# A smart street lighting system based on IPv6-enabled wireless sensor network

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**Abstract**

In this paper, we propose a smart street lighting system based on IPv6-enabled wireless sensor network. We discuss the main drawbacks of RPL routing protocol for P2P communication in large-scale 6LoWPAN networks. Then, we address such drawbacks by proposing a new routing algorithm, named *GeoRank*, which integrates RPL protocol with GOAFR position-based routing protocol. Simulations were performed on networks extracted from real street maps. The obtained results show that *GeoRank* finds shorter routes than RPL in high link density conditions and GOAFR in low link density conditions. Thus, *GeoRank* shows to be adaptive to variable link densities found in large-scale networks. Further, *GeoRank* avoids the use of bandwidth-consuming control messages required in RPL, while being more scalable in terms of memory usage than storing-mode RPL.

*Keywords:* Wireless Sensor and Actuator Networks, Smart Street Lighting, Internet of Things, Smart Green Cities, Routing, IPv6, 6LoWPAN

## 1. Introduction

The street lighting system of a city plays an important role on its infrastructure. It is responsible of guaranteeing the society security and living during nighttime, traffic safety, and city appearance. Most commonly used lamp types in street lighting are the high pressure discharge lamps, e.g.: mercury vapor lamps, high-pressure sodium (HPS) lamps, and metal halide (MH) lamps (Sanchez et al., 2010; Dalla Costa et al., 2010b). However, with the efficiency and color quality of light emitting diodes (LEDs) steadily improving, LED lamps have been recently introduced as an alternative to replace the conventional lighting systems (Gacio et al., 2010; Chiu et al., 2010).

The use of LEDs in street lighting systems started to be reported in the last few years, and it is being considered a very good solution to replace the HID-based lighting systems, because of the longer lifetime, higher luminous efficiency in mesopic visual conditions, and higher CRI (Long and Zhou, 2008; Dalla Costa et al., 2010a). Moreover, LED lamps may also be dimmed to reduce its power consumption. Therefore, the presence of LED lamps in the modern street lighting systems brings a need for better management, in order to decrease the maintenance cost and power consumption (e.g.: by lamp dimming).

The addition of communication capability to the street lighting system goes towards such a goal. With a communication network, one can monitor the status information of each lamp (state, current, voltage and power measurements, etc.) and have better control of the system (e.g.: dimming). If the system is connected to a network, the lamp power can be monitored and the luminary can be quickly replaced when a failure occurs, because a

2

decrease of active power consumption is observed. Not only a preventive maintenance of the system can be easily programmed, but also software updates can be done (which allows future enhancements and addition of new functions). Then, a street lighting system with communication capability is justified by its advantages.

However, a street lighting system features a large number of independent devices, with geographic distribution depending on the city streets. Then, adding communication capabilities to these devices requires a complex network topology, as well as interoperability, scalability, security, robustness, low cost, ease to use and maintenance. A few contributions in the literature suggest some technologies that can be used to control a street lighting system. Some use the power lines for data transmission (PLC) (Denardin et al., 2003; Maizonave et al., 2006), while others use wireless communication, such as cellular networks (Liu et al., 2009; Yue et al., 2010), wireless sensor networks (Mendalka et al., 2010; Jing et al., 2010) and both combined (Lee et al., 2006; Jing et al., 2007).

The main drawbacks of the PLC technology are noisy medium, high signal attenuation, susceptibility to interference from nearby devices, time-varying network topology, high complexity and poor scalability, despite its existing infrastructure and extensive coverage. The most suitable area for PLC seems to be the medium voltage distribution network, usually combined with wireless technologies in the low voltage distribution network through a hybrid architecture (Papadopoulos et al., 2013). Similarly, the scalability and reliability of cellular networks are not questionable, especially under low load traffic. However, the literature has already demonstrated that the limitations

of the cellular networks for energy-constrained and/or processing-constrained devices are the tight synchronization requirement and high signalling overhead (Bontu et al., 2014). Furthermore, the dependency on the cellular carriers are usually not desirable in the smart cities/internet of things context. On the other hand, wireless sensor networks scalability is highly dependent on the routing algorithm performance. Therefore, designing a routing algorithm with high scalability and low overhead is a challenging requirement. It is important to note that we do not completely discard the PLC and cellular technologies for smart cities, but just reinforced that such technologies may be implemented as hybrid solutions, in order to develop redundant or complementary systems.

