Low complexity nano-networks routing scenarios and strategies

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Abstract

One of the big challenges in nano-networks is the capacity to route packets using simple strategies, in inhospitable and stimulating environments. The strict physical limitations coming from the nano-devices are constraining the design of communication protocols and strategies. Considering the current fabrication processes, existing published strategies require devices at least in micrometer dimensions, what is far yet from what is expected. In this paper, the proposal is on the road to nanometers devices, while considering extremely low energy consumption. The major contributions of this paper are the formulation of the nano-networks routing problem, the proposal of a low complexity Finite State Machine (FSM)-based paradigm to implement routes generation and routing algorithms and the evaluation of the proposed nano-networks routing and strategy.

Keywords:
Nano-networks, Finite-State-Machine, Routing, Reachability, Low Complexity, Packet Delivery Ratio, Energy Consumption, SDN, NFV.

1. Introduction

In 1665, Robert Hooke invented the microscope, although it is widely agreed Antoine van Leeuwenhoek (1632-1723) was the first to discover and publish some drawings of the first bacteria seen through the microscopes he made.

As we know, the collaborative work of the microorganisms can concern individuals million times bigger, for instance under the shape of illness.

At the present time, the capacity to design and fabricate nano-devices and nano-machines is a challenging and promising research area. As with bacteria, the nano-devices are able to show their full capacity when working collaboratively. Since nano-devices are machines, communication strategies are required to release those features: external communication involves nano-devices and external devices or gateways, internal communication is restricted only to nano-devices. Required communication protocols are attracting the interest of the community in order to be able to provide a fully functional network of nano-devices, a nano-network. Different kinds of communications have been discussed in the literature, namely:

– Akyildiz et al. (2008) address all possibilities of nano-communications: electromagnetic waves (EM), acoustic communication, nano-mechanical communication and molecular communication;

– Akyildiz and Jornet (2010) address molecular and EM nano-communications; and

– Akyildiz et al. (2011) focus on EM nano-communications;

- Iftikhar et al. (2019) focus on Human Body Communications (HBC);
- Ahmad et al. (2019) present a complete survey of clustering schemes in Mobile Ad Hoc Networks (MANTEs).

Akyildiz et al. (2011) provided an overview of the two main expected alternatives for the future nano-communications, that are electromagnetic communications and molecular communications. The authors provided an initial better understanding of the research issues in those alternatives. Rikhtegar and M. Keshtgary (2013) mentioned the four main nano-scale communication techniques: nano-mechanical, acoustic, chemical or molecular and electromagnetic communications. However, the paper focused on the molecular and electromagnetic communications, considered the promising nano-scale communication approaches. Some other authors have considered a nano-network based in molecular communications, but the majority of works up to now are based in electromagnetic communications, as it is done in this work, considering that it is currently the most promising in terms of practical implementation in the near future.

In this work we focus on EM nano-communications as it is currently the most promising in terms of practical implementation in the near future.

The nano-network environment is considered inhospitable and challenging. The strict physical limitations coming from the nano-devices are constraining the design of communication protocols and strategies. A wide range of nano-networks applications has been considered in Balasubramaniam and Kangasharju (2013) while their security issues have been addressed in Dressler and Kargl (2012).

In previous relevant works, the challenges in nano-network environments have been analyzed and studied, ranging from: i) the material architecture of nano-devices (although fully functional and efficacious nano-machines have not been fabricated to date, various solutions have been prototyped and tested Jornet (2013)); ii) the appropriate frequencies selected for the propagation of signals and waves in the channel (the Terahertz band channel supports transmission rates at Terabits per second, but over very short distances, below one meter Jornet et al. (2013)); the required consequent nano-antennas, the energy consumption and energy harvesting system (Wang (2008), Cottone et al. (2009), Gammaitoni et al. (2009)), since no batteries can be incorporated according to the current state of the knowledge; the medium access control strategies (e.g. Jornet et al. (2013) proposed a centralized MAC protocol. Jornet et al. (2012) proposed the Physical-layer Aware MAC Protocol for Electromagnetic Nano-networks (PHLAME)).

The current communication networks are usually based in layered models (for instance Internet). In OSI or ARPA models ITU-T (1994) each layer provides a set of functions. The application layer, on top, exploits the aggregation of services from all layers below.

This strategy is also used for nano-networks, appropriately adapted with some extensions to better support the limitations of the nano-devices. In this paper, we consider the following layers, from bottom to top: the physical layer, concerning signals and mechanical issues of the devices, including antennas, power, frequencies and modulation of signals. The Medium Access Control (MAC) layer includes the strategies and protocols to access the shared media according to the physical layer constraints, especially regarding power consumption and transmission effectiveness. The network layer, in charge of providing a scheme to route the data from the source to the destination. Again, the limited processing power of the nano-machines constrains the strategies to be used in this layer. Finally, the application layer, including the required tools and interfaces to provide applications.

It is out of the scope of this work to discuss the technologies involved in the implementation of the physical and MAC layers. A review of such technologies is provided in A.Galal and X.Hesselbach (2018) and a complete model considering the low processing power of the nodes is proposed. We assume that an adequate choice of lower layers is made to implement the nano-network.

According to this model, the data and control planes are decoupled, in order to externalize the control functions from the nano-machines to facilitate the deployment of the nano-network with very simple devices located in the data plane. Consequently, the Software Defined Network (SDN) technology has been adopted to be part of the model.

Besides, since the expected huge amount of nano-devices, network functions and applications have been also externalized decoupling services to be provided from the hardware, in order to reduce the computational requirements in the physical nano-network. Network Function Virtualization (NFV) is able to provide the technological solutions to cover this issue using appropriate interfaces to communicate with the nano-network A.Galal and X.Hesselbach (2018).

In this paper we focus on the nano-network network layer (see Fig. 1 on page 7) and the contributions may be summarized as:

- formulation of the nano-networks routing problem;
- proposal of a low complexity Finite State Machine (FSM)-based paradigm to implement routes generation and routing algorithms;
- evaluation of the proposed nano-networks routing strategy.

The paper is organized as follows. After this Introduction, Section 2 reviews the most representative routing protocols used in wireless sensor networks (WSN). Section 3 reviews the adopted nano-networks' architecture. Section 4 reviews the concepts of convolutional codes, describes the trellis coded paradigm to implement routing, explains the different routing modes that can be used and evaluates the benefits of its adoption in the case of nano-networks. Section 5 describes the novel nano-networks routing scenarios strategy. Section 6 evaluates the proposed nano-networks routing scenarios strategy and compares it with the most representative routing protocols used in wireless sensor networks. Finally, Section 7 summarizes the conclusions and indicates the future works that will be developed.

2. Nano-networks routing related works

Since the pioneer works introducing the nano-networks with their unique characteristics and wide range of applications Akyildiz et al. (2008), Akyildiz and Jornet (2010), Akyildiz et al. (2011), Balasubramaniam and Kangasharju (2013), the nano-network environment is considered inhospitable and challenging. The strict physical limitations coming from the nano-devices are constraining the design of communication protocols and strategies.

An extensive review of routing protocols proposed to be employed in nano-networks have been done covering the years from 2008 until 2020. Due to space limitations, it is not possible to describe each of them in this paper. In this section we briefly present the approaches and strategies proposed by significant related works.

Many research works have specifically addressed the design and implementation of strategies and protocols for forwarding and routing in nano-networks. The interested reader should refer to Pierobon et al. (2014), Tsioliaridou et al. (2015), Tsioliaridou et al. (2016), Liaskos et al. (2016), Tsioliaridou et al. (2017), Yu et al. (2017), Oukhatar et al. (2017), Arrabal et al. (2018b), Afsana et al. (2018), Wang et al. (2018), Fahim et al. (2020), Wang et al. (2020), Aliouat et al. (2020), Lemic et al. (2020) to get an overall view of the different schemas.

In Abuali et al. (2018) is not proposed any new routing protocol, but the performance evaluation of three of them, namely: controlled flooding, coordinate/routing for nano-networks, and hierarchical Ad hoc On demand Distance Vector (AODV).

All the aforementioned works have common assumptions about the characteristics and capabilities of the nano-devices implementing the nano-networks such as limited processing and storage resources, resilience and randomly distributed deployment. However, they may be found significantly different in respect to their approaches and strategies concerning basic issues of the routing process such as path selection, forwarding scheme, topology awareness, deployment dimension, and node mobility.

Single-path routing protocols (e.g. Pierobon et al. (2014), Yu et al. (2017)) provide a way for a nano-node receiving a packet to forward the packet to an specific next-hop nano-node, which can significantly reduce energy consumption. With single-path routing protocols, nano-nodes may have different capabilities and functions. On the other hand, multi-path routing protocols (e.g. Tsioliaridou et al. (2015), Liaskos et al. (2016)) are based in multiple paths to reach a nano-node destination, providing the resilience needed in the case of failures. With multi-path routing protocols, nano-nodes usually have the same capability and functions.

While single-path routing protocols have essentially a unicast forwarding strategy (e.g. Liaskos et al. (2016)), multi-path routing protocols may have different approaches for their multicast or broadcast forwarding strategy with alternative solutions to the pure flooding, based on probabilistic estimates (e.g. Oukhatar et al. (2017)) or some topology awareness (e.g. Tsioliaridou et al. (2017), Yu et al. (2017)).

With respect to the topology awareness, most works are based on the knowledge of the node physical relative position even if the node have not unique address (e.g. Tsioliaridou et al. (2016)). A few works assume a topological logical address scheme for their forwarding objectives Oukhatar et al. (2017).

About half of the works address nano-networks applications in a 2D dimension node deployment scenario (e.g. Arrabal et al. (2018b), Afsana et al. (2018), Wang et al. (2018)) as well the other half consider 3D scenarios (e.g. Oukhatar et al. (2017), Abuali et al. (2018)).

Most works also assume static nano-nodes and only a few ones address the nano-node mobility capability (e.g. Oukhatar et al. (2017), Abuali et al. (2018), Fahim et al. (2020).

All these works developed experiments for performance evaluation using simulation tools varying from customized platforms (e.g. Arrabal et al. (2018b)) to more general purpose network simulation tools as the NS-3 NanoSim (e.g Yu et al. (2017), Afsana et al. (2018), Fahim et al. (2020)). Each one adopted a customized set of simulation metrics for its own study purposes but it could be identified a set including the most common metrics such as reachability, packet delivery ratio, successful packet transmission ratio, packet average hop count, latency and energy consumption. Lemic et al. (2020) point out that it is difficult to compare the performance results of the network layer protocols surveyed due to the large variety of applications scenarios, evaluation topologies and metrics.

