A Novel Table Finite State Machine-Based Routing Algorithm Implementation

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Abstract. State machine is a concept originally proposed for computational numerical systems and used for modeling systems with applications in several fields. Governed by its own logic, an input produces a change of state and an output on the machine. The routing by FSM technique uses this dynamic to generate numerical sequences that represent the network nodes and the routes through which data transmission is allowed. With this, the number of transmissions is reduced and, consequently, the energy consumption. Due to its low complexity, the technique is particularly interesting in the context of networks with limited resources, such as wireless sensor networks and nanodevice networks. In this work, we show that for several scenarios the technique becomes inefficient due to the large number of routes produced and we propose a new implementation whereby the packet size remains reduced for a wide range of routing parameters.

Keywords: Finite State Machine, Wireless Sensor Networks, Nanonetworks, Routing Protocols.

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1 Introduction

The COVID-19 pandemic has highlighted the capacities of adaptation and domination of microscopic organisms whose complexity of action is surprising in view of the lack of resources. In engineering, during the last decades, the understanding of this form of life has already inspired several works directed to the construction of machines in nanometric scales capable of performing elementary tasks such as temperature measurement, mobility and information exchange. The advancement of science in the field of nanomaterials, mainly with graphene and carbon nanotubes, has been solidifying and directing these works with increasingly feasible possibilities.

Individually, a nanodevice is extremely limited in terms of energy, locomotion and computational resources. In most applications, it is not possible to acquire and store comprehensive knowledge of the network or transmit data over long distances. Controlled locomotion is also a big challenge. Therefore, the formation of communication networks becomes fundamental to alleviate these limitations based on collaborative work.

A nanonetwork is an example of a limited resource network. More traditional examples include *ad hoc* networks, wireless sensor networks (WSNs) and wireless body area networks (WBANs). In this type of networks, routing techniques play a central role. In addition to enabling packet delivery, the algorithms need to be simple enough to handle individual device limitations. In recent decades, this discussion has intensified with the rapid growth in the number of connected devices, the so-called Internet of Things (IoT).

The Finite State Machine-based (FSM-based) routing technique was originally proposed in the context of WSNs [1], highlighting its low complexity and ability to reduce power consumption and latency. It was later considered for nanogrids, showing excellent results compared to the Flooding technique [2].

The technique is based on route generation to limit the number of packet transmissions. The route generation process does not depend on the network topology and has parameters that make them more or less restrictive, allowing balancing energy consumption with the packet delivery rate, improving efficiency. However, we show in this work that the technique presents good results only for a limited range of these parameters. This is because the number of routes tends to increase exponentially, making the packet too large, which increases latency and energy consumption.

In this work, we suggest a new implementation of FSM-based routing, with the purpose of keeping the package's size reduced, increasing the number of scenarios for which the technique becomes plausible. The route generation process is also simplified. We consider the context of its application in nanonetworks based on electromagnetic communication in the terahertz range, which constitutes one of the most challenging network scenarios. With the new approach, we achieved a packet size reduction from 42% to 99%. Furthermore, we show that the transmission of packets with the new implementation is feasible with the amount of energy that the nanodevices will be able to store, in such a way that a single charge cycle is enough to transmit a considerable amount of data.

After this brief introduction, the remainder of the paper is organized as follows: Section 2 provides a brief overview of previous related works; Section 3 addresses the adopted methodology and the routing techniques of interest to this work; Section 4 presents the scenarios, mathematical models and metrics considered, and the obtained results; Section 5 concludes the paper and proposes some future work.

2 Related Works

In the literature, numerous works deal with routing techniques for resource-limited networks, many with more complete analyses, including energy models, network architecture and methods for recharging devices. Several studies were published presenting reviews and classifications regarding these works. Therefore, and due to space limitations, we will not discuss all of them here.

Depending on the nature of the technique, it can be considered hierarchical, when the nodes assume different roles in the transmission process, or anarchistic, when all nodes have a similar participation. The routing can also be classified regarding the origin of decision making, which can be centralized in some nodes or distributed throughout the network.

Another important factor in most real applications is the mobility of the nodes. Some techniques are not feasible in scenarios with nodes mobility or impose considerable restrictions on them.