Recently, the 6LoWPAN protocol has been standardized by IETF as an adaptation layer to enable IEEE 802.15.4-based low power and lossy networks (LLNs), such as wireless sensor networks, to reuse existing IPv6 protocol for networking layer (Montenegro et al., 2007). The IP protocol is an open, mature and field proven technology, with free and well documented standards (RFCs), and thus it is very reasonable to reuse it for wireless sensor networking instead of creating new proprietary protocols. However, 6LoWPAN protocol does not define the routing protocol, which shall be defined apart. Thus, IETF has standardized RPL as the routing protocol for IP-based LLNs (Winter et al., 2012).

However, very recent empirical studies showed that RPL has some drawbacks, as higher amount of control messages than data messages, mainly for constructing routes from the sink to the nodes (downward routes in RPL vocabulary) (Heurtefeux and Menouar, 2013; Xie et al., 2010; Baccelli et al.,

2011). By the other hand, in a street light system, nodes are static and a routing protocol could benefit of this condition to find routes with less control overhead than RPL. The routing algorithms that use position to find routes in a communication network are known as geographic routing algorithms and a large body of literature has been devoted to the research on those algorithms in last few decades (Karp and Kung, 2000; Giordano et al., 2001; Subramanian et al., 2007; Denardin et al., 2011).

Our main contribution in this paper is to propose a modification into RPL protocol, in order to better support P2P communication. The proposed technique intend to integrate a geographic routing algorithm in the RPL protocol to reduce the amount of control message required for P2P communication. We further propose a smart street lighting system based on IPv6-enabled wireless sensor network, which makes use of the new routing algorithm for message exchanging. This paper is organized as follows: Section 2 presents an overview of the 6LoWPAN protocol, describing succinctly its operating modes, routing strategies and main drawbacks. In section 3 we address the geographic routing technique, highlighting its pros and cons. In section 4, the *GeoRank* algorithm is presented, depicting its working principle. We evaluate, by simulation, the performance of the proposed algorithm in Section 5. Finally, we conclude this paper in Section 6.

## 2. 6LoWPAN

6LoWPAN is a protocol definition, standardized in RFC 4944 (Montenegro et al., 2007) and RFC 6282 (Hui and Thubert, 2011), that works as an adaptation layer between the IPv6 network layer and the IEEE 802.15.4 MAC

(Media Access Control) layer, as depicted in figure 1. It is required because IEEE 802.15.4 standard, which defines MAC and PHY layers for low power and low data rate wireless networks, is able to carry packets with maximum size of 127 bytes, while IPv6 packets requires a MTU (minimum transmission unit) of 1280 bytes. Thus, the overall goal of 6LoWPAN is to allow IPv6 packets to be carried on top of IEEE 802.15.4-based wireless sensor networks, by defining fragmentation and compression mechanisms of the IPv6 packets and thus enabling IPv6-based wireless sensor networks (Mulligan, 2007).

In addition to fragmentation and header compression, 6LoWPAN also supports mesh networks, as most wireless sensor networks are expected to require multi-hop communication. Two possible configurations for mesh networking are defined by 6LoWPAN: *mesh under* and *route over*. In mesh under, the mesh networking must be provided by the link layer and all IPv6 hosts are only one IP hop away from the border router that is connected to an external IP network (this router is known as 6LoWPAN Border Router (6LBR)). By the other hand, in route over, the routing is done at the IP layer and hosts may be multiple IP hops away from a 6LBR. Thus, every router in the networks act as an IP router. However, although 6LoWPAN supports mesh networking, the decision of how mesh routing is actually performed is out of the scope of the 6LoWPAN specification.

## 2.1. Routing in 6LoWPAN

In order to address the lack of a routing protocol for 6LoWPAN networks, the RPL protocol has been proposed in RFC 6550 by IETF. Accordingly, RPL provides support for point-to-point (P2P), point-to-multipoint and multipoint-to-point traffic flows (Winter et al., 2012).
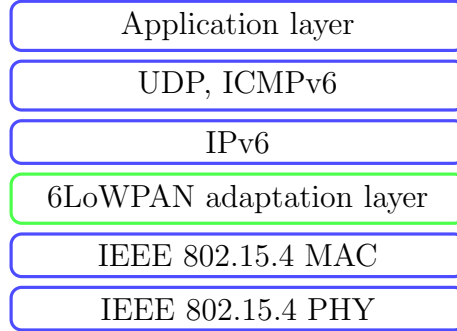
Figure 1: 6LoWPAN architecture

