On the Impact of Network Topology on Wireless Sensor Networks Performances Illustration with Geographic Routing

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Illustration with Geographic Routing

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***Abstract*—Wireless Sensor Networks (WSN) are composed of constrained devices and deployed in unattended and hostile environments. Most papers presenting solutions for WSN evaluate their work over random topologies to highlight some of their “good” performances. They rarely study these behaviors over more than one topology. Yet, the topology used can greatly impact the routing performances. This is what we demonstrate in this paper. We present a study of the impact of the network topology on algorithm performance in WSNs and illustrate it with the geographic routing. Geographic routing relies on node coordinates to route data packets from source to destination. We measure the impact of different network topologies from realistic ones to regular and very popular ones through extensive simulation and experimentation campaigns. We show that different topologies can lead to a difference of up to 25% on delivery ratio and average route length and more than 100% on energy costs.**

I. Introduction

Wireless sensor networks (WSNs) consist of sets of mobile wireless nodes communicating without the support of any pre-existing fixed infrastructure. Such large scale WSNs offer great application perspectives. Sensors are tiny devices with hardware constraints (low memory storage and low computational resources) that rely on battery. Sensor networks thus require energy-efficient algorithms to make them work properly in a way that suits their hardware features and application requirements. A low power sensor node has limited transmission power and thus can communicate only to a limited number of nodes, called its the neighborhood. Multi-hop communications are used to route data from source to destination.

Many algorithms are evaluated using only a random topology. Sometimes, only random topology is used for performances evaluation. Results are thus closely related to this particular topology. Using nodes position information has been proved to be an efficient way to route messages [1]. In geographic routing algorithms, a node applies a heuristic only based on its own position, its neighbors’ and the destination’s positions in order to choose the next hop. Since the routing relies on nodes’ position, it is legitimate to wonder how position may interfere on geographic routing performances and behaviors.

This is why in this paper, we evaluate and understand the impact of the network topology on WSN solutions and in particular on geographic routing. Being aware of how a topology impacts the performances will be helpful to design solutions for wireless sensor networks. In this article, we study different position-based routing algorithms in combination with different network topologies. We show the impact of these latter on routing performances through both extensive simulation and experimentation campaigns. Result show that different topologies can lead to a difference of up to 25% on delivery ratio and average route length and more than 100% on overall cost of transmissions. We thus outline that solutions for WSNs should be evaluated on topologies relevant to the target application on several different topologies if not applicable.

The rest of the paper is organized as follows: Section II presents related work on topology impact. The studied algorithms and topologies are described in Sections III and IV. Section V describes the simulation and experimentation settings. Results are given in Section V and discussed in Section VII. We finally conclude in Section VIII.

II. Related work

Many research and performance studies have been made on protocol evaluations and energy consumption. However, there has been only little research on how the network topology impacts WSN performances. Most of the research on the topic rather focuses on how to efficiently place nodes on a field to achieve the best performances for a given algorithm. Although similar, the approach is the opposite to the one we aim.

Dhillon and Chakrabarty [2] focus on effective nodes placement for maximizing coverage and surveillance with a minimum number of resources. They use a probabilistic detection model where a sensor has a given probability of sensing an event, depending on its distance to the event. Interest points are placed on a grid and obstacles are considered. With these hypotheses, the authors propose two algorithms to cover each interest point with a minimal confidence level. Dasgupta et al. [3] propose SPRING, a sub-optimal algorithm to place nodes in order to maximize the network lifetime with covering constraints. They achieve better performances than a random placement. Some works study algorithms to place and to move nodes in order to get field coverage and network connectivity like Wang et al. in [4] and [5].

Younis and Akkaya compiled in a survey research addressing different techniques of nodes placement for area covering, energy consumption optimization and network connectivity [6]. Differentiation between data nodes, relay nodes and multi purpose nodes is also addressed in this survey. They highlight that nodes position impacts network lifetime and fault-tolerance. They do not address the impact of node topology but give a first approach on the influence of some network performances.

Another research studies the impact of topology but considers the Internet topology [7], [8]. Bhardwaj et al. [9] explore simple nodes placement scenarios to study sensor

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network lifetime theoretical bounds and how far data gathering techniques are from these bounds. In this study, nodes are assumed to have an initial amount of energy which decreases when a node receives, sends or senses. It is also assumed that the network lifetime ends when a given region of the field is not covered anymore. Studying theoretical limits of network lifetime provides a relevant element for comparison to design algorithm aiming at maximizing network lifetime. This article does not study specifically nodes placement in the network but event placement and shows its impact on network performances.

