is accomplished by the use of a new material called graphene [1]. In carbon plasmonic nano-antennas, the propagation speed of electromagnetic waves can be up to two orders of magnitude lower than in classical materials. Moreover, the Terahertz Band allows for high transmission rates over very short distances. Recent studies have shown that the communication range of a single node may be further increased with the use of the $0.1 - 0.54$ THz window [3]. The authors showed that, when using this window, the free-space propagation loss becomes the dominating factor in channel characteristics, minimizing molecular absorption and achieving the largest transmission distance.

At higher layers, authors in [7] proposed the Rate Division Time Spread On-Off Keying (RD TS-OOK) as a modulation scheme in nano-communication. A logical ”1” is transmitted as a femtosecond-long pulse and a logical ”0” is encoding as silence. Each node uses different symbol and coding rates, while the only limitation is time related: keep the pulse duration much smaller than the symbol duration. A handshake-based MAC protocol, namely the PHLAME, is then proposed on top of RD TS-OOK. During the handshake process the coupled nodes choose the optimal for their communication parameters. The nanonodes are either connected in a full mesh, or operate by a full-flood example [10]. A harvesting-aware MAC protocol is proposed in [4], which uses a hierarchical cluster based architecture where all nanonodes communicate directly with the nanocontroller in one hop. It is noted, however, that clustering-based approaches were originally introduced by Srinkath et al [11]. Nanonodes are clustered into groups and communication abilities are delegated only to their more-powerful cluster masters (controllers). Later, a dual-mode solution is presented in [12][12], where the authors propose a receiver-initiated MAC protocol, which supports both centralized and distributed nanonetwork types. Finally, a centralized routing framework based on hierarchical clustering architecture in conjunction with Time Division Multiple Access is introduced in [13]. In this study, the communication between a data source and a controller is either multi-hop or direct, based on nano-controller’s evaluation. Still, in all the above mentioned schemes, nano-nodes should support an explicit addressing scheme, a timing system for duty-cycle operation, as well as quite a few powerful cluster heads, dispersed uniformly throughout the covered area.

A flood-based, extremely lightweight data dissemination scheme was introduced in [6]. According to this approach, a beacon node initially emits pulses (“packets”) periodically, which are disseminated via a flooding scheme. This stage acts as an environmental sounding, called “node maturity process”, during which nanonodes are classified as either “infrastructure” (re-transmitter) or network “user”, based on their reception quality. Once the maturity process is complete, the nodes can communicate by running any protocol (e.g. PHLAME or flood) over the formed infrastructure. Through theoretical analysis and simulations, it was demonstrated that the infrastructure nodes form regular patterns around the beacon. The study focused in rectangular grid topologies, where it was shown to addresses the three design challenges of nanonetworking: i) high scalability and coverage with regard to number of nodes in the network ii) limited complexity and iii) high energy efficiency.

While the work of [6] founded and evaluated the concept of dynamically-forming infrastructure in ad-hoc nanonetworks, it faced three limitations. Firstly, its operational parameters required topology-dependent optimization, Secondly, the nodes were assumed to have (simple) digital signal processing capabilities and floating point computation support. Thirdly, its operation focused on 2D rectangular grid topologies only.

The present study introduces a lightweight routing and addressing scheme, which suffers from none of these limitations.

3. JOINT COORDINATE/ROUTING FOR NANONETWORKS (CORONA)

This section presents the proposed approach to geographic routing in nanonetworks. First, we present a technique for assigning addresses in a nanonetwork in the form of a coordinate system. Each nanomachine derives its own coordinates dynamically during the process. This “addressing” information assigned to each nanomachine may not be unique. Instead it may be shared by all nodes in the same area. We will then present the routing scheme operating on top of the aforementioned addressing.