The RPL protocol is based on directed acyclic graph (DAG). DAGs are directed graphs formed by a collection of $n$ vertices labeled from the set $\{1,2,...,n\}$, such that the presence of the edge $(i, j)$ implies that $i < j$. Therefore, each directed edge connects one vertex to another, such that there is no way to start at some vertex $v$ and follow a sequence of edges that eventually loops back to $v$ again (Thulasiraman and Swamy, 1992). All edges are contained in paths oriented toward and terminating at one or more root nodes. These root nodes are known as Low power and Lossy Network Border Routers (LBR), which are devices that connects the LLN to another routing domain such as a Local Area Network (LAN) or the internet, where a different routing protocol may be in operation. In addition to its functionality as a routing device, the LBR acts as a sink node to a WSN as well as a data collector or aggregator (Vasseur, 2014).

In RPL, a DAG grounded at a single LBR is called a Destination Oriented Directed Acyclic Graph (DODAG). For a specific DODAG each node is assigned to a rank such that rank increases as the node is far from the LBR. Note that the rank of the nodes along any path to the LBR must be

monotonically decreasing, avoiding routing loops, as shown in the figure 2. Therefore, forwarding a packet to the LBR roughly consist in choosing the neighbor node with the lowest rank.
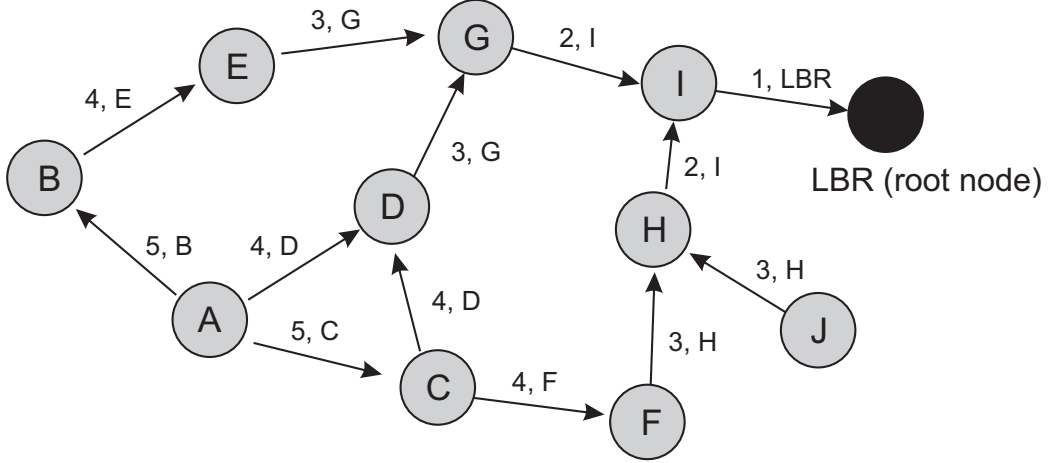


Figure 2: Example of a Destination Oriented Directed Acyclic Graph(DODAG).

Nodes running RPL exchange control messages to setup and maintain the DODAG, which in the 6LoWPAN implementation are ICMPv6 messages. The 1 byte code in the ICMPv6 header is used to differentiate between different sub-type of control messages (Conta et al., 2006). The sub-type used to build the DODAG is called DAG Information Object (DIO) (Winter et al., 2012). All the nodes in the network regularly broadcast a DIO to its one-hop neighbors, indicating their activity and rank. The instant at which a node issues a DIO is governed by a Trickle timer (Levis et al., 2004), which is reset only when an inconsistency arises, i. e., very few DIOs are exchanged when the topology is stable. RPL provide optimized paths to one or more LBRs with very little information stored in the routing table. The information

stored is limited to its one-hop neighbors and their parents in the DODAGs. A parent of a node within a DODAG is one of the immediate successors of the node on a path towards the DODAG root.

Despite of its advantages, the default RPL using DODAGs does not provide routes from the LBRs to other nodes in the network, which in RPL are known as down routes. Down refers to the direction from DODAG roots towards leaf nodes, following the reverse direction of DODAG edges. The availability of such routes is desirable in several scenarios, mainly in those with actuators nodes and where selective queries to sensors nodes are required. Thus, a RPL router that requires a path from a LBR to itself should send a DAO (Destination Advertisement Object) message to the LBR through the DODAG edges. The nodes that receive a DAO message forward the message as soon as the timer DelayDAO expires, being this time determined by the implementation, according to (Winter et al., 2012). Therefore, routes for any destination inside the network, other than the LBRs, are provided by these destinations through DAO messages.