Ishizuka and Aida [10] study random node failure and battery exhaustion behavior on stochastic topologies with different properties. They study three different topologies : *simple diffusion*, *constant placement* and *R-random placement*. The *simple diffusion* simulate a deployment from the air, the node density is then higher close to the deployment point. The *constant placement* topology has a constant density which is often used in simulations of wireless sensor networks. Finally in *R-random placement*, designed by the authors of the article, nodes are scattered depending on the angle and distance from the base station. This work shows that *simple diffusion* has a low probability of sensing events while *constant placement* has low fault tolerance. The proposition of the authors, *R-random placement*, allows good fault tolerance and a good sensing coverage, offering a interesting proposition. This article highlights the difference in terms of performance between several topologies although they all use random nodes placement and do not cover placement in a city.

Finally, Vassiliou and Sergiou [11] study the impact of different topologies on three congestion control algorithms (textitSenTCP, *Directed Diffusion* and *HTAP*). Authors show that performances are clearly affected by the topology in terms of transmission delay or delivery ratio. The impact of node topology is one more time highlighted in this article but studied topologies are still simple and do not match in city topologies.

Literature overview shows that node placement impacts performances in WSN but the presented works focus on proposing algorithms for optimizing node deployment and showing the impact on network performances of topologies is a side effect of the contribution. In this paper we focus on the impact of node topology on network performances and then cover a wider range of topologies and focus on performance metrics to highlight the differences.

Motivations: Thus, although aware of the impact of the topology on network performance, the community does not measure it. In this paper we consider network topologies of really different kinds. Even if they show similar properties (number of nodes, area or degree), those topologies provoke different behaviors. We show that those topologies impact differently WSNs algorithm performances in particular with geographic routing algorithms and measure this impact to allow a better understanding. We show differences in term of behavior by conducting extensive simulations and experiments and analyze different algorithms on different topologies.

III. ALGORITHMS

The studied algorithms are different variants of greedy geographic routing algorithms. A geographic routing algorithm uses node position to route data. The basic idea is that, at every routing hop, the data packet should be closer from the destination considering a given metric. The difference between the variants we study is the metric used to select the next hop. They are shown on Fig. 1. They are:
• *Greedy* [12]: chooses the closest node to destination.
• *MFR* [13]: minimizes the distance between the destination and the orthogonal projection of the chosen node on the line between the source and the destination.
• *NFP* [14]: chooses the closest node to the source.
• *Compass* [15]: chooses the node that minimizes the angle neighbor-source-destination ($\widehat{eSD}$ in Fig. 1).

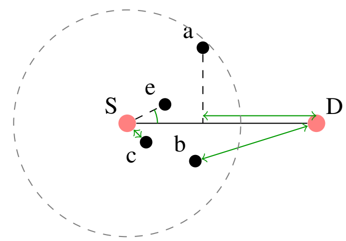


Fig. 1. Comparison of geographic algorithms. Node a is chosen by *MFR* algorithm, node b by *Greedy*, node c by *NFP* and node e by *Compass*.

IV. TOPOLOGIES

The simulations are run on five different topologies and experimentations on four different topologies. They are chosen to be different one from each other and representative of either what can be found in literature or real world situations. All these topologies have one connected component, i.e. for any chosen node in the network it is possible to reach any other node also in the network using a multihop route.

The first topology used in both simulations and experimentations is *random* topology. In simulations, 1619 nodes are deployed randomly on a $600\ \mathrm{m} \times 450\ \mathrm{m}$. For experiments running on FIT-IoT LAB [16], a subset of 60 nodes is selected among the 256 nodes available.

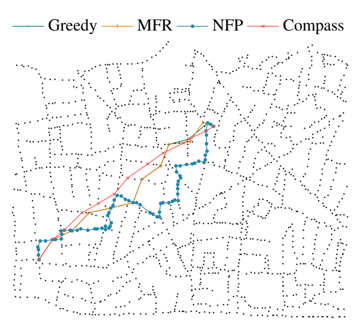


Fig. 2. City topology with an example of route.

The *random hole* topology is a variant of *random*. Node placement is similar but a circular area of $100\ \mathrm{m}$ radius, randomly placed in the field, does not contain any node.