Most of these works assumed an nano-network architecture based on a PHY layer implementing the TS-OOK protocol (e.g. Tsioliaridou et al. (2017)) as well as a transparent MAC layer (e.g. Abuali et al. (2018)). However, Pierobon et al. (2014), Afsana et al. (2018) assumed a MAC protocol based on TDMA schemes for energy saving objectives. Abuali et al. (2018)@AODV used NanoSim built-in MAC protocols for their performance evaluation studies.

In Ferjani and Touati (2019) is proposed a geographic routing algorithm for efficient data dissemination in electromagnetic nano-networks.

Aliouat et al. (2020) compare classical ad hoc routing protocols with routing protocols proposed for nano-networks in terms of the complexity involving the amount of memory space required by the protocol. It is shown that protocols like AODV and OLSR (Optimized Link State Routing) have higher complexity when compared to flooding, Pierobon et al. (2014), Tsioliaridou et al. (2017), among others routing nano-networks protocols. In Lemic et al. (2020) it is pointed out that the majority of wireless sensor networks (WSN) routing protocols are optimized for up to a few hundreds motes, while some of the application domains enabled by THz nanonetworks require significantly larger number of nanonodes.

Complexity is an important issue in the design and implementation of nano-network routing protocols. It strongly depends on the nano-network architecture and its optimization objectives. For example, routing protocols that have energy consumption considerations (e.g., energy-aware) implies more complex implementations. Therefore, a complexity analysis of routing protocol for nano-networks should consider, for the sake of fairness, their overall application objectives and architecture.

In Yao et al. (2019) is presented a survey about routing techniques in wireless nano-networks including most of the works earlier referenced. In this survey, the selected routing protocols are comprehensively analyzed and classified based on three principles: network architecture, node mobility and routing path. It is introduced the notion of nano-network architecture that can be either flat, if nano-nodes are supposed to be equal to each other, or hierarchical, where nano-nodes have different hierarchies. The routing protocols surveyed are assumed to be static, so the mobility of nano-nodes could not be used in the classification study. According to different classification rules, one routing protocol could belong to multiple classifications.

Lemic et al. (2020) provide an overview of the current contributions on the different layers of the protocol stack implementing terahertz nano-networks for envisioned applications like software-defined metamaterials, wireless robotic materials, in-body communication and on-chip communication. In particular, this work discusses recent (2014-2018) network layer protocols proposals using a classification approach a little different from Yao et al. (2019), namely, relay and forwarding, flooding-based routing and pathfinding routing. It points out that most network layer proposals focus on minimizing power consumption and energy efficiency but using metrics that provide an incomplete vision of their overall performance. Moreover, it concludes that mobility is an important issue for nano-networks routing protocols.

Table 1 summarizes the information acquired from the analyzed publications.

Table 1: Main characteristics of the analyzed forwarding and routing strategies

Reference	Routing Protocol	Path Selection		Forwarding Strategy			Topology				Node Mobility	Simulation tool
		Single-path	Multi-path	Unicast	Multicast/ Broadcast	Flooding	Awareness		Dimensions			
							Physical	Logical	2D	3D		
Pierobon et al. (2014)	MHTD	X		X			X		X			NA
Tsioliaridou et al., (2015) and Tsioliaridou et al. (2016)	CORONA		X	X	X		X			X		Any-Logic
Liaskos et al. (2016)	DEROUS		X	X			X		X			Any-Logic
Tsioliaridou et al. (2017)	SLR		X	X			X			X		Any-Logic
Yu et al. (2017)	TEForward	X		X			X		X			Nano-Sim (NS-3)
Oukhatar et al. (2017)	EFBA		X		X	X		X		X	X	Nano-Sim (NS-3)
Arrabal et al. (2018b)	EMHB/DEA		X		X	X	X		X			BitSi-mula-tor
Afsana et al. (2018)	ECR	X		X			X		X			Nano-Sim (NS-3)
Wang et al. (2018)	MDRQEN	X		X			X		X			(NS-3)
Abuali et al. (2018)	Flooding @NanoSim		X		X	X				X	X	Nano-Sim (NS-3)
	AODV	X		X			X			X	X	Nano-Sim (NS-3)
Ferjani and Touati (2019)	GRA	X		X			X		X			probably Nano-Sim (NS-3)
Fahim et al. (2020)	EWMA/ABC	X	X	X	X		X		X		X	NanoSim
Wang et al. (2020)	MDR-L	X		X	X			X	X			TeraSim

In this work we proposes a novel forwarding and routing low complexity and flexible strategy for nano-networks based on finite state machines (FSMs) (See Section 4).

FSMs allow to build a logical nano-node addressing scheme of low complexity that provides the flexibility to implement different strategies of multi-path, multicast routing and forwarding, single hop, multi-hop, flooding, physical or logical clustering, mobility, 2D or 3D nano-node deployment.

Resilience is implemented by means of the multi-path routing and forwarding strategy. The FSM-based routes generation procedure avoids the building and storage of routing tables, does not need any signaling routine to discover neighboring nodes, which saves energy and minimizes latency.

In order to perform network complex computations (routing decisions, network partitions, services scheduling, etc), processing workloads are moved to upper layers of the adopted architecture (see Section 3), where high performance devices are provided.

3. A review of the adopted nano-networks' architecture

A unified architecture model for nano-networks has been proposed A.Galal and X.Hesselbach (2018). The model is classified in 4 layers, as shown in Fig. 1.

The nano-network layer contains the nano-devices, providing the basic physical functions required to be able to exchange information: signals, mechanical issues, frequencies, modulation schemes and medium access control strategies. According to this model, the nano-network layer encompasses the functions of the physical, MAC and network layers.

The SDN layer provides flexible control of the traffic to be transmitted. It is also used to facilitate the provisioning of IoT functionalities in the upper layer, such as addressing and simple network services.

In order to perform network complex computations (routing decisions, network partitions, services scheduling, etc), processing workloads are moved to upper layers, where high performance devices are provided. In case of major computational requirements, the NFV layer is able to provide resources from small or even big high-performance centers.

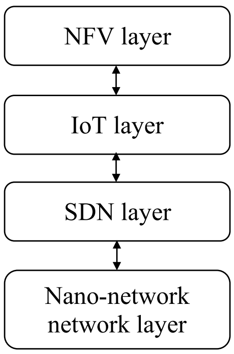

Figure 1: Nano-networks unified architecture model.

To be able to implement the required southbound interface between the SDN and the nano-network layers, a set of atomic (basic and simple) functions have been defined in order to provide a generic way to communicate nano-devices and the control plane. The combination of the eight defined functions shown in Table 2, on page 8, guarantees the execution of any type of action. The set of functions are technology agnostic. They can be performed unicast or broadcast. Not all functions must be implemented, only the ones required for each scenario. Some functions might not be possible to be implemented in some cases due to physical reasons. Exact definitions, sequence diagrams and examples are presented in A.Galal and X.Hesselbach (2018).

Table 2: Set of functions of nano-networks

Function	Description
void **ACTIVATE** (activation-time, ID)	This function is generated by the controller to trigger the nano-device by sending a signal to a certain nano-device's ID to make it active on a specific time. Nano-device's ID can be a specific device or a group of devices.
void **DEACTIVATE** (deactivation-time, ID)	This function is generated by the controller to deactivate the nano-device by sending a signal to a certain nano-device's ID to deactivate it on a specific time.
void **OPERATE** (execution-time, ID)	This function is generated by the controller and it sends an order to a certain nano-device's ID to a start a specific operation during a certain execution time.
void **MOVE** (location, ID)	This function is generated by the controller and sent to the nano-device. It drives a nano-device with a certain ID to a deterministic location.
void **ABORT** (ID)	This function is generated by the controller and sent to the nano-device. It can be used to exit the nano-device from the network and terminate its functionality after a certain process has been accomplished in the area of interest.
data, ID **LISTEN** (void)	This function is generated by the nano-device and it is received by the controller to listen the possible coming messages from a nano-device with a specific ID.
ID **ACK** (message)	This function is generated by the nano-device with a specific ID and it represents an acknowledgement message coming from the activated nano-device to the controller.
location **LOCATE** (ID)	This function is generated by the nano-device and it is received by the controller. It is used to send the location of a certain nano-device with a specific ID to the controller.

4. FSM-based routes generation

figures/Whatever the routing protocol is developed or elected to be used with nano-networks a mechanism to find or generate routes between source and destination nodes has to be devised.

Given the few resources available in nano-routers it is necessary to employ a very simple mechanism of route generation where the main requirements are:

i) avoidance of routing tables to save the resources that are necessary to build and store the tables;

ii) avoidance of any signaling routine to discover neighboring nodes to save energy and minimize latency.

In this section we make a short presentation of Trellis Coded Networks (TCNets) and show their flexibility to implement routing mechanisms in nano-networks.

TCNets have been introduced in Filho and Amazonas (2012), Filho and Amazonas (2013), Filho and Amazonas (2017) where their main properties have been described in detail. In Filho and Amazonas (2014) it has been shown how the TCNets solve the problems of hidden and exposed nodes in WSNs and in Filho and Amazonas (2018) the authors present a set of novel application enabled by TCNets. TCNets constitute an interesting alternative to implement the network layer in nano-networks. The main advantages of TCNets that motivate their use in networks with limited resources are:

- elimination of routing tables;
- reduced latency because no signaling messages exchange is necessary as is the case, for example, with the AODV (Ad hoc On-Demand Distance Vector Routing) and DSR (Dynamic Source Routing) protocols that need route request (RREQ) and route reply (RReply) signaling packets to establish a route;
- self-recovery mechanism in case of failure derived from the robustness of the trellis decoding mechanism.

TCNets are implemented by means of finite state machines (FSMs) where each state is associated to a node of the network. A route in the network corresponds to a sequence of states to be visited in the FSM. Fig. 2 shows a network node modeled by a state of a FSM. In the figure, *state (i)* represents *node (i)* and *state (j)* represents *node (j)*.

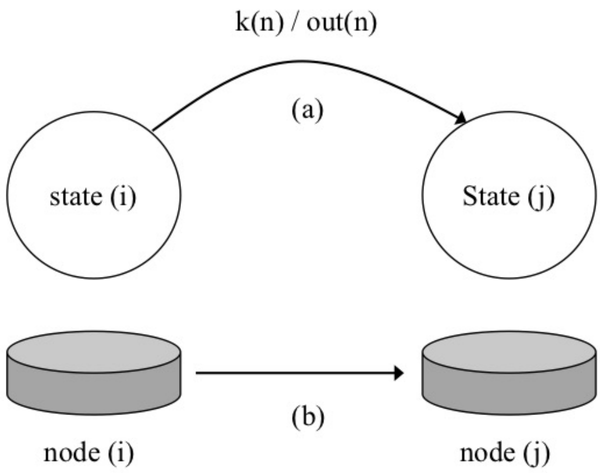

Figure 2: Network node modeled by a state of a FSM.