The RPL specification defines two modes of operation for the DAO mechanism, storing and non-storing modes. In non-storing mode, each node has to propagate its parent list up to the root. After receiving such topology information, the root computes the path to the destination. Such mode of operating generally makes use of unicast DAO messages to the DODAG root. The storing mode is fully stateful, i.e., each intermediate router in the path towards the root node stores the routes to the destinations in its routing table. To make this possible, each intermediate node adds its downward route to the DAO message, which is unicast to the selected parent(s).

These down routes generated by DAO messages are extremely important to point-to-point communication in the network. An example of the necessity of P2P messages is a scenario where actuators require data from sensors to decide when and how to act. Therefore, if the application needs P2P communication, each pair of nodes must request at least one downward path in order to allow such message exchange. In the worst case, the message is sent from the source router towards the LBR and, thereafter, from the LBR to the destination node, as shown in figure 3. If the RPL protocol is being performed in the non-storing mode, all point-to-point communication will be conducted by one or more LBRs, which are the only nodes in the network that store downward routes.
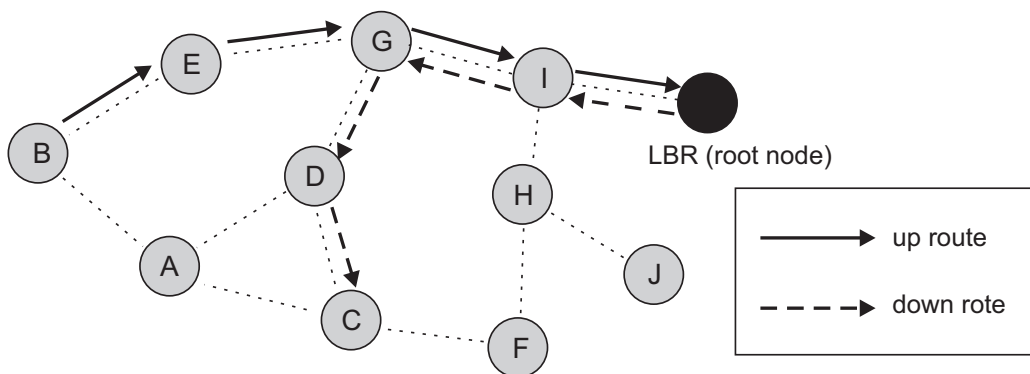


Figure 3: P2P communication between routers $B$ and $C$ through a DODAG root using RPL.

## 2.2. Drawbacks of the RPL protocol

The RPL protocol has several possible drawbacks, depending on the application. Generally, we can point out three usual problems. First, one can easily realize that the P2P routes provided by RPL can be much larger

than the shortest available route, causing high traffic on the DODAGs routes (worsening nearby root nodes), as discussed in (Xie et al., 2010) and (Baccelli et al., 2011). Second, the DAO message exchange may lead to excessive packet collisions, mainly in scenarios with lots of link losses. Thus, the generated downward routes are proactive and initiated by the destination. Therefore, in order to an actuator make a request to a sensor, the sensor should know that an actuator needs to communicate by point-to-point mode. Third, proactive routing also impacts on the size of the routing table, i.e, the more down routes exists, the greater the memory required to store those paths.

Even, there are problems related to the DAO operating modes. In non-storing mode, RPL requires the use of IPv6 source routing mechanism. Therefore, a Source Routing Header (SRH) for use strictly between RPL routers in the same RPL routing domain was proposed in RFC 6554. However, RPL source routing implements a policy where each IPv6 hop between the source and destination of the source route is specified within the SRH. Such approach leads to a large overhead and increases the consumption of the already scarce bandwidth. Further, as the IEEE 802.15.4 standard has a limited maximum transmission unit (MTU), that may also imply in increased fragmentation. Therefore, successful delivery of an IP packet depends on the successful delivery of all possible fragments, which are not desirable once the LLNs are generally characterized by high packet loss rates.

In addition to the fragmentation issue, the maximum length of the routing header is limited to 255 octets (Montenegro et al., 2007), which restricts the maximum path length to 127 hops if an address compression mechanism is applied (Clausen and Herberg, 2011). This limitation may exclude scenarios

11

with long chain-like topologies, such as street lighting systems and traffic lights along a street.