The third topology (Fig. 2), named *city*, represents a WSN deployment in an European city. Nodes are placed in a pseudo-randomly fashion on streets in order to maintain connectivity. The *city small* topology is a variant of the *city* topology, nodes

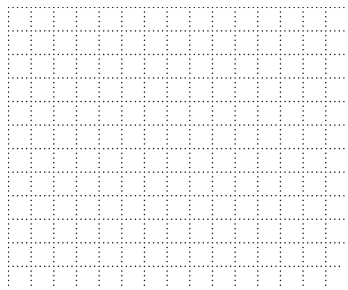


Fig. 3. City grid topology

placement is the same but the area is a subset of *city*. The *city grid* is a theoretical representation of a city like Manhattan. Nodes are equidistantly placed in lines and rows.

V. SIMULATIONS

The impact on topologies is measured using the WSNET simulator[1]. For each topology and algorithm combination, we measure the following performance parameters:

- *Delivery ratio*: as the number of data messages received divided by the number of messages sent for the whole network;
- *Average route length*: as the number of hops a data message travels from the source to the destination;
- *Overall energy cost*: as the sum of the cost of all messages sent. The cost of a transmission is defined as $r^\alpha + C$ where r is the set range in meter, α and C are constants and depends on the hardware and the propagation model as defined in [17].

The range of nodes is set from $25m$ to $50m$ by steps of $5m$. The data traffic model is as follows. Every 15ms, two nodes are chosen randomly to be the source and the destination of one data packet. The size of a data packet is arbitrary set to 10 bytes plus the header size of 88 bytes. As we do not consider the size for the cost analysis it is not really relevant. Each combination of topology and algorithm is run 50 times. Table I summarizes the simulation parameters.

TABLE I. SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
α	4	Duration (s)	60
C	2^8	Mac	idealmac

A. Delivery ratios

Fig. 4, 5, 6 and 7 compare the delivery ratio metric for the different studied algorithms. They show that for low degrees (15), *city* and *city grid* topologies show a difference of 25% on delivery ratio performance with the NFP algorithm (Fig. 5). Delivery ratio for *city grid* is really high and almost 100% regardless of the method. This is due to the fact that there is almost no dead end in this topology. A node will almost always find a forwarding neighbor in the direction of the destination. The only counter example is on the edge of the network. On *city grid*, if a source node at the end of a branch (after the last intersection) sends a message to a destination node at the end of another branch, the message may be routed towards the end of the branch and fails at this point.

Figures also depict that the denser the network, the higher the delivery ratio and the less differences between topologies.

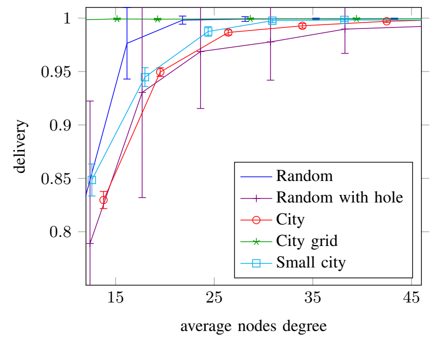


Fig. 4. Delivery ratio for Greedy routing.

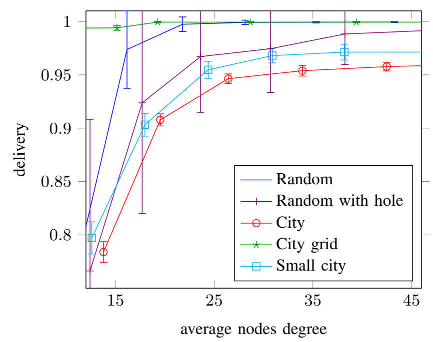


Fig. 5. Delivery ratio for NFP.

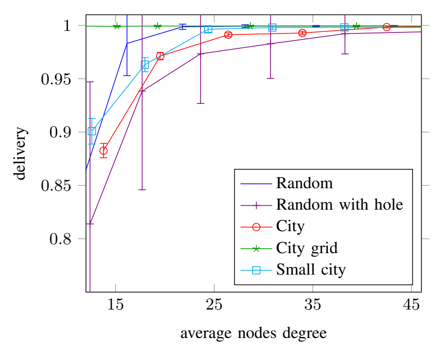


Fig. 6. Delivery ratio for MFR.