According to the characteristics of the routing techniques, they can be classified into some categories [3]:

- routing based on probabilistic values: transmissions are governed by probability values assigned to nodes;
- routing based on node clustering: based on specific criteria, groups of nodes are established in order to simplify connections in the network;
- routing based on node classification: each node takes on a role in transmitting the data, reducing and orchestrating the flow of data;
- routing based on hop counting: the number of transmissions is reduced from the hop count, which can be established by different criteria;
- routing based on *wake up*: nodes have an energy saving state that can be activated or deactivated based on different criteria;
- other techniques are based on miscellaneous concepts to limit the number of retransmissions in order to promote network efficiency.

Tab. 1 summarizes the characteristics of the main related works considering the points raised in this brief summary.

3 Methodology

This work employs the concept of Trellis Coded Network (TCNet), proposed for modeling networks by finite state machines [23], aiming to generate routes with low complexity in communication nanonetworks [2]. In order to evaluate the performance of the technique, an algorithm was developed in R [24] for numerical simulation with randomly generated networks. Exploring different situations, scenarios were mapped in which FSM routing did not perform well. This section presents the fundamentals of the technique and a proposal for an efficient implementation to enhance its performance.

Table 1: Main related works

Work	Classification	Decision	Architecture	Mobility
[4]	Probabilistic	Centralized	Hierarchical	Static
[5]	Probabilistic	Centralized	Hierarchical	Mobile
[6]	Node Clustering	Semi-Distributed	Hierarchical	Static
[7]	Node Clustering	Centralized	Hierarchical	Static
[8]	Node Classification	Distributed	Anarchist	Static
[9]	Node Classification	Distributed	Anarchist	Static
[10]	Node Classification	Distributed	Anarchist	Static
[11]	Hop Counting	Distributed	Anarchist	Static
[12]	Hop Counting	Distributed	Anarchist	Static
[13]	Hop Counting	Distributed	Anarchist	Static
[14]	Wake Up	Distributed	Anarchist	Static
[15]	Wake Up	Centralized	Hierarchical	Mobile sensors, static controllers
[16]	Wake Up	Centralized	Hierarchical	Mobile sensors, static controllers
[17]	Others	Distributed	Hierarchical	Mobile sensors, static controllers
[18]	Others	Distributed	Hierarchical	Mobile sensors, static controllers
[19]	Others	Distributed	Hierarchical	Static nanodevices distributed in a mobile body
[20]	Others	Centralized	Hierarchical	Mobile sensors, static controllers
[21]	Others	Centralized	Hierarchical	Static
[2]	Others	Centralized	Anarchist	Static

Source: Adapted from [3] e [22], and extended by the author

3.1 Finite State Machine-based Routing Technique

Fundamentally, FSMs can be classified into two types:

- Mealy machine: the output depends on current state and current input;
- Moore machine: the output depends on current state only.

For every Mealy machine, there is an equivalent Moore machine. In general, the implementation of the Mealy machine is simpler, since, for its full description, it requires an equal or less number of states than the Moore machine.

In FSM-based routing, the machine output has very useful applications, mainly for error checking [1], but it is not a requirement for the technique to work and is not be considered in this work.

Fig. 1 exemplifies the mapping of state transitions on a machine with only two states, s_1 and s_2, where an entry x_1 leads to state s_1 and an entry x_2 leads to state s_2. The machine outputs are not shown.

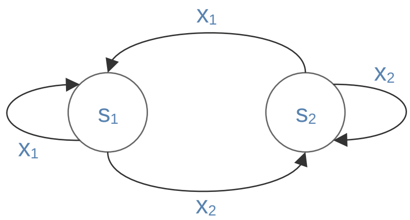


Figure 1: Simple example of a Finite State Machine

As illustrated in Fig. 2, a network can be modeled by an FSM, with each node represented by a machine state. In this way, the connection between two nodes is represented by a state transition in the machine. Thus, for a network with N nodes, an FSM with N states of $N_b = \log_2(N)$ bits is required. Furthermore, two routing parameters must be established: length of input sequence (L_x) and number of hops (N_h).

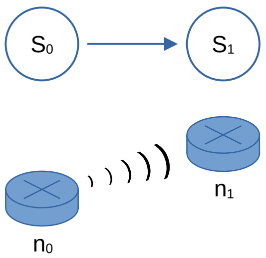


Figure 2: Network modeled by FSM

Numerous rules can be established to govern the state transitions. Prioritizing the low complexity, one possibility is the bits shifting. In this case, the machine states must be understood as vectors of N_b bits and sequences of length L_x bits are introduced to obtain a state transition. Fig. 3 illustrates this process for an FSM of $N_b = 4$ bits, moving from state $S_0 = 1101$ to state $S_1 = 0111$ from an input sequence of $L_x = 2$ bits.