If each node in the network implements the FSM then it has a complete knowledge of the network's logical topology without the need of building and storing a routing table. This is quite adequate to be employed in WSNs and nano-networks because the FSM may be of very low complexity employing only shift registers and exclusive-or (XOR) gates as can be seen in Fig. 3. When an input sequence $k(n)$ is applied to the FSM, the machine goes from *state (i)* to the *state (j)*. In the network, this means that a packet is sent from *node (i)* to *node (j)*. When the FSM makes the transition from *state (i)* to the *state (j)* it generates an output sequence $out(n)$.

Fig. 3 shows an $N = 8$ states FSM. The current and next states are given by $\{s_2, s_1, s_0\}$ and $\{s_3, s_2, s_1\}$ respectively. The input sequence $k(n)$ is stored in the register's position s_3. The output sequence is given by $out(n) = \{n_1, n_2\}$, where $n_1 = s_3 \oplus s_2 \oplus s_1 \oplus s_0$ and $n_2 = s_3 \oplus s_2 \oplus s_0$.

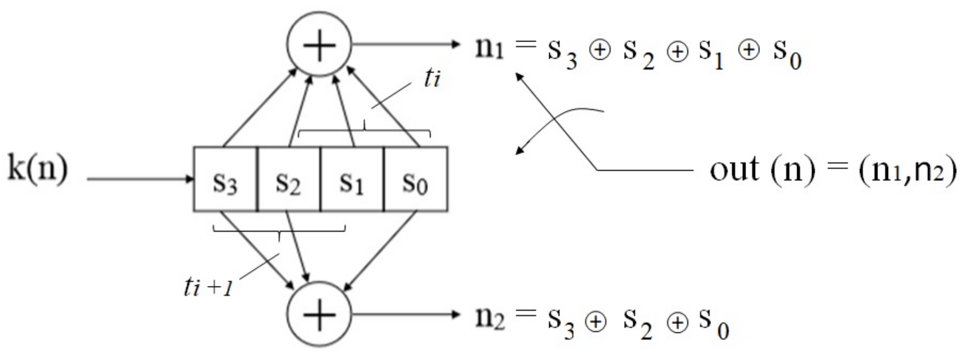

Figure 3: An 8 states FSM.

Table 3 shows the state table for the FSM represented in Fig. 3. The states, $k(n)$ and $out(n)$ are represented using decimal notation.

Table 3: State table for the FSM represented in Fig. 3

Current state	***k*(n)**	**Next state**	***out*(n)**
0	0	0	0
0	1	4	3
1	0	0	3
1	1	4	0
2	0	1	2
2	1	5	1
3	0	1	1
3	1	5	2
4	0	2	3
4	1	6	0
5	0	2	0
5	1	6	3
6	0	3	1
6	1	7	2
7	0	3	2
7	1	7	1

The number of registers needed to implement an N states FSM is $1 + \log_2 N$ providing an inherent scalability of the architecture.

In this work we don't use the output sequence $out(n)$ that is an essential feature to deal with transmission errors, node failures, hidden and exposed nodes. These aspects, that are also important for nano-networks, will be dealt with in future works. For this reason, we designate the routes generation procedure proposed in this work as finite state machine (FSM)-based routes generation, a simplified version of TCNet.

Let's consider a nano-network with the following characteristics:

- N = 32: the nano-network has 32 nodes that is logically represented by a FSM with 32 states.
- the FSM states are represented by 5 bits.
- The next state is obtained by shifting-in 2 bits ($k(n) = \{k_1, k_0\}$)

This being so, the current state is represented by $s(n) = \{s_4, s_3, s_2, s_1, s_{\}}$ and the next state is $s(n+1) = \{k_1, k_0, s_4, s_3, s_2\}$. For an input sequence $k(n)$ with 2 bits, from a current state $s(n)$ up to four states can be reached directly corresponding to the four combinations of 2 bits available for $k(n)$.

Table 4 shows the state table for a 5 bits FSM and an input sequence $k(n)$ of 2 bits. For example, looking at the first line of the table, if the current state is (in decimal notation) $s(n) = 0$, and the input sequence is $k(n) = \{0, 1\}$ then the next state is $s(n+1) = 8$. If the current state is (in decimal notation) $s(n) = 1$, for the same input sequence $k(n) = \{0, 1\}$ then the next state is $s(n+1) = 8$ too.

If, instead of using an input sequence $k(n)$ of 2 bits an input sequence of 3 bits were used then from any current state 8 states could be directly reached.

Finding paths is equivalent to find an input sequence $k(n)$ that will make the FSM traverse a set of states and end at the state corresponding to the destination node. In this work we adopt this idea for the routing procedure.

Find paths between the source node s = 12 and the destination node d = 23: in this case the source ID = 12 ⇒ (01100) and the destination ID = 23 ⇒ (10111).

- **Case 1: direct paths**

  $k(n) = \{k_1, k_0\} \rightarrow (01100) \Rightarrow (k_1, k_0 011) \Rightarrow$ always different from (10111) ⇒ there is no direct path between s = 12 and d = 23.

Table 4: State table for a 5 bits FSM and an input sequence $k(n)$ of 2 bits

Current state	**k(n)** =	Next state for			
		00	**01**	**10**	**11**
0, 1, 2, 3		0	8	16	24
4, 5, 6, 7		1	9	17	25
8, 9, 10, 11		2	10	18	26
12, 13, 14, 15		3	11	19	27
16, 17, 18, 19		4	12	20	28
20, 21, 22, 23		5	13	21	29
24, 25, 26, 27		6	14	22	30
28, 29, 30, 31		7	15	23	31

– **Case 2: 2 hops paths**

In this case it is necessary to consider two input 2 bits sequences applied one after the other that will be represented as $k(n) = \{k_3, k_2, k_1, k_0\}$.

$k(n) = \{k_3, k_2, k_1, k_0\} \rightarrow (01100) \Rightarrow (k_3, k_2, k_1, k_0 0) \Rightarrow$ always different from $(10111) \Rightarrow$ there is no 2 hops path between s = 12 and d = 23.

– **Case 3: 3 hops paths**

In this case it is necessary to consider three input 2 bits sequences applied one after the other that will be represented as $k(n) = \{k_5, k_4, k_3, k_2, k_1, k_0\}$.

$k(n) = \{k_5, k_4, k_3, k_2, k_1, k_0\} \rightarrow (01100) \Rightarrow (k_5, k_4, k_3, k_2, k_1) = (10111) \Rightarrow$ there are two possible choices for k_0 and consequently two distinct paths between s = 12 and d = 23.

For $k(n) = \{k_5, k_4, k_3, k_2, k_1, k_0\} = (101110) \rightarrow (01100)$ the traversed states are:

. $(01100) = 12$

. $(10011) = 19$

. $(11100) = 28$

. $(10111) = 23$

For $k(n) = \{k_5, k_4, k_3, k_2, k_1, k_0\} = (101111) \rightarrow (01100)$ the traversed states are:

. $(01100) = 12$

. $(11011) = 27$

. $(11110) = 30$

. $(10111) = 23$

Increasing the length of the input sequence $k(n)$ longer paths may be generated. The procedure to generate paths of any length is very simple as it is sufficient to:

- assign the logical ID of the destination node to the most significant bits of $k(n)$;
- generate all possible combinations for the remaining bits of $k(n)$.

The procedure may be followed by a routes filtering algorithm to select, for example, only the disjoint routes or to avoid any specific node.

5. Novel nano-routing scenarios strategies

Routing in nano-networks is a very challenging task for the following reasons, at least:

- the nodes have very few resources available in terms of energy, storage and processing power;
- the nodes have a high failure being not available to perform any task;
- the nodes may be distributed in such a way that the network is not connected;
- the nodes may not know their physical location;
- the nodes may be highly mobile.

In summary, it can be said that in general terms routing has to be provided for a network with unknown and changing topology.

5.1. Routing scenarios

We consider scenarios with the following characteristics.

Application domain. Nano-networks may be employed in many different domains going through new meta-materials, automation, surveillance, medicine, among others. It is out of scope of this work to discuss any specific application but to consider general scenarios in which the topology is 2D, the devices are assigned to perform specific tasks, task-wise the network is made of heterogenous devices and the nodes may be highly mobile. The extension to the 3D case is straightforward and is not be dealt with in this paper.

Nodes. Two types of nodes are considered: i) nano-routers; and ii) nano-devices.

Nano-routers are in charge of receiving / exchanging commands from / with the SDN controller and prepare the messages to be broadcast to the nano-devices within its coverage area. Alternatively, the nano-router may have to send a message to another nano-router to execute the command. The destination nano-router may be within the transmission range of the source or not. Nano-routers have a logical individual identity and, optionally, one or several logical group identities.

Nano-devices are very small and specialized machines in charge to execute a task as, for example, measure the temperature, measure the environment's ph, to release a medicine and so on. They are restricted to receive and execute commands, and to transmit their sensed data and ACK messages to their controlling nano-router. They do not have an individual identity. They are addressed at the physical level by selecting, for example, the radio-frequency they are able to receive.

Communication. It is implemented by wireless radio-frequencies. Only the nano-routers are able to transmit commands to the nano-devices and messages to other nano-routers or to the gateway. The communication is always made in broadcast mode with a controlled level of transmission power. The nano-router may transmit in two different modes. When it transmits to the nano-devices under its control it employs its nominal unit transmission power so the range is limited to its nominal coverage area minimizing the interference with the adjacent cells. When it has to transmit a message to another nano-router that may be located far away from the source, it may increase its transmission power to increase the probability that the message arrives at the destination. The transmission power is limited so the transmission range is confined to a few cells away from the source.

Figure 4 illustrates a nano-router transmitting in three different modes. The nano-routers are represented by the colored circles in the center of the cells. In the first mode, indicated by $(Tx\ range) = 1$, the central (blue) nano-router is employing its unit transmission power and the signal arrives at all nano-devices within its coverage area represented by the central hexagon cell (blue circle). In the second mode, indicated by $(Tx\ range) = 2$, the central nano-router is employing the second level of its transmission power and the signal arrives at the (red) nano-routers located in the cells adjacent to the central cell (pink circle). In the third mode, indicated by $(Tx\ range) = 3$, the central nano-router is employing the third level of its unit transmission power and the signal arrives at the (yellow) nano-routers located in the cells adjacent to the central cell and at the (yellow) nano-routers located in the outer cells (yellow circle). The actual transmission power employed in each of the cases depends on the size of the network and electromagnetic propagation conditions of the environment. The propagation and absorption loss of electromagnetic waves in the THz band has been studied in Jornet and Akyildiz (2011), Abbasi et al. (2016).

The transmission is a configurable and an application specific variable that is used to achieve a tradeoff between the energy consumption, packet delivery ratio and latency.