3.1 Setting up the Coordinate system

The proposed coordinate assignment system relies on standard triangulation, popularized in several systems and studies [14]. An example and an overview of the assumed system is given in Fig. 1. We assume a rectangular area over which a large set of nanonodes is uniformly placed. The layout may be well-arranged or random, provided that the average node density remains uniform over the surface. This layout

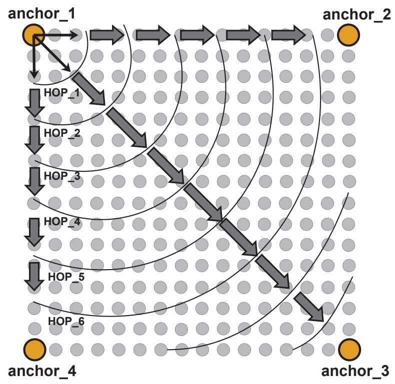

Figure 1: Coordination system setup. Each user-selected vertex anchor broadcast a single setup packet. Each node retransmits and updates its distance from the corresponding anchor, measured in hops traversed.

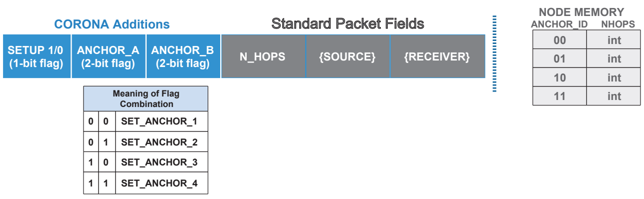

Figure 2: CORONA requirements in terms of packet header additions (left) and node memory (right)

is important for monitoring and controlling industrial and artificial materials [15]. The coordinates of a node comprise four parts, each corresponding to the distance of the node from the four anchors placed at the area vertexes. For example, the concentric arcs in Fig. 1 roughly correspond to the hop distance between *anchor_1* and every node in the network.

Therefore, according to CORONA, each node must obtain its distance from the *anchor_1*-*anchor_4* nodes. This is accomplishing during a setup phase, during which the anchor nodes sequentially transmit a single packet with special flags sets. The receiving nodes are thus notified to update their observed hop count from the corresponding anchor and retransmit the packet. The necessary packet headers and node fields are given in Fig. 2. When an anchor node, e.g. *anchor_1* is to execute its part in the setup process, its sets the *SETUP* packet flag to 1, and *ANCHOR_A* to the *SET_ANCHOR_1* value (0, 0). (The *ANCHOR_B* field is used in the routing process, discussed below). Next, it sets the *N_HOPS* field to one and broadcasts the packet. Each receiving node understands via the *SETUP* flag that the packet serves initialization purposes. It proceeds to read the *ANCHOR_A* value and sets the corresponding distance in its memory to the *N_HOPS* value. It then increases *N_HOPS* by one unit and retransmits the packet. In this manner, all nodes are informed of the distance from *anchor_1*. After a safe timeout, the process is repeated for *anchor_2*-*anchor_4*, concluding the setup process.

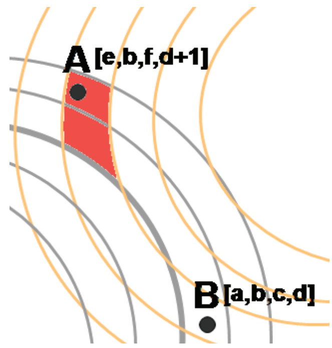

Figure 3: Using facing anchor points for packet routing may disallow the communication between certain network areas.

3.2 The Packet Routing Process

A triangulation-based coordinate system on a 2D plane requires three anchors to uniquely identify an area. However, given that CORONA assumes rectangular areas with anchors placed at the vertexes, even two anchors may suffice. Firstly, an area with theoretically duplicate coordinates usually lies outside the rectangle area. Secondly, if both areas with identical coordinates happen to lie within the network area, the result will just be a temporary increase in the number of retransmitting nodes. (In the case of CORONA this is avoided, as explained later). Therefore, the routing process of CORONA uses only two of the four anchor coordinates per each packet transmission. The decision is taken by the sender node of an original packet. The decision is taken based on which pair of anchors yields the lowest number of retransmissions for transferring a packet, *pkt*, from a source node S with coordinates (s_1, s_2, s_3, s_4) to a receiver node R with coordinates (r_1, r_2, r_3, r_4). Once the optimal anchor pair, $(i,\, j)$ is chosen, a node T with coordinates (t_1, t_2, t_3, t_4) deduces whether to retransmit a packet or not based simple integer comparisons:

$$(t_i \in [s_i,\, r_i]) \,\&\&\, (t_j \in [s_j,\, r_j]) \tag{1}$$

The criterion (1) essentially states that the retransmitting nodes lie within the area defined as the intersection of the rings:

1. $Radius \in [s_i,\, r_i]$, $Center = anchor\_i$.
2. $Radius \in [s_j,\, r_j]$, $Center = anchor\_j$.

It is critical, however, that the intersection of the two rings be a connected area. The opposite would disallow the communication between nodes S and R. It is not difficult to show that this condition always holds when the anchors are place on non-diagonally-facing vertexes. In these cases, all concentric circles have a single common point within the rectangle area. This does not always hold for diagonally-facing anchors. An example is given in Fig. 3, where the use of the top-right and bottom-left anchors bans the communication between areas A and B, since the ring intersection is segmented.

Therefore, a sender S needs only consider anchor pairs that lie on the same side of the rectangle area, namely the pairs

$p_1 = \{anchor\_1, anchor\_2\}$, $p_2 = \{anchor\_2, anchor\_3\}$, $p_3 = \{anchor\_3, anchor\_4\}$ and $p_4 = \{anchor\_4, anchor\_1\}$. As stated, the selection criterion is based on which pair offers the smallest number of hops to reach the destination R. This can be adequately expressed via the following lightweight process:

1. Calculate $D_i = |s_i - r_i|$, $i = 1 \dots 4$.
2. Obtain the optimal pair as follows:

$$p_* = argmin_{p_k} \left\{ D_{p_k^{anchor\_i}} + D_{p_k^{anchor\_j}}, k = 1 \dots 4 \right\} \quad (2)$$

Step 1 essentially provides a metric of distance between S and R per coordinate, while step 2 chooses the two anchors that offer the smallest aggregate distance. The sender S then proceeds to transmit its packet as described.

4. SIMULATIONS

In this Section we evaluate the performance of the proposed CORONA scheme versus alternative solutions. Particularly, CORONA is compared to the Dynamic Infrastructure (DIF) scheme of [8] and a probabilistic flood approach (FLOOD, e.g. [16]). The simulations consider 2D topologies, namely a uniform grid and a uniform random layout, and 10,000 nodes. The selected layouts fill a fixed, square area, with dimensions $10 \times 10mm$.

All subsequent runs assume that the nodes nearest to the four corners of the square area act as *anchors* for CORONA. The physical-layer parameters are summarized in Table 1 and are typical for studies on nano-networks [7]. We employ the SINR approach to simulate the packet reception process [17]. The connectivity of the nodes is circular, assuming the use of a patch antenna [18]. In each case, the connectivity radius is defined by the Tx Power, the Noise Level, the $SINR_{thresh}$ and the attenuation model (FSPL):

$$\frac{P(radius)}{Noise\,Level} < SINR_{thresh} \Rightarrow$$
$$\frac{P_{TX}}{FSPL(radius) \cdot NoiseLevel} < SINR_{thresh} \Rightarrow$$
$$radius < \sqrt{\frac{P_{TX}}{SINR_{thresh} \cdot NoiseLevel}} \cdot \frac{c}{4\pi \cdot F} \quad (3)$$

F being the operating frequency and c the speed of light in vacuum. A Guard Interval of $0.1nm$ is assumed, meaning that multiple receptions of the same packet arriving within this interval add up to the power of the useful signal. All DIF-specific parameters are taken from [8].

We allow for a $3\mu sec$ warm-up for all compared schemes. Then, with an inter-arrival time of $100nsec$, we randomly select a sender and a receiver among the nodes. The sender sends a single packet, which is transferred to the receiver in a manner defined by each compared scheme. We repeat this process for 100 random pairs and we log:

- The successful node-to-node packet exchange ratio (i.e. how many out of the 100 pairs communicated successfully).