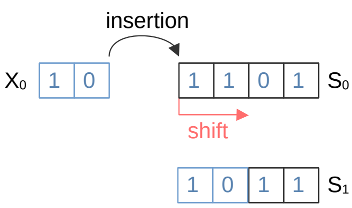


Figure 3: Bit-shifting operation

FSM-based routing is implemented by the aforementioned generation of routes process that will govern the transmission of packets along the network, requiring only the knowledge of the ID of the source node and the ID of the destination node. To exemplify the process, let's consider the following scenario:

- number of nodes in the network: $N = 16$
- number of bits of the FSM: $N_b = \log_2(N) = 4$
- source node ID: 13 (1101)
- target node ID: 6 (0110)
- number of hops: $N_h = 3$
- length of the input sequence: $L_x = 2$

Fig. 4 outlines the route generation process. To simplify the illustration, we use variables instead of bits.

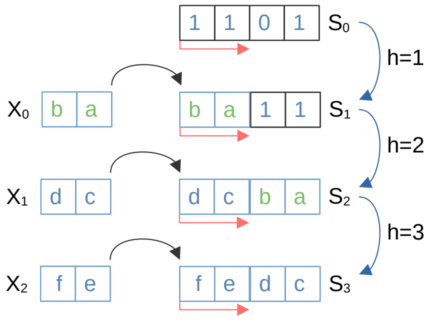


Figure 4: Sequence generated by the bit-shifting process

The bits c, d, e and f make up the last state of the machine and, therefore, are defined by the target node ID. Thus: $c = 0$, $d = 1$, $e = 1$ and $f = 0$. The bits a and b remain undetermined, being considered *free bits*, and can assume any value (0 or 1). In practice, as we have 2 bits free, $2^2 = 4$ routes will be produced:

- $a = 0,\ b = 0$

  $13\,(1101) \rightarrow 3\,(0011) \rightarrow 8\,(1000) \rightarrow 6\,(0110)$

- $a = 1,\ b = 0$

  $13\,(1101) \rightarrow 7\,(0111) \rightarrow 9\,(1001) \rightarrow 6\,(0110)$

- $a = 0,\ b = 1$

  $13\,(1101) \rightarrow 11\,(1011) \rightarrow 10\,(1010) \rightarrow 6\,(0110)$

- $a = 1,\ b = 1$

  $13\,(1101) \rightarrow 15\,(1111) \rightarrow 11\,(1011) \rightarrow 6\,(0110)$

Assuming that node 7 receives the packet on the first hop, it must determine that it is not the destination. It must then determine whether any of the available routes predict it will receive the packet on the first hop. In this case, only the second route meets the requirement and the remaining routes are considered invalid. Therefore, node 7 must delete the invalid routes and retransmit the packet. In this way, the packet size is not constant, but decreases along the transmission.

3.2 Table Implementation of the Routing by FSM

In many situations, depending on the routing parameters, the FSM-based routing technique produces a large number of routes, which makes the packet generation and transmission process too costly, limiting the applicability of the technique.

To work around this situation, we propose a new implementation, which we refer to as T-FSM-based routing, by which a route generator is produced and transmitted. In this way, routes are generated along the transmission instead of only by the source node. This generator consists of a table built from the routing parameters. Fig. 5 shows the table built for the example presented in Section 3.1.

h = 1	1	1	0	1	Source Node ID
h = 2	a	b	1	1	
h = 3	1	0	a	b	
	0	1	1	0	Target Node ID

Figure 5: Table implementation of the FSM-based routing technique

The first row in the table is the binary ID of the source node. The last row in the table is the binary ID of the target node. The middle rows are composed of source and target node IDs shifted L_x times to the right and to the left, respectively. Depending on the parameters used, some gaps may appear, which are equivalent to free bits. The table is transmitted without the first row.

With this implementation, upon receiving the packet, the node must determine whether it is the destination by comparing its ID with the last row in the table. If not, it must determine whether it belongs to the route by comparing its ID with the first row in the table. Being an intermediate node, it must fill in the gaps present in the first row of the table throughout the entire table using its own ID and retransmit the packet.