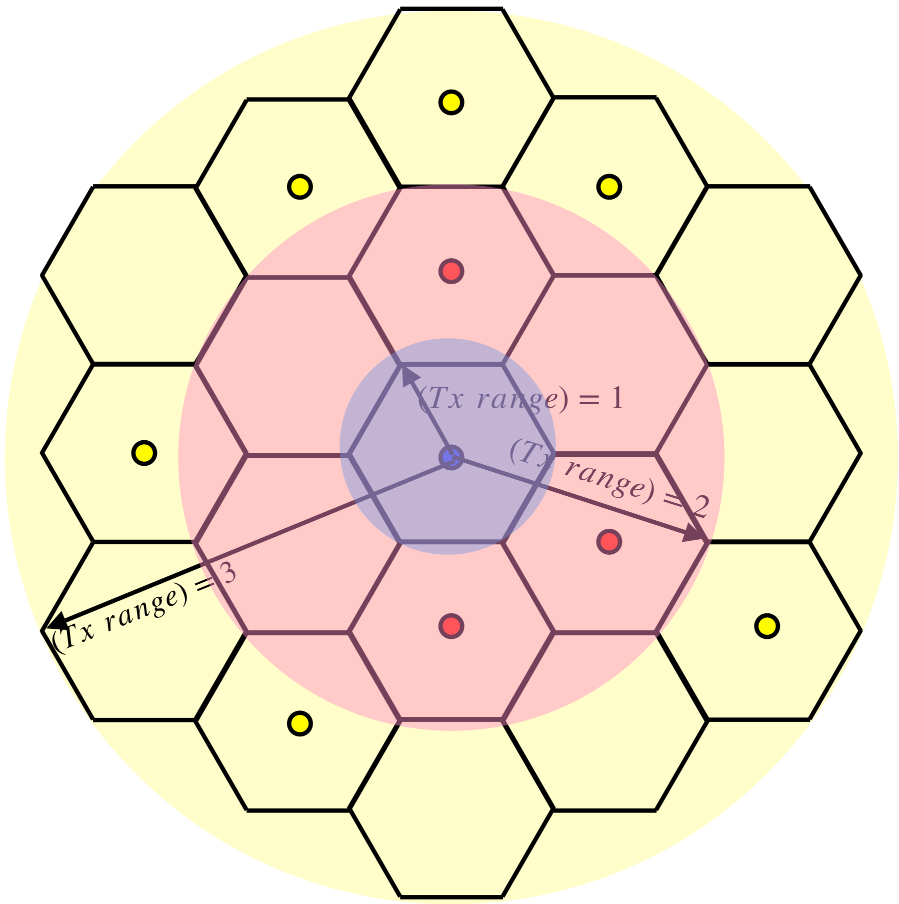

Figure 4: An illustration of a nano-router transmitting with three different power levels.

Physical layer protocol. It is out of the scope of this work to evaluate the performance of the proposed routing procedures as function of the employed physical layer protocol. Without loss of generality, it is assumed, as by most of the nano-networks research papers, that the TS-OOK (e.g. Arrabal et al. (2018a) Arrabal et al. (2018b)) modulation scheme is used because of its high temporal multiplexing capability.

MAC layer protocol. It is out of the scope of this work to evaluate the performance of the proposed routing procedures as function of the employed MAC layer protocol. Without loss of generality, it is assumed, as by most of the nano-networks research papers, that the transparent MAC (e.g. Abuali et al. (2018) Afsana et al. (2018)) scheme is used because of its simplicity where the received packet from the network layer is transmitted to the physical interface without handling any flow control, error control or adding any headers to the packet.

Routes generation. We adopt the FSM-based routes generation procedure outlined in Section 4.

The evaluation of the routes generation and associated communication protocols has been implemented using the software R. R is a language and environment for statistical computing and graphics. The term "environment" is intended to characterize it as a fully planned and coherent system, rather than an incremental accretion of very specific and inflexible tools, as is frequently the case with other data analysis software. R provides a wide variety of statistical (linear and nonlinear modelling, classical statistical tests, time-series analysis, classification, clustering, ...) and graphical techniques, and is highly extensible. R is not a network simulation tool as, for example, the NanoSim (NS-3) (e.g. Abuali et al. (2018)). Using R we wrote a simple events oriented simulator to evaluate the metrics defined in Section 5.2 [1].

5.2. Evaluation metrics

We define *reachability* (r) as the percentage of node pairs that can communicate directly without any intervening intermediate node.

We evaluate r as function of the transmission range and the density of nodes in the considered area. This results help to interpret the routing strategies performance for different scenarios of interest.

Once the topology is known the corresponding adjacency matrix is evaluated by simply comparing the distance between two nodes with the transmission range. The percentage of $1's$ in the adjacency matrix is the *reachability* (r) of the network.

The nano-routing scenarios strategies will be evaluated according to the following metrics:

- Packet Delivery Ratio (PDR) is the ratio between the number of packets that arrived in the destination and the number of packets sent between source and destination.

- Average Number of Hops (ANH) is evaluated considering only the routes that are able to deliver a packet to the destination. It is a measure of the average latency.

- Energy Consumption per Packet (ECP) is the sum of the energy spent by each node participating in route. The energy model considers the following contributions:
  - E_{rg} is the energy necessary to generate a route;
  - E_{tx} is the energy necessary to transmit a packet;
  - E_{fw} is the energy necessary to forward a packet, i.e., the energy necessary to identify that the packet has not arrived at the destination and must be forwarded to the next hop;
  - E_{rx} is the energy necessary to receive a packet;
  - E_{dc} is the energy necessary to decode a packet and prepare it to be processed by the destination node.

  The energy necessary to transmit a packet, E_{tx}, is given by Eq. (1).

$$E_{tx} = (E_{tx})_c \times (Tx\ range)^{\alpha_{tx}} \quad (1)$$

  where

  - $(E_{tx})_c$ is the energy transmission coefficient;
  - $(Tx\ range)$ is the target transmission range; and

[1] Information about the R project is available in its website https://www.r-project.org.

– α_{tx} is the energy transmission exponent. Different values of α_{tx} enable to model different propagation environments Abbasi et al. (2016).

The energy necessary to take a packet from source s to destination d is given by Eq. (2).

$$\mathrm{ECP} = E_s + N_h E_h + E_d \tag{2}$$

where E_s, E_h and E_d are the energy consumed by the source, hidden and destination nodes, and N_h is the number of hidden (intermediate) nodes in the route. E_s, E_h and E_d are, respectively, given by Eqs. (3), (4) and (5).

$$E_s = E_{rg} + E_{tx} \tag{3}$$

$$E_h = E_{rx} + E_{fw} + E_{tx} \tag{4}$$

$$E_d = E_{rx} + E_{dc} \tag{5}$$

- Energy Consumption per Message (ECM) is the sum of ECP for all packets sent between a source and a destination nodes.
- Total energy is the sum of ECM ($\sum(ECM)$) for all messages sent from a node to a set of destination nodes.

6. Evaluation and results

The parameters used in the simulations are:

- topologies: random and uniform over a 10×10 area denoted by A ([2]);
- transmission range varying in unit steps from 1 up to covering completely the area of the network;
- density of nodes $\delta_n \in \{0.16, 0.32, 0.64, 1.28\}$ leads to the number of nodes by $N = \delta_n \times A$ ([3]).

Figures 5 and 6 show the reachability of uniform and random topologies as a function of the transmission range and of the density of nodes. It can be seen that:

- there is no noticeable difference between the uniform and random topologies;
- the reachability is not affected by the density of nodes;
- to achieve a reachability of 60% the transmission range has to be around 6, i.e., meaning 60% of the networks' area and consequently consuming large amounts of energy.

[2]The units are arbitrary as the reachability results are not affected by such units.

[3]Without loss of generality these density of nodes values have been adopted because they lead to a number of nodes that is a power of 2 easing the routes generation procedure (see Section 4).

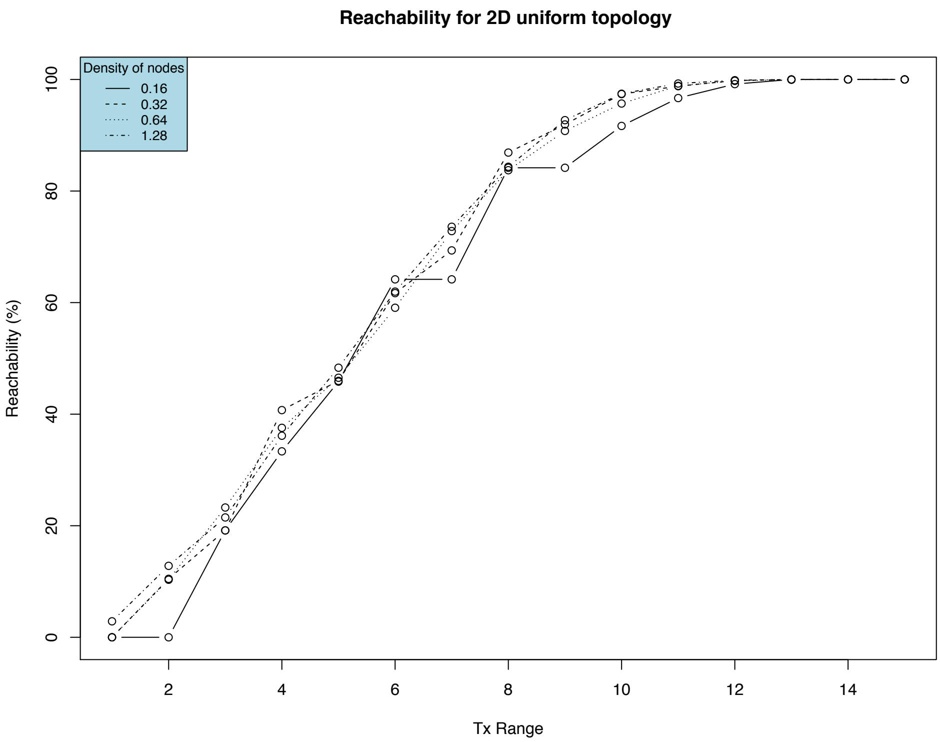

Figure 5: Uniform topologies' reachability.