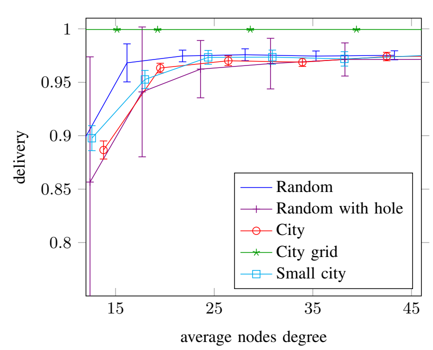


Fig. 7. Delivery ratio for Compass.

[1] http://wsnet.gforge.inria.fr/

B. Average routes length

Fig. 8, 9 and 10 depict the average route length of every successfully routed packet. Due to page limitation, *Compass* is not shown but the results are similar to *MFR*. For *greedy*, *MFR* and *Compass* (Fig. 8 and 10), all topologies except *small city* get similar results. *Small city* gets lower route length because the network diameter (due to simulation settings) is lower than other topologies. The only routing method that shows significant differences is *NFP* (Fig 9). Excluding the *small city* topology (because of the lower network diameter), results show differences of up to 20% between the *random* and *city* topologies.

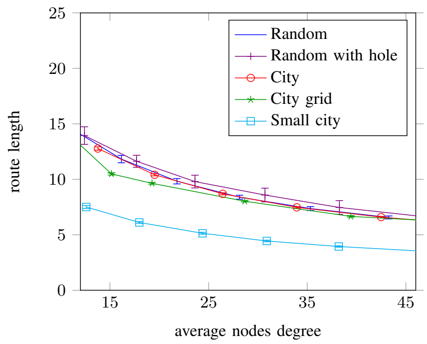


Fig. 8. Average route length for Greedy routing.

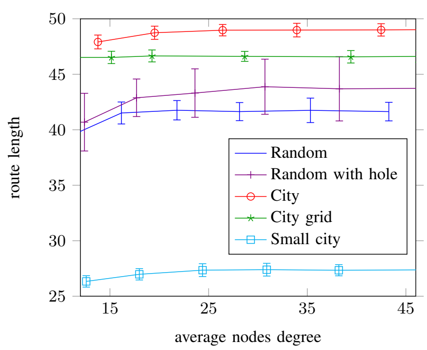


Fig. 9. Average route length for NFP.

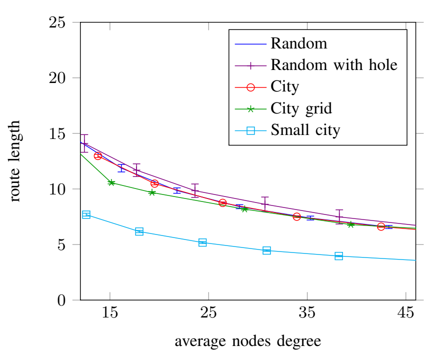


Fig. 10. Average route length for MFR.

C. Energy cost

The overall cost is shown on Fig. 11, 12 and 13. *MFR* method is not shown but the results are similar to the ones of *Greedy*. Due to its lower diameter, all studied algorithms differ from 150% to 300% between *small city* and the closest topology. On Fig. 12, *NFP* shows important differences against different topologies concerning the overall cost that can go up to a factor of 10 between two topologies. The cost of *city grid* is constant since the chosen neighbor is the closest to the current node and in this topology, the closest neighbor is always at a constant distance. For *city*, the closest neighbor is no more at a constant distance but the variation between two neighbors is lower than for *random* and *random hole* topologies. This is why *NFP* is less efficient on *city* than *city small* topologies but still performs better than on *random* and *random hole* topologies.

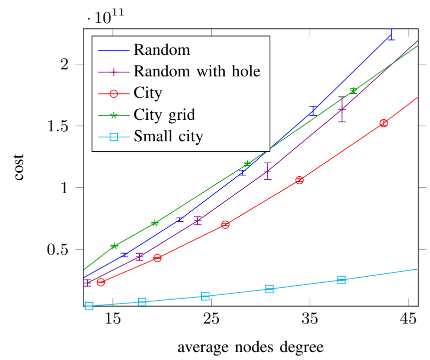


Fig. 11. Global cost for Greedy routing.

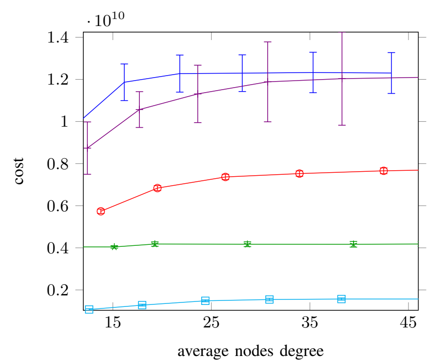


Fig. 12. Global cost for NFP. (same legend as Fig. 11).