Considering the previous example, the source node, 13 (1101), will transmit the table as shown in Fig. 6, excluding the first line that matches its own ID.

a	b	1	1
1	0	a	b
0	1	1	0

Figure 6: Example of the transmitted table in the first hop

Assuming again that node 7 (0111) receives the packet on the first hop, it must determine that it is not the target by comparing its ID with the last row of the table. It must then determine that it is an intermediate node by comparing its ID with the first row in the table. Therefore, it must complete the gaps present in the first line according to its ID, making $a = 0$ and $b = 1$ throughout the entire table. It then deletes the first line and retransmits the packet. The table relayed by node 7 will be as shown in Fig. 7.

The procedure is repeated by each intermediate node till the packet arrives at the destination node.

1	0	0	1
0	1	1	0

Figure 7: Example of the transmitted table in the second hop

4 Results

We consider simulations of nanonetworks consisting of nanodevices distributed over a 2D square area with a side of 20 mm and densities $\rho = 0.32$ and $\rho = 1.28$, given in number of nodes per unit area. It is expected that the T-FSM routing technique to stand out especially in scenarios with dense networks and with a high number of nodes.

An important factor which has a strong influence on the results is the transmission range γ_{max}. This parameter depends on the environment and, in general, is exponentially related to the energy consumption, one of the main limited features of nanodevices [25].

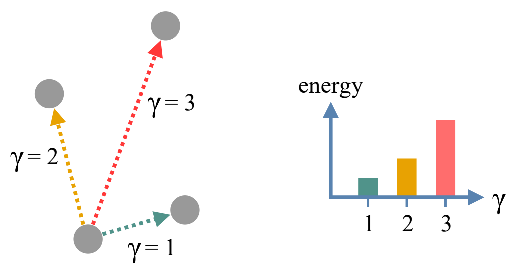


Figure 8: Transmission range γ and the energy consumption.

Several studies propose energy models and energy recharge techniques to nanonetworks. More realistic scenarios consider the use of ultra-nano-capacitors based on onion-type carbon electrodes capable of storing up to 800 pJ of energy and could be recharged, for example, by elements with piezoelectric properties [26]. In this model, transmitting a 1 pulse to $\gamma_{max} = 10$ mm requires 1 pJ of energy. Considering the TS-OOK modulation, in which bits 0 would not consume energy, and the packet containing a bit ratio 0s to 1s of $W = 0.5$, one load cycle would be sufficient to transmit a packet of 1600 bits.

Different values were used for the routing parameters: $N_h = \{2, 3, 4, 5, 6\} \times L_k = \{1, 2, 3\}$. In addition, restrictions were imposed on the γ transmission range. As the choice of these parameters is a matter of design, only the best results are presented. Each result constitutes the average of the results obtained for 50 different random networks.

Tab. 2 presents detailed results for networks of different densities. In the case of $\gamma_{max} = 7$ mm, a packet size reduction of up to 98% with the T-FSM based routing was achieved. With $\gamma_{max} = 10$ mm, the difference between the two approaches is still outstanding, with a packet reduction of at least 42% with the new implementation. In this case, 1 battery cycle would be enough to transmit up to 5 packets with T-FSM, whereas, in denser networks, almost 5 cycles are required for the transmission of a single packet with the original implementation of the technique.

Fig. 9 exemplifies the packet size behavior for the FSM and T-FSM techniques, which decreases along the transmission path due to the discarding of invalid routes. It can be seen that the T-FSM-based routing implementation always provides smaller packets than its FSM-based counterpart. In fact, the new approach achieves a huge reduction of the packet size when compared to the FSM package.

5 Conclusions

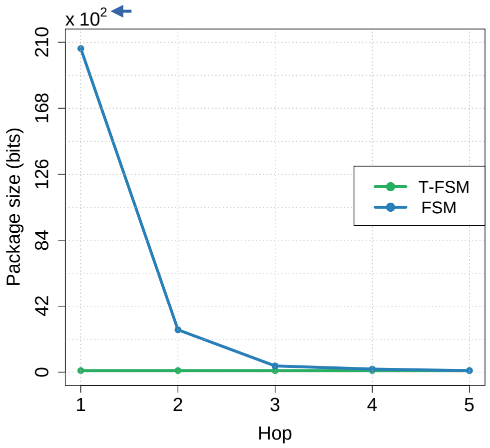
Previous studies report good results of the FSM-based routing technique in networks with limited resources. In this work, we identify scenarios in which the application of the technique would not be feasible in its original implementation and propose a new approach through which we managed to reduce the packet size by up to 99% in the considered scenarios, which improves its performance in terms of consumption of power and latency and enables it in numerous new scenarios.