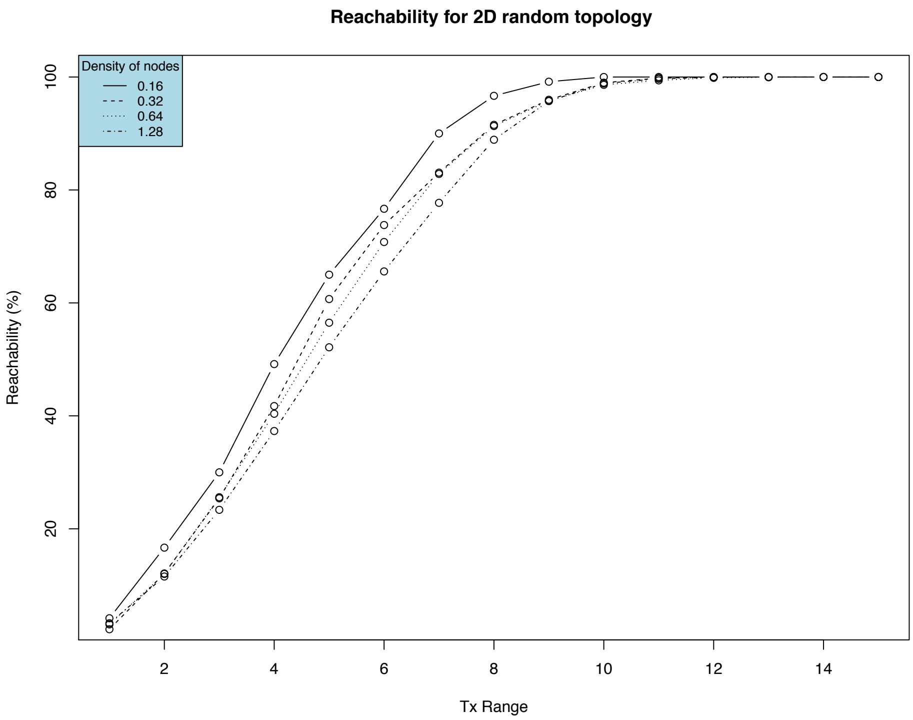

Figure 6: Random topologies' reachability.

Figures 7 and 8 show the number of neighbors of uniform and random topologies as a function of the transmission range and of the density of nodes. It can be seen that:

- there is no noticeable difference between the uniform and random topologies;
- as expected, the number of neighbors increases when either the transmission range or the density of nodes increases;
- however the increase of the number of neighbors is not reflected in an increase of the reachability because when the number of neighbors increases the number of no-neighbors also increases.

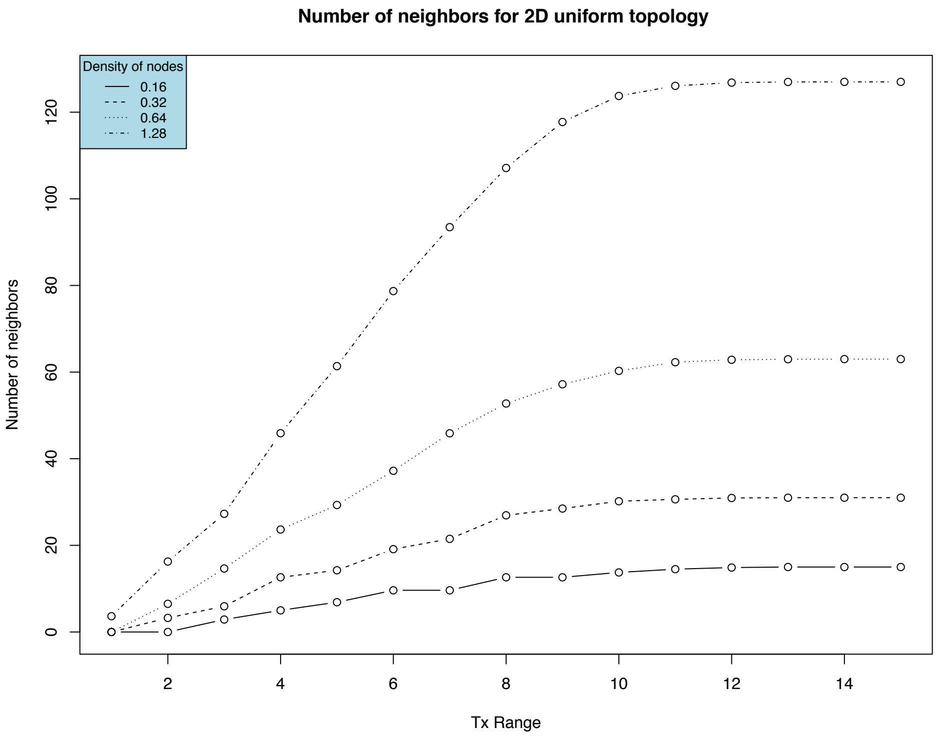

Figure 7: Uniform topologies' number of neighbors.

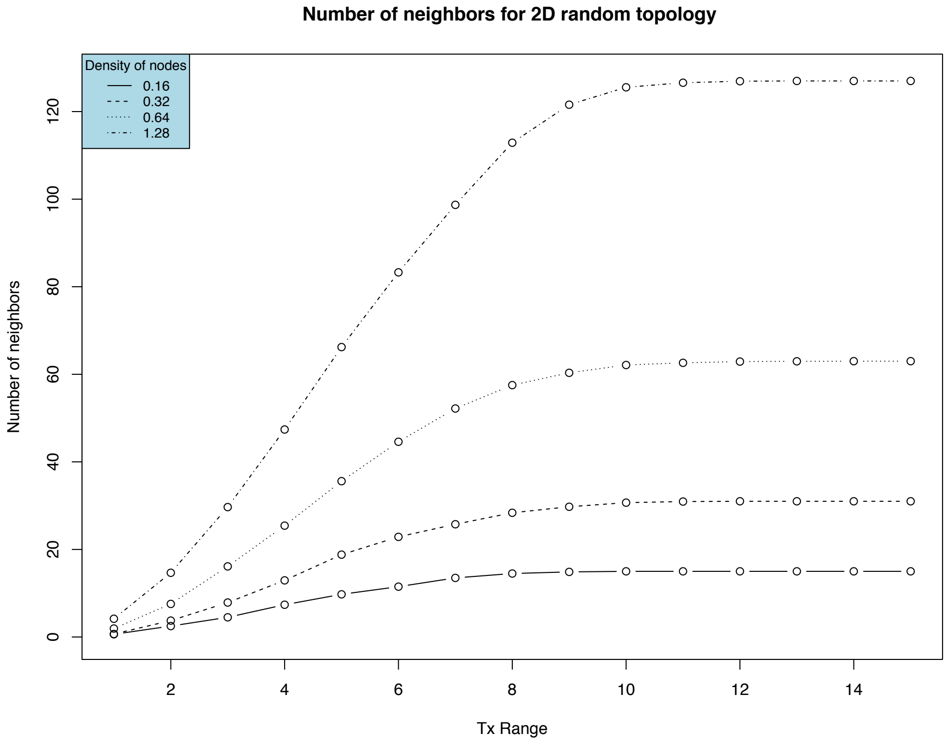

Figure 8: Random topologies' number of neighbors.

In order to evaluate the FSM-based routes generation procedure and the associated communication protocols we adopt a simple end-to-end multipath routing scenario. In this scenario the objective is to send a message from one source node to one destination node following one or a few determined routes. The scenario has the following characteristics:

- each node (nano-router) has an individual logical identity;
- the nodes don't know their physical position;
- the nodes don't store any routing table;
- the source node generates a certain number of routes to the destination node;
- the source node transmits a packet corresponding to each generated route;
- all nodes in the route transmit in the broadcast mode and use the same transmission power;
- all nodes have means to detect duplicate packets and to discard them.

The routes generation process is described in Section 4 and is characterized by two parameters:

- k-sequence – is a binary sequence that codes the logical identity of the nodes belonging to the route. This sequence has a pre-defined length (k-sequence length): the larger its value, the larger is the number of nodes that may be chosen as the next hop;
- maximum number of hops – defines the maximum number of nodes that may belong to a route: the larger its value, the larger is the number of generated routes.

The routes generation process is completely blind in the sense that the node selected to be the next hop may be out of the reach of the forwarding node given the limited transmission power. This being so, even though the generated route is logically correct it may not be a valid path and in this case the transmitted packet will be lost along the way and not reach the destination node.

A typical simulation consists of choosing a source reference node among the central (C), top left (TL), top right (TR), bottom left (BL) or bottom right (BR) nodes, generating routes to all other networks' nodes and evaluating the performance.

Due to the large variety of application domains, topologies and evaluation metrics, it is very difficult to compare the results of various strategies. So, we adopted the flooding scheme as the reference to compare our results with. Flooding implements message retransmission by all involved nodes without identification of duplicated messages. Flooding is simple and reliable due to redundant transmissions and being independent of any topology-dependent initialization. Unmodified flooding involves a high number of redundant transmissions making it quite inneficient by nature, when one-to-one communication is required, since all nodes in the network receive each message (Lemic et al. (2020)).

Table 5 shows the input parameters used in the simulations with typical values assigned to them. The parameters whose values were changed along the simulation runs are indicated in *italics*.

Table 5: Simulation parameters typical values

Parameter	**Value**
Routing Parameters	
k-sequence length	$\{2, 3, 4\}$
Maximum number of hops	$\{3, 4, 5\}$
Reference source node	$\{\mathrm{C}, \mathrm{TL}, \mathrm{TR}, \mathrm{BL}, \mathrm{BR}\}$
Random topology setup	
Geometry	Square
Side size	10
Density of nodes	$\{0.32, 0.64, 1.28\}$
Energy model parameters	
E_{rg}	5
$(E_{tx})_c$	2
α_{tx}	2
E_{rx}	1
E_{fw}	1
E_{dc}	3

Figure 9 shows the 32 nodes random topology used in the simulations. The central node (number 28) is indicated by a red triangle.