Table 1: Simulation Parameters

Parameter	Value
Frequency	$100GHz$
Normal Tx Power (P_{TX})	$2\,dBnW$
Noise Level	$0\,dBnW$
Node Sensitivity ($SINR_{thresh}$)	$-10dB$
Attenuation Model	Free Space (FSPL)
Guard Interval	$0.1\,nsec$
Packet Inter-arrival	$100\,nsec$
Packet Duration	$10\,nsec$

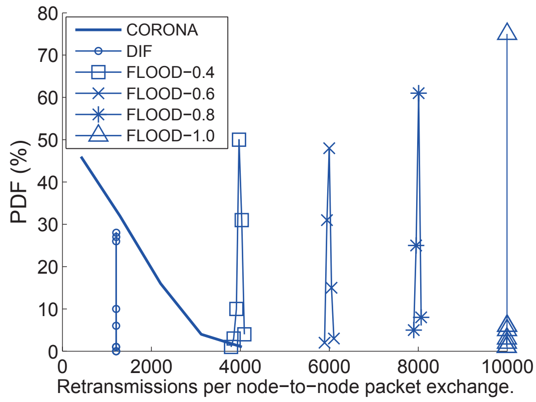

Figure 4: Probability distribution function (PDF) of nodes involved in the transmission of a packet from a random source to a random destination. A grid topology is used.

- The number of retransmitting nodes involved per each of the 100 packet exchanges, forming a probability distribution function (PDF).
- The network-wide (i.e. global) i) packet retransmission rate, ii) successful packet reception rate, iii) packet loss rate. These metrics are defined as the aggregates over all nodes and over all 100 exchanges, divided by the duration of the simulation (i.e. the time for 100 exchanges) minus the warm-up period.

Figures 4 and 5 present the results pertaining to the grid layout. The PDF of nodes involved per transmission pair is given in Fig. 4. It is obvious that the FLOOD approach involves every single of the 10,000 nodes in the network, for each transmission pair, when the flood probability is 1.0 (FLOOD-1.0). This number drops proportionally to the flood probability, when the latter is decreased to $p = 0.8, 0.6, 0.4$ respectively. Notice that the respective PDFs are narrow peaks around the means defined by $p \times 10,000$. We remark that p is a parameter that requires manual, precise tuning, which may not be viable for nanonetworks. For example, Fig. 5 demonstrates that even wild variations of p may offer small performance advantage. All compared FLOOD variations and DIF achieve perfect packet exchange ratio (100%), but with a global packet reception rate almost five times higher than CORONA.

Furthermore, FLOOD incurs the highest global packet trans-

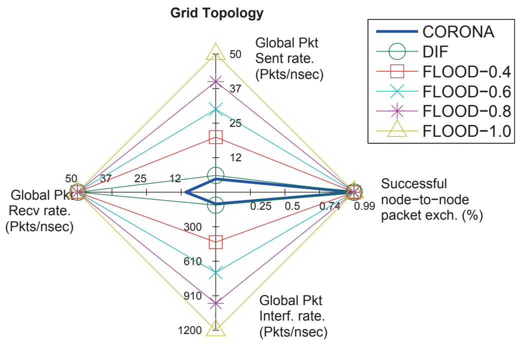

Figure 5: Radar plot for the setup of Fig. 4, presenting the successful packet transmission ratio, as well as the global packet send/receive/loss rate.

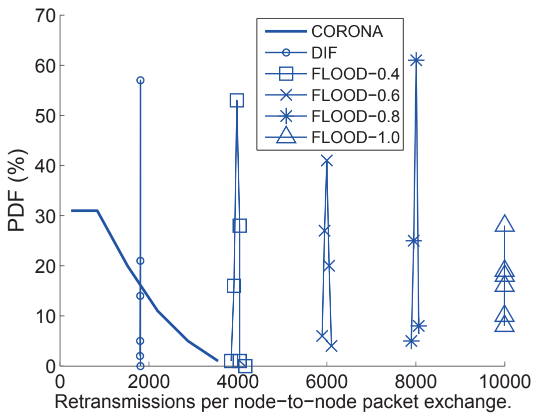

Figure 6: PDF of nodes involved in the transmission of a packet from a random source to a random destination, assuming a random topology.