Future works can use network simulators that take into account latency in packet transmission and specific network evaluation metrics, as well as larger networks in terms of size and density, which should reinforce the results.

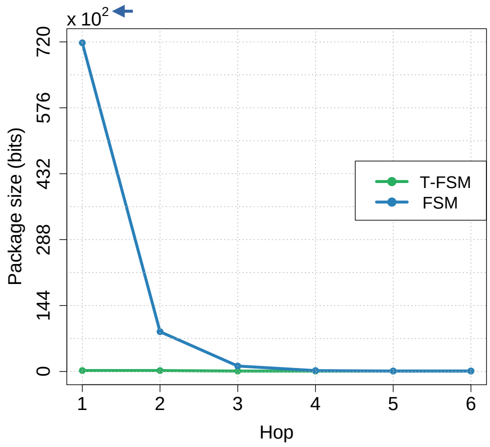
It is also possible to explore the optimization of routing parameters and algorithms that add versatility and adaptability to the technique based on the route generator table.

Table 2: Results

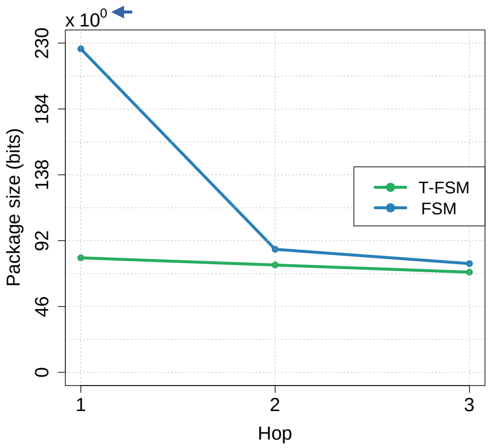
γ_{max} (mm)	7		10	
ρ (nodes/mm²)	0.32	1.28	0.32	1.28
PDR	0.95	0.95	0.88	1
ANH	3.16	3.41	2.09	2.45
Max Package Size (bits) with FSM (bits)	20700	72000	226	7250
Number of Cycles per Package with FSM	13.06	45.13	0.27	4.66
Max Package Size (bits) with T-FSM (bits)	86	112.08	45	90
Number of Cycles per Package with T-FSM	0.18	0.2	0.15	0.18
Total Amount of Transmitted Data with FSM (bits)	23750	81953	388	8572
Total Amount of Transmitted Data with T-FSM (bits)	430	560	225	450
Redution Ratio	98.19%	99.32%	42.01%	94.75%



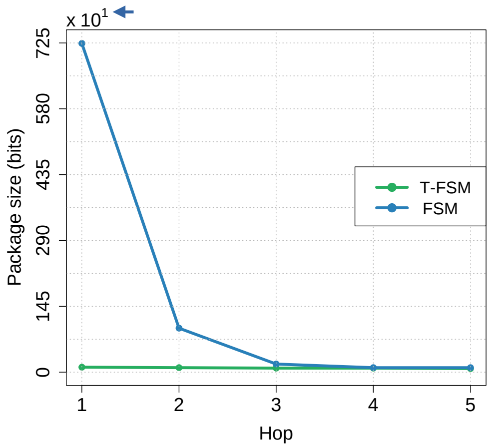
a) $\rho = 0.32$, $N_b = 7$, $N_h = 5$, $L_x = 3$, γ_{max}= 7mm



b) $\rho = 1.28$, $N_b = 9$, $N_h = 6$, $L_x = 3$, γ_{max}= 7mm



c) $\rho = 0.32$, $N_b = 7$, $N_h = 3$, $L_x = 3$, γ_{max}= 10mm



d) $\rho = 1.28$, $N_b = 9$, $N_h = 5$, $L_x = 3$, γ_{max}= 10mm

Figure 9: Packet size across transmissions for various routing techniques.

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