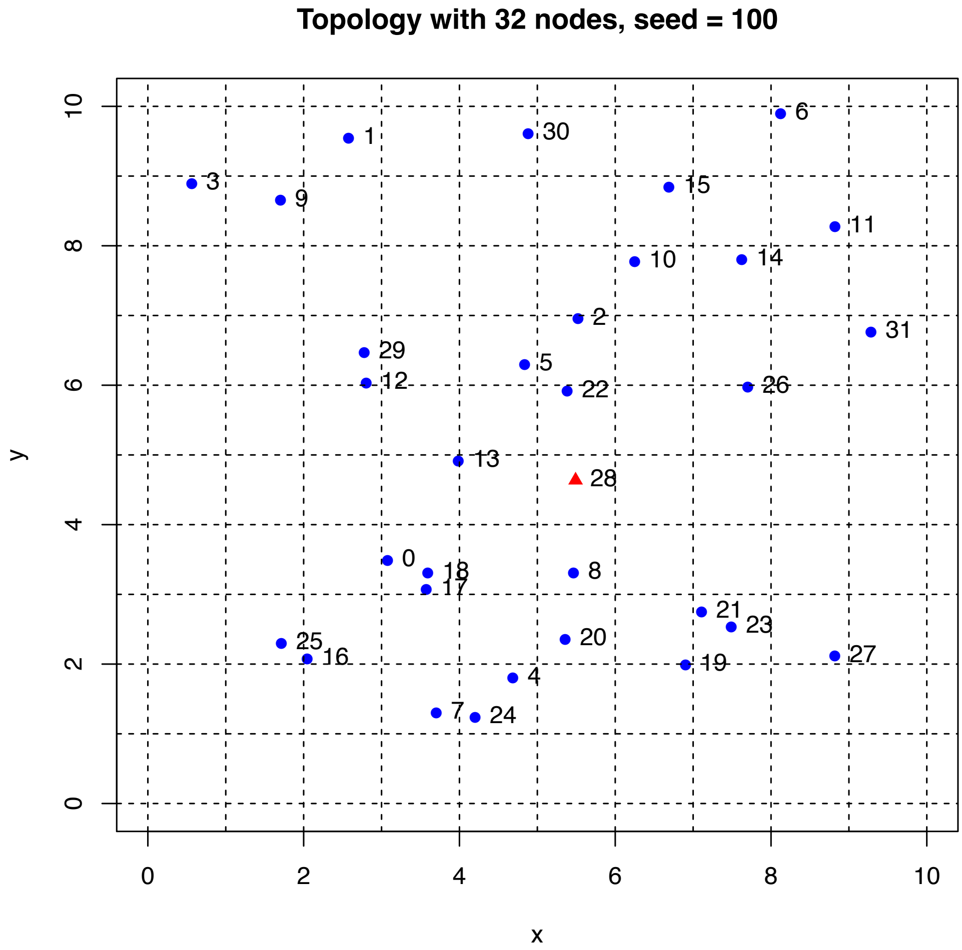

Figure 9: Random topology with 32 nodes.

For this topology and with simulation parameters given in Table 5, a total of 275 routes have been generated. For each of these routes the minimum transmission range to make the route valid was evaluated. The distribution of the minimum transmission range values in shown in Figure 10.

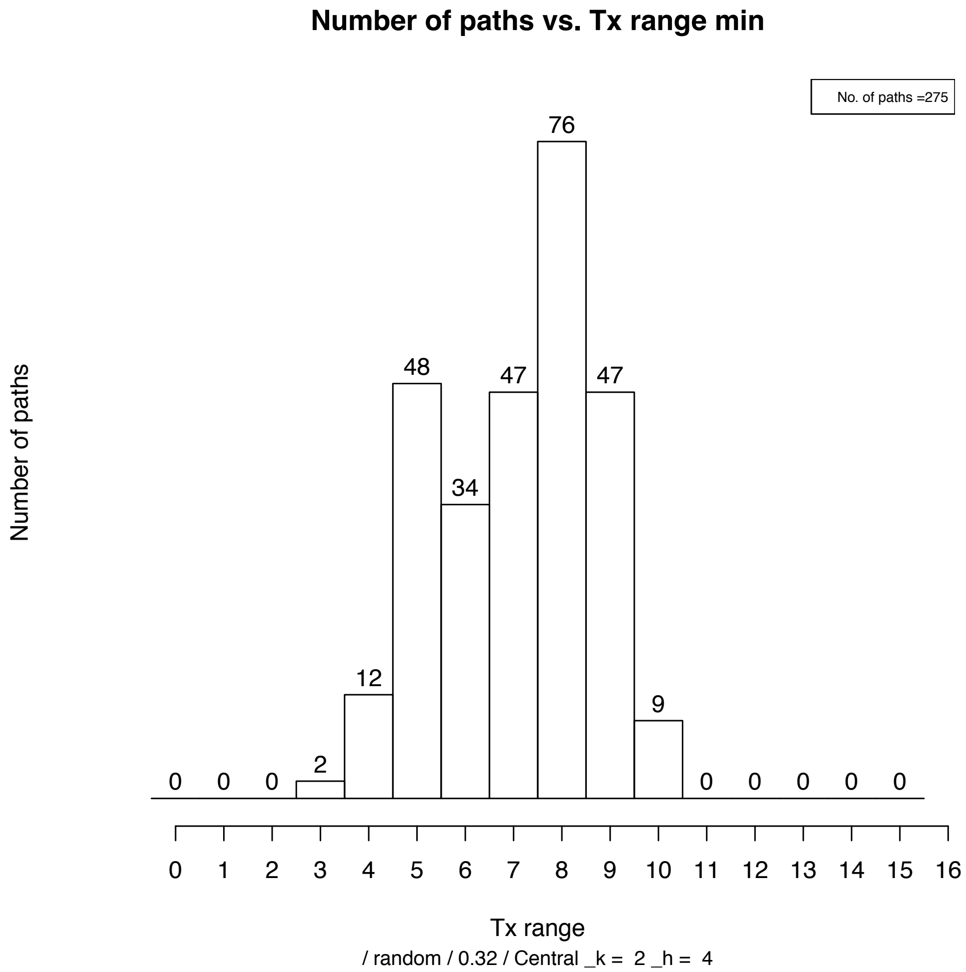

Figure 10: Minimum transmission range distribution.

Figure 11 shows the PDR as function of the transmission range.

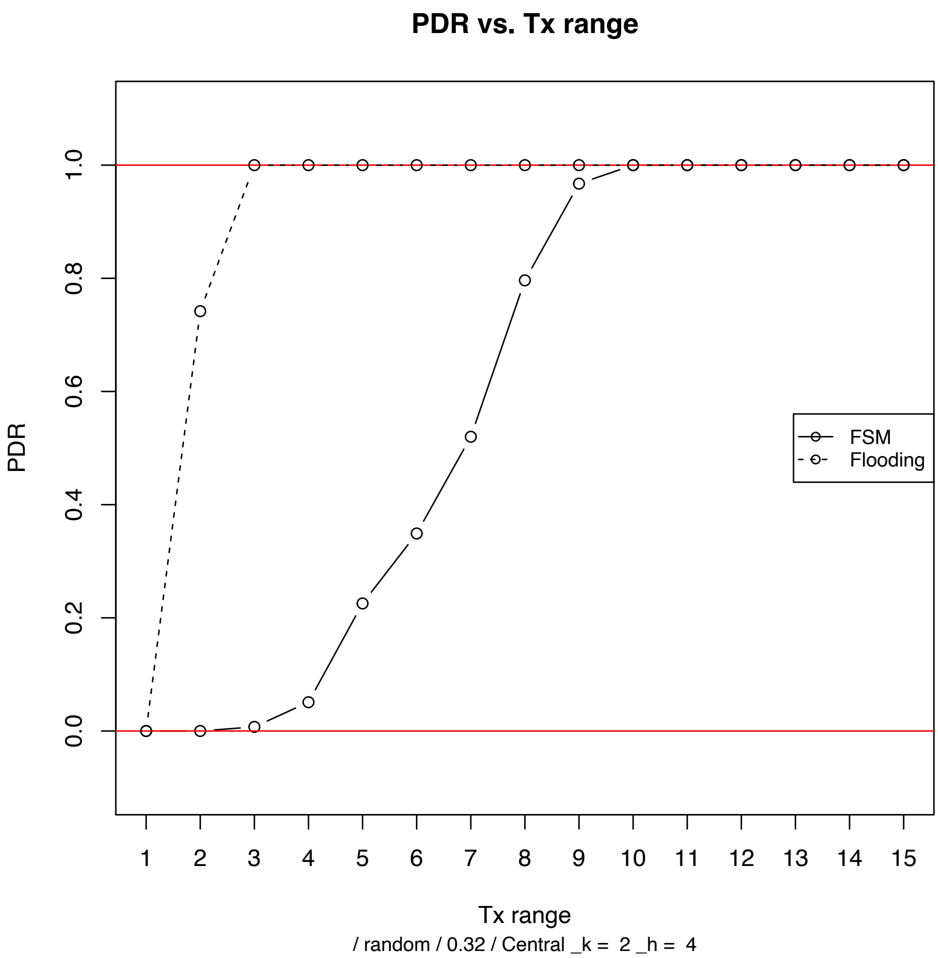

Figure 11: PDR as function of the minimum transmission range.

According to Figures 10 and 11 it can be seen that for the FSM-based scheme to achieve a PDR at least of 50% it is necessary to have a minimum transmission range of 7, while for the flooding-based scheme a minimum transmission range of 2 is enough. This result is not surprising due to the unconditional retransmission of messages employed by the flooding-based scheme.

Figure 12 shows the total energy consumption as function of the minimum transmission range. The solid lines are the results for the FSM-based scheme while the dashed lines are for the flooding-based one. The lines in black represent the total energy necessary to ensure that all 275 generated routes are valid. In this case, all nodes use the same transmission power. We assumed that the energy transmission exponent α_{tx} is equal to 2. This represents a best case, as the value 2 corresponds to the propagation loss in the free space. More realistic scenarios require a larger value of α_{tx}. It is clearly observed that for any transmission range greater than 2 the flooding-based scheme energy consumption may be orders of magnitude higher than for the FSM-based one.

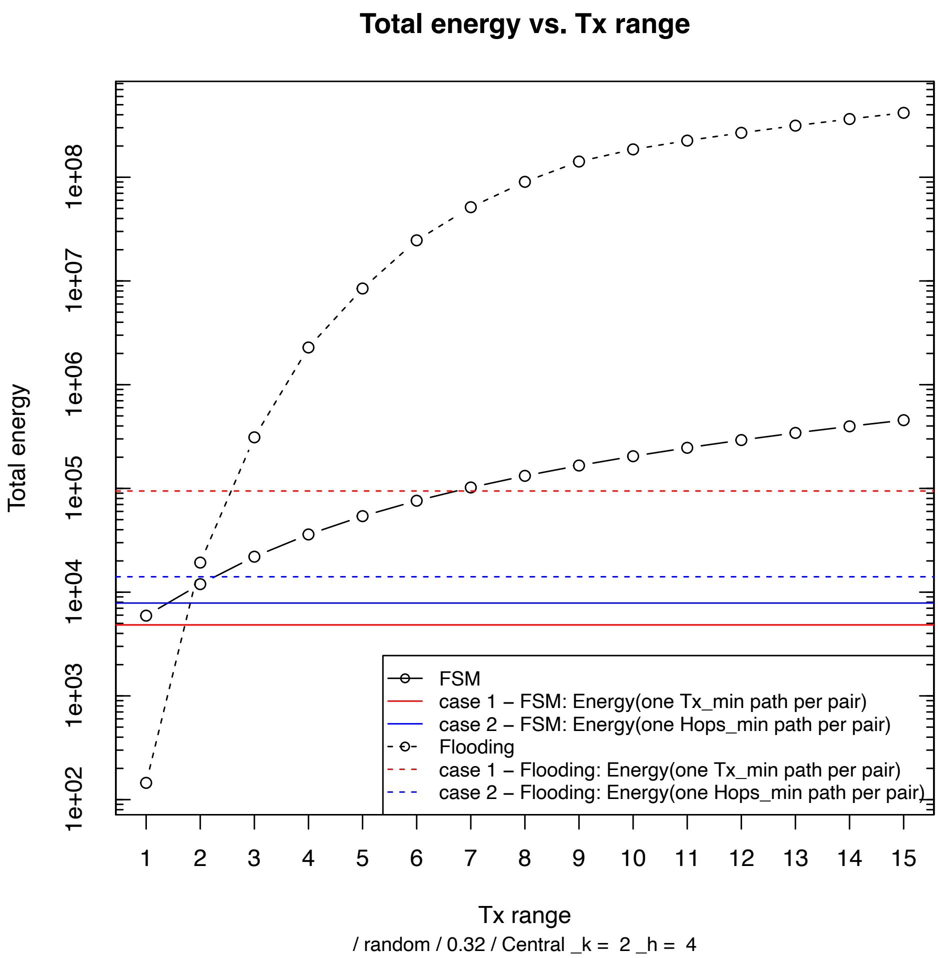

Figure 12: Energy consumption as function of the minimum transmission range.