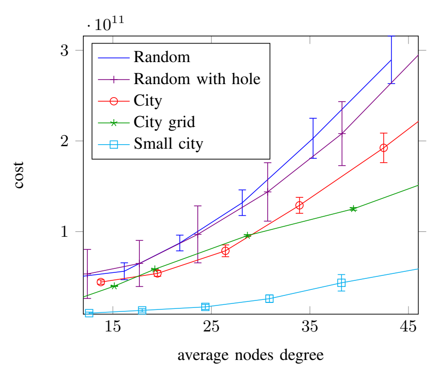


Fig. 13. Global cost for Compass.

VI. Experimentations

We performed experimentations using the FIT-IoT LAB testbed [16]. Nodes are equipped with a 16 bit *MSP430* CPU with 10kB of Ram and either a 2.4Ghz *Texas Instrument cc2420* radio chip or a sub-gigahertz *Texas Instrument cc1100* radio chip. We choose the Rennes site which offers a flat topology and use a subset of nodes to create different topologies. We ran the four methods with all available power transmission (7) on four different topologies. Nodes used are equipped with the 2.4Ghz *Texas Instrument cc2420* radio chip.

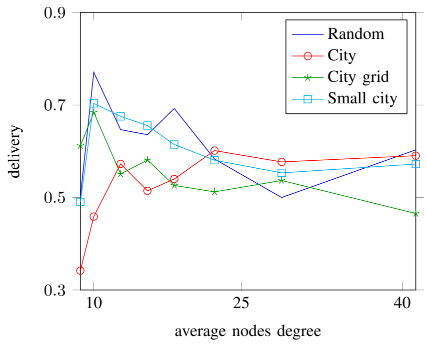


Fig. 14. Delivery ratio for Greedy routing on SensLAB.

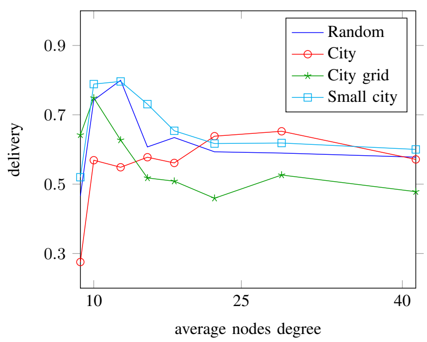


Fig. 15. Delivery ratio for NFP routing on SensLAB.

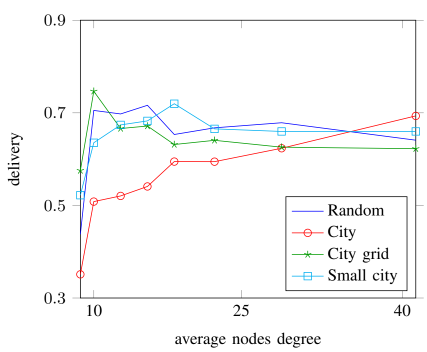


Fig. 16. Delivery ratio for MFR routing on SensLAB.

Experimentations show slighter differences than simulation (Fig. 14, 15, 16 and 17). While simulation results show strictly increasing delivery ratios, in experimentations, delivery ratio increases with node degree and then decreases because of the increase of packet collision due to longer communication range.

Because of the limited number of nodes offered by the testbed, the topologies are not as different as they are with simulations. However, even if the results do not show as much difference as with simulations, we observe a gap between the

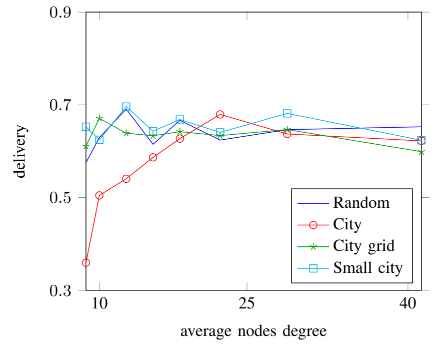


Fig. 17. Delivery ratio for COMPASS routing on SensLAB.