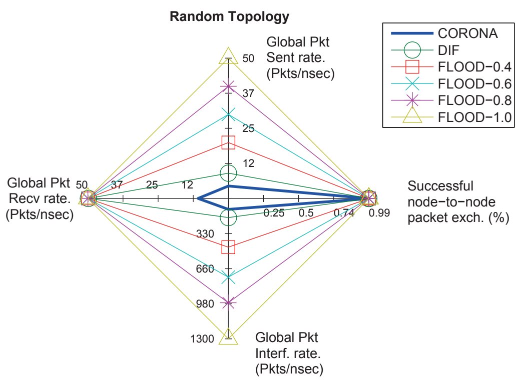

Figure 7: Radar plot for the setup of Fig. 6, presenting the successful packet transmission ratio, as well as the global packet send/receive/loss rate.

mission and packet loss rates. This is expected, given that all nodes blindly participate in every packet exchange. However, this performance can be crippling for the very limited power supply of the nanonodes. The DIF scheme performs much better than FLOOD in any case, without requiring any tuning. However, in Fig. 4 we notice that the corresponding PDF is a very narrow peak around an average of ~ 1200 retransmissions. This number is approximately equal to the number of nodes elected to serve as retransmitters by the DIF scheme. In other words, for each random sender-receiver pair, the complete Dynamic Infrastructure participates to the packet transmission process. In turn, this may quickly deplete the nodes serving as retransmitters (infrastructures), since they handle all the packet transmission load of the network. (We notice, however, that once depleted, these nodes are automatically substituted by others). Nonetheless, the performance of DIF surpasses FLOOD in every aspect shown in Fig. 5.

On the other hand, CORONA exhibits interesting traits. In Fig. 4 we observe that the PDF of CORONA is not a narrow peak, meaning that the number of retransmitters participating to a packet exchange varies considerably. This is expected, given that the packets now travel over paths defined by their coordinate system, as described in Section 3. In essence, the performance of DIF corresponds roughly to an average scenario for CORONA from this aspect. However, shorter paths are more probable for CORONA, as shown by the form of the corresponding PDF. Furthermore, Fig. 5 shows that CORONA combines a perfect packet exchange ratio (100%) with a considerably reduced global packet send, receive and interference rate. The gains of CORONA over FLOOD and DIF also validate the shorter-packet-path claim. In terms of global packet interference and send rate, DIF and CORONA behave similarly in the grid layout assumed in Fig. 5. These metrics are representative of the energy-efficiency of the schemes. However, the global packet reception rate is much lower for CORONA. This metric expresses the communication multiplexing potential. In essence, for each packet exchange, DIF involves approximately five times more (redundant) auditors than CORONA. This means that in the case of simultaneous packet exchanges among multiple sender-receiver pairs, DIF would be expected to cause unnecessary interference, limiting the multiplexing potential of the wireless medium.

Finally, in Fig. 6 and 7 we study the same metrics in a random node layout. The relative performance of the compared schemes is retained, but the difference between CORONA and DIF increases to the benefit of the proposed scheme. In random layouts, the pattern of retransmitters chosen by DIF is no longer well-formed (i.e. symmetric), while the number of retransmitters also increases [6, 8]. This naturally translates to more nodes involved pair packet exchange (Fig. 6) and higher global packet send and interference rates (Fig. 7).

5. CONCLUSION

The present study introduced a joint coordinate and routing system for nanonetworks (CORONA). CORONA uses distances from user-selected anchor points to define arc-shaped paths among any pair of nodes. These paths were shown to efficiently serve point-to-point communication needs, while reducing considerably the number of required packet retransmissions, promoting energy-efficiency in the highly restricted nano-environment.

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