Obviously, to use the 275 paths to send the messages from the reference source node to all destination nodes represents a waste of energy.

An alternative strategy may be envisaged such that for each pair of nodes only the best route is used. The lines in red and blue in Fig. 12 represent the total energy consumption when only the best route is used for each pair of nodes according to the following criteria:

- case 1 (red line): smallest transmission range
  - FSM-based scheme: Total energy = 4837;
  - Flooding-based scheme: Total energy = 94507.
- case 2 (blue line): smallest latency, i.e., the minimum number of hops
  - FSM-based scheme: Total energy = 7855;
  - Flooding-based scheme: Total energy = 14074.

For the FSM-based scheme, Figs. 13 and 14 show the number of hops for every route between the central node and each other network's node for cases 1 and 2, respectively. In the former case the ANH is equal to 3, while in the second case is equal to 2.35.

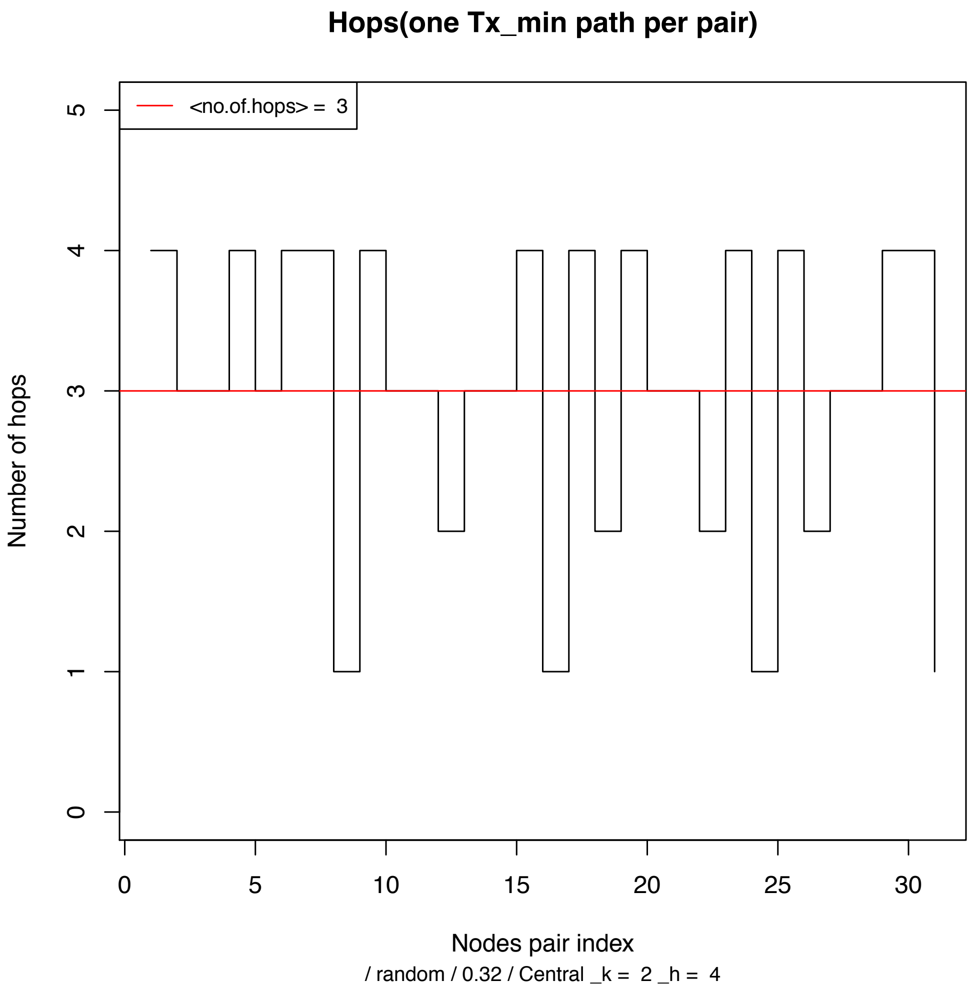

Figure 13: Number of hops for the case 1 energy optimization strategy.

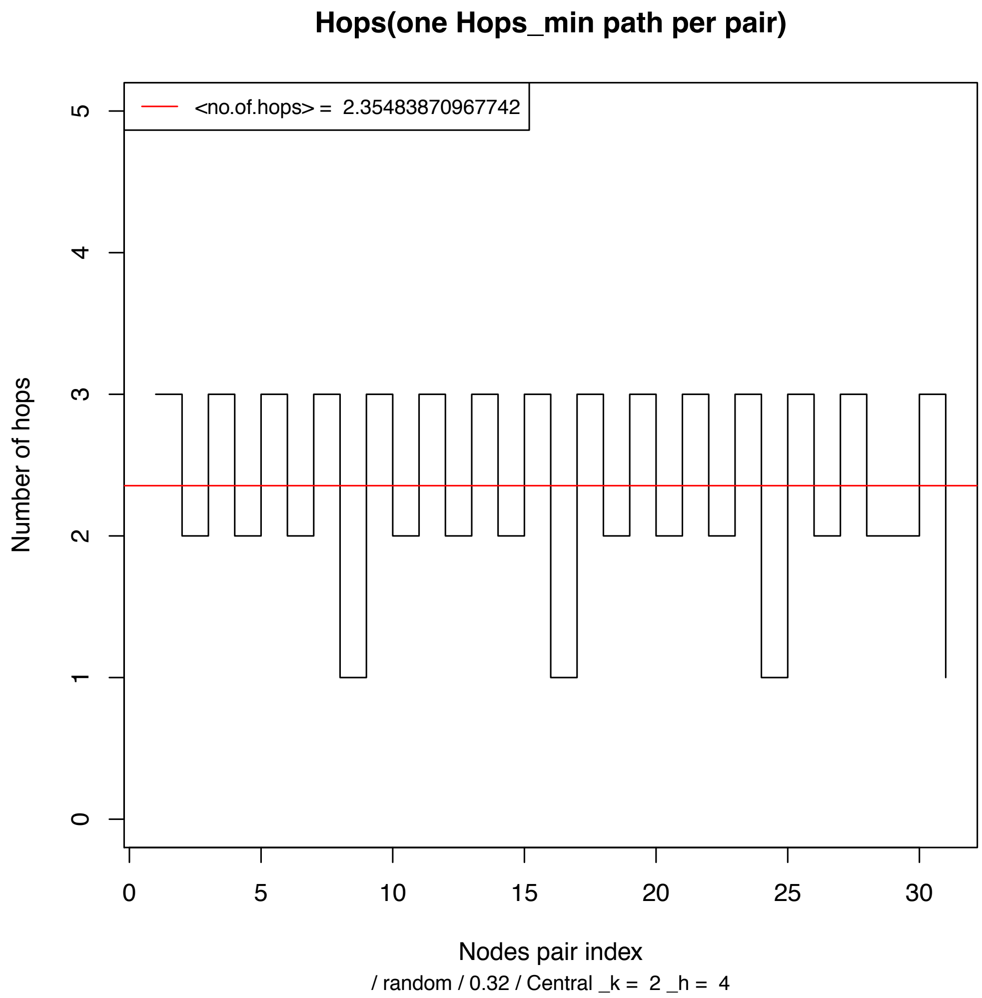

Figure 14: Number of hops for the case 2 energy optimization strategy.

6.1. Results discussion

The use of just the best route between the source node and the destination node is a minimum energy solution but without any resilience to cope with failures.

The energy values that have been evaluated represent lower limits because it was considered only the energy consumption of the nodes belonging to a route. However, as any forwarding node transmits in broadcast within its transmission range, all the nodes in the coverage area receive the packet and must decode it to check if they have to forward or discard the packet. The energy spent by the nodes that discard the packets as well the energy eventually spent with ACK responses have not been taken into account.

Tables 6 (page 27), 7 (page 27) and 8 (page28) show the simulation results for density of nodes equal to 0.32, 0.64 and 1.28, respectively, different values of the k-sequence length and the maximum number of nodes, both for the FSM-based and flooding-based schemes. These results were obtained for the central node as the source node. Similar results were obtained for all other cases.

For the FSM-based scheme, it can be seen that the average distance between pairs of nodes does not change much increasing the density of nodes. The immediate consequence of this is that the $(Tx\ range)_{min}$ necessary to achieve PDR > 0.5 is either 7 or 8 in all cases. This result can be easily explained taking into account the reachability and number of neighbors behaviors depicted in Figures 6 and 8, respectively.

According to these figures, increasing the density of nodes the reachability remains almost constant in spite of the increase in the number of neighbors. This result suggests that this strategy is not adequate if the objective is to implement point-to-point communication using the minimum amount of transmission power in order to avoid inter-cells interference.

The k-sequence length and the maximum number of hops have a huge impact on the number of routes that are found. The k-sequence length has much more impact than the maximum number of hops because as we increase it we increase the number of nodes that can be reached in just one hop. In other words, we increase the breadth of the multipath. The k-sequence length and the maximum number of hops are the parameters that control the search across the solution space. However, increasing these parameters there is an explosive increase of the computing time and the number of solutions that are found and that should be filtered. Such increase is incompatible with the processing and storage resources of the nano-routers.

It can also be seen that the quality of solution either in terms of total energy per pair or latency, measured by the ANH varies with the k-sequence length and the maximum number of hops. The best solution has always been found when the k-sequence length was largest.