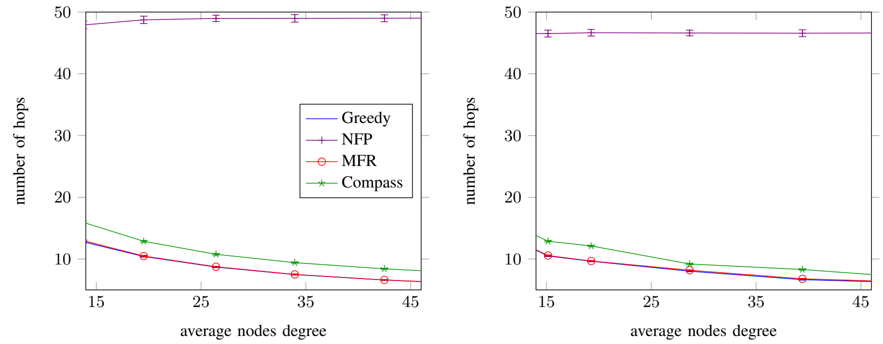
different topologies for all methods. Fig. 14 show differences between *random* and *city* of more than 20% below a degree of 10. It is interesting to observe that *city small* and *random* topologies achieve really similar performances with a similar curve profile. We explain this behavior again by the limited differences between the different topologies especially between *random* and *city small*.

VII. Discussion

The previous section shows that depending on the kind of topology we target and the application requirements (low energy consumption, high delivery ratio), the best algorithm is not always the same. If we consider the delay as an important point for instance we will avoid the *NFP* algorithm as the route length is more than thrice more than other algorithms (Fig. 18).

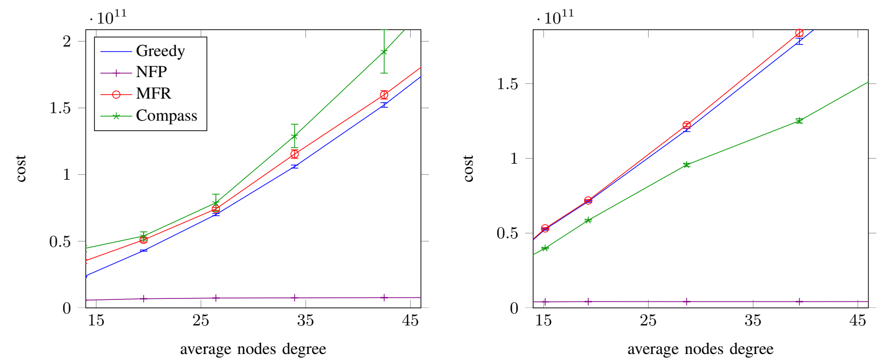
In this context if we now want to optimize the energy consumption we will need to consider the topology as we may find that the best algorithm (excluding *NFP*) depends on topology. Indeed for a *city* or *random* topologies, the best choice is *Greedy* but for the *city grid* topology *Compass* is better. This comparison is illustrated on Figure 19.

When designing and testing their algorithms, random topology is often chosen. This choice can be made for the convenience (easy to set in a simulator), because one does not suspect that there can be big differences with other topologies or because no specific application is envisionned. It is important in the designing process to consider the targeted application in order to guide the design to the targeted performances on the targeted topology. We give an example where we need to deploy two WSNs in two different contexts. In both cases, we consider the delay to be critical. The first context is the monitoring of a critical area (volcano, forest, etc) where sensors are dropped from the air. The second context is control of lampposts in Manhattan. In the former, the topology is random while in the latter, the topology is close to *city grid*. *NFP* is the most energy efficient algorithms for both *random* and *city grid* topologies but since the delay is an important issue in the applications considered, *NFP* should be avoided as its delay is 3 to 4 times higher than other algorithms. So as we avoid *NFP* because of delays, we see that *Compass* is the most efficient on *city grid* topology but, on *random* topology, *Greedy* is the most efficient. Thus, *Greedy* is selected for the monitoring of critical areas but *Compass* for the control of lampposts in Manhattan.



(a) *City* (b) *City Grid*

Fig. 18. Route length comparison for two topologies.



(a) *City* (b) *City Grid*

Fig. 19. Cost comparison for two topologies.

VIII. Conclusion

This paper showed the impact of the topology should not be neglected. Indeed, performances can vary of up to 25% regarding delivery ratio and route length and up to 100% for energy cost. These results show the significance of network topology and highlight the fact that this aspect should not be under-evaluated. Design of efficient algorithms in WSN should always take the topology and the application into account.

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