Table 6: Simulation results: density of nodes = 0.32; number of pairs of nodes = 31; average distance between nodes = 4.689

				FSM-based scheme					
k-seq length	**Max no. hops**	**No. routes**	**(Tx range)$_{min}$ (PDR > 0.5)**	**Total energy case 1**	**Total energy per pair case 1**	**ANH case 1**	**Total energy case 2**	**Total energy per pair case 2**	**ANH case 2**
2	4	275	7	4837	156.0	3.00	7855	253.4	2.35
3	4	3602	7	3015	97.2	2.55	5489	177.1	1.74
2	5	977	8	4757	153.4	3.22	7855	253.4	2.35
4	3	3736	7	1533	49.4	2.26	3919	126.4	1.48
				Flooding-based scheme					
k-seq length	**Max no. hops**	**No. routes**	**(Tx range)$_{min}$ (PDR > 0.5)**	**Total energy case 1**	**Total energy per pair case 1**	**ANH case 1**	**Total energy case 2**	**Total energy per pair case 2**	**ANH case 2**
-	4	-	2	94507	3048.6	2.84	14074	454	1
-	5	-	2	305875	9866.9	3.35	14074	454	1
-	3	-	2	20773	670.1	2.48	14074	454	1

Table 7: Simulation results: density of nodes = 0.64; number of pairs of nodes = 63; average distance between nodes = 4.997

				FSM-based scheme					
k-seq length	**Max no. hops**	**No. routes**	**(Tx range)$_{min}$ (PDR > 0.5)**	**Total energy case 1**	**Total energy per pair case 1**	**ANH case 1**	**Total energy case 2**	**Total energy per pair case 2**	**ANH case 2**
2	4	313	7	13157	208.8	3.33	18085	287.1	2.62
3	4	3724	7	5399	85.7	2.79	7993	126.9	1.88
2	5	1182	7	12239	194.3	3.84	18085	287.1	2.62
4	3	4052	7	4337	68.8	2.38	8247	130.9	1.75
				Flooding-based scheme					
k-seq length	**Max no. hops**	**No. routes**	**(Tx range)$_{min}$ (PDR > 0.5)**	**Total energy case 1**	**Total energy per pair case 1**	**ANH case 1**	**Total energy case 2**	**Total energy per pair case 2**	**ANH case 2**
-	4	-	2	561114	8906.6	3.05	28602	454	1
-	5	-	2	3224897	51188.8	3.65	28602	454	1
-	3	-	2	105449	1673.8	2.57	28602	454	1

Table 8: Simulation results: density of nodes = 1.28; number of pairs of nodes = 127; average distance between nodes = 5.1305

FSM-based scheme									
k-seq length	**Max no. hops**	**No. routes**	**(Tx range)$_{\min}$ (PDR > 0.5)**	**Total energy case 1**	**Total energy per pair case 1**	**ANH case 1**	**Total energy case 2**	**Total energy per pair case 2**	**ANH case 2**
2	4	329	7	40897	322.0	3.54	55133	434.1	3.27
3	4	4405	8	17841	140.5	3.36	29751	234.2	2.43
2	5	1283	8	32691	257.4	3.99	55133	434.1	3.27
4	3	4210	7	11305	89.0	2.64	22355	176.0	1.87
5	3	32552	7	6237	49.8	2.58	14785	116.4	1.75
Flooding-based scheme									
k-seq length	**Max no. hops**	**No. routes**	**(Tx range)$_{\min}$ (PDR > 0.5)**	**Total energy case 1**	**Total energy per pair case 1**	**ANH case 1**	**Total energy case 2**	**Total energy per pair case 2**	**ANH case 2**
-	4	-	2	3157411	24861.5	3.01	57658	454	1
-	5	-	2	35354782	278384.1	3.20	57658	454	1
-	3	-	2	528900	4164.6	2.61	57658	454	1

The energy comsumption savings that can be provided by the FSM-based scheme compared to the flooding-based scheme, for the same maximum number of hops, can be summarized as shown in Table 9. It can be seen that the FSM-based scheme provides significant savings.

Table 9: Total energy savings provided by the FSM-based scheme when compared with the flooding-based scheme

Density = 0.32			
k-seq length	**Max no. hops**	**Total energy case 1 savings**	**Total energy case 2 savings**
2	4	94.88%	44.19%
3	4	96.81%	61.00%
2	5	98.44%	44.19%
4	3	92.62%	72.15%
Density = 0.64			
k-seq length	**Max no. hops**	**Total energy case 1 savings**	**Total energy case 2 savings**
2	4	97.66%	36.77%
3	4	99.04%	72.05%
2	5	99.62%	36.77%
4	3	95.89%	71.17%
Density = 1.28			
k-seq length	**Max no. hops**	**Total energy case 1 savings**	**Total energy case 2 savings**
2	4	98.70%	4.38%
3	4	99.43%	48.40%
2	5	99.91%	4.38%
4	3	97.86%	61.23%
5	3	98.82%	74.36%

Table 10 summarizes the advantages and drawbacks of the FSM-based scheme.

Table 10: FSM-based scheme advantages and drawbacks

Advantages	Drawbacks
Routing generation is easy to be implemented	The minimum transmission range necessary to achieve large PDR is too high
Packet forwarding does not require the use of routing tables	The inter-cell interference may be too high
Multipath routing can be easily implemented	The scalability of the strategy with the values of k-sequence and maximum number of hops is poor

The proposed strategy is not adequate to be used when the objective is to provide point-to-point communication between nano-routers that may be far apart and the available transmission power is limited. However, it has to be realized that the inadequacy of the strategy comes from the complete lack of knowledge about the networks' physical topology. This fact suggests a secondary scenario for which the strategy fits well.

6.2. In-range scenario issues

Let's assume that all the nano-routers are within the transmission range of each other. In this case, in spite of the physical position of the nano-routers to be unknown the nano-network is completely connected.

It is adopted an SDN architecture that enables an application to send commands to or query a set of nano-routers. A possible solution to this situation is as follows:

- an application instructs the SDN controller to query a set of nano-routers. For example, to get a temperature reading collected by a group of sensors assigned to different nano-routers;
- the SDN controller instructs the gateway to prepare a packet with the request;
- the gateway sends the request by broadcasting to all nano-routers in the nano-network;
- upon receiving the request, each queried nano-router prepares a packet with the temperature readings and broadcasts it back to the gateway.

In this case, the nano-routers will compete to access the medium and the classical problem of collision detection (CD) and/or collision avoidance (CA) has to be solved. However, as nano-routers have very few available resources, the known ways of implementing CA/CD are not feasible.

A possible and known way to solve the issue is to make the gateway to query the nano-routers in a round-robin fashion. This solution introduces a huge latency and may deprive the gateway of energy if it is not power connected.

Another way is to generate a route traversing all nano-routers and implementing a solution as follows:

- an application instructs the SDN controller to query a set of nano-routers. For example, to get a temperature reading collected by a group of sensors assigned to different nano-routers;
- the SDN controller, using the FSM-based routes generation described in Section 4, defines a route to traverse all nano-routers of interest and return the packet to the gateway;
- the SDN controller instructs the gateway to prepare a packet with the request;
- the gateway sends the request by broadcasting to all nano-routers in the nano-network;
- the gateway enters into a listening mode to wait for the return packet.

All nano-routers in the nano-network receive the packet, but only the first one in the route prepares a new packet with its temperature reading and broadcasts it. This new packet is also received by all nano-routers but only the second one in the route adds its own reading to the payload and broadcasts the new packet. The procedure is repeated until the last nano-router broadcast its packet that is collected by the gateway and the cycle finishes.

The procedure may be refined assuming that the nano-routers are usually in a sleeping mode to save energy. A packet sent by the gateway awakes all nano-routers and they check if they belong to the route. If not, they return to the sleeping mode and do not decode the packets broadcasted during the query.

There are no simultaneous transmissions and collisions do not occur.

If multiple queries have to be implemented, it is up to the SDN controller to schedule them. If they have to be simultaneous, the SDN may choose disjoint set of nano-routers to attend the queries and the high temporal multiplexing capacity of the TS-OOK deals with the collision issue.

7. Conclusions and future works

In this work, after an introduction of the relevance of nano-networks we presented the benefits provided by adopting a SDN-NFV-based architecture. The set of nano-networks functions necessary to implement a broad scope of applications have been illustrated.

A multipath end-to-end communication scenario has been analyzed for which we adopted a FSM-based routes generation approach. The routes generation procedure is completely blind in the sense that no information about the physical location of the nodes is provided. Such procedure is compatible with the limited available resources of nano-routers. FSM-based routes generation does not employ routing tables, and provides means to optimize either the latency or the energy consumption. The implementation is based on a very low complexity hardware made of shift registers and XOR gates. In addition, FSM-based routes generation is scalable as the FSMs size increases as $\log_2(N)$ where N is the number of the network's nodes.

The k-sequence length and the maximum number of hops have a huge impact on the number of routes that are found. The k-sequence length has much more impact than the maximum number of hops because as we increase it we increase the number of nodes that can be reached in just one hop. In other words, we increase the breadth of the multipath. The k-sequence length and the maximum number of hops are the parameters that control the search across the solution space. However, increasing these parameters there is an explosive increase of the computing time and the number of solutions that are found and that should be filtered. Such increase is incompatible with the processing and storage resources of the nano-routers.

A drawback of the proposed strategy is that it may be necessary to work with high levels of the transmission power when the nano-routers are spread over a large area. This drawback is a consequence of the blindness of the method as no information about the physical location of nodes is employed whatsoever. On the other hand, if all nano-routers are within the coverage area of each other it is possible to implement applications where packet collisions are completely avoided.

For all simulated cases the FSM-based strategy has shown a total energy comsumption much lower than a simple flooding-based scheme.

An extensive review of proposed routing protocols to be employed in nano-networks covering the years from 2008 until 2020 has been done and summarized.

In general terms, we may say that our approach differs from the published solutions in the following aspects:

- it is a much simpler approach as it does not employ any mechanism to discover the physical location of nodes;
- the routes generation procedure is implemented by a simple FSM that needs limited resources;
- unicast, multicast and broadcast can be implemented without any change of the FSM-based routes generation procedure;

- the FSM-based routes generation procedure can be combined with any suitable mechanism to estimate the physical position of the nodes;
- the SDN/NFV proposed architecture allows the complexity to be dealt at the higher layers freeing the nano-routers to be quite simple.

The proposed approach seems to be very promising and in future work we will investigate how to enhance it to improve the performance when the nano-routers are spread over a large area; how to exploit the resilience of trellis decoding to demonstrate the robustness of the approach in the presence of failures; how to mitigate problems related to hidden and exposed nodes; and how to deal with mobility. Three new scenarios will be studied. Two of them will further exploit the possibility of implementing routing and forwarding strategies without awareness of the physical topology: i) the introduction of logical clustering; ii) the introduction of relay functionality without increasing the complexity of the nano-routers. The third scenario will exploit the processing power of the SDN/NFV architecture and will include the knowledge acquisition of the physical topology.

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