In storing mode, each router has to be able to store all the routes downwards its position in the formed DODAGs. This implies that, for routers near to the root node, the required storage is only bounded by the number of paths to all other routers in the network (Clausen et al., 2014). As RPL targets networks consisting of thousands of memory-constrained devices, the required storing capacity on these devices may not be compatible with the basic precepts of the WSANs.

Due to these not negligible drawbacks, it is wise to develop some work around able to improve the RPL protocol deficiencies, mainly that related with P2P messages. One of the possible approaches is the use of geographic routing techniques, which are routing algorithms known by its low overhead and high scalability features (Karp and Kung, 2000; Giordano et al., 2001; Subramanian et al., 2007).

## 3. Geographic Routing

Geographic routing mainly relies on a simple greedy geographic forwarding strategy, where each router node must select a locally optimal neighbor with a positive progress towards the data packet destination (Chen and Varshney, 2007). Such approach is largely known by its low overhead and scalability, which can easily be observed due to its low control message system, i.e., a router in a geographic routing strategy only needs to know its direct neighborhood.

In the geographic routing approach, the destination address is the position

of the destination node, instead of a topological address. To discover a node position in the network, each router node must implement a location service. This service is responsible to determine its own position and the destination position. A node position could be obtained by pre-configuration if the node is stationary, or by a GPS receiver. As network nodes are static in the street lighting case, the location information of the nodes can be stored during the installation process.

When considering realistic outdoor scenarios, such as a city, any block could turn into a void. A void occurs when all neighbors of a router node are farther away from the destination node than the router itself. In this case, the router fails to locate a next hop node through greedy strategy. If only the greedy-forwarding algorithm is used, packets have to be discarded when a void is reached. However, a void does not necessarily mean that there is no route to the destination, because if the network is connected, a valid topological path exists by circumventing the void.

Many researchers argue that a dense deployment of wireless nodes can reduce the likelihood of the void occurrence in the network (Giordano et al., 2001; Al-Karaki and Kamal, 2004; Chen and Varshney, 2007). Indeed, in scenarios without obstacles that can be true. However, in outdoor large scale wireless networks it is unlikely to have such scenarios. Void handling techniques is an important issue to be addressed in such networks.

Among the main non-hybrid void handling techniques, the Greedy Other Adaptive Face Routing (GOAFR) algorithm and its variations is one of the approaches that can get closer to the optimum path when traversing voids (Kuhn et al., 2008). However, recently some hybrid strategies report

having overcome the traditional geographic routing algorithms in terms of hop count, as the Coordinate Depth Forwarding (CDF) technique (Denardin et al., 2011).

Hybrid strategies allow aggregating several techniques in order to achieve better performance than a single technique. In the next section, we propose a hybrid approach that combines the simplicity of the DODAGs routes formed by RPL protocol, the scalability and guaranteed delivery feature of GOAFR algorithm and the inherent optimal paths of the CDF heuristics. However, instead of using directly the hop count in order to generate the optimal paths claimed by CDF, we propose to change its routing metric to the DODAG rank and study its behavior in network topologies based on real street maps. Therefore, the proposed approach allows to join the best characteristics of RPL and GOAFR into a new routing protocol, resulting in better performance than a single instance of each one would present. This new routing protocol is named *GeoRank* to represent the integration of the geometric based behavior of GOAFR with the rank based behavior of RPL, and it will be explained in the following section.

## 4. GeoRank

Mainly due to its greedy step, GOAFR algorithm is able to perform quite well in networks with high link density, discovering paths often optimal or near-optimal paths, in contrast to RPL, which is constrained to route only through the DODAGs and thus, being unable to find the optimal paths. By the other hand, in networks with low link density, mainly around the critical density (Kuhn et al., 2008), GOAFR has a performance loss and may usually

14

find paths longer than RPL. Therefore, a hybrid approach that leverages the best of both algorithms according to the network link density is proposed. This approach is mainly suitable for large scale and heterogeneous networks, such as a network of wireless street light nodes, where the link density varies from low to high depending of the more or less presence of obstructions and buildings in different places of the network. The operation of *GeoRank* is illustrated in figure 4 and the algorithm is outlined below in Algoritm 1.

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**Algorithm 1** GeoRank

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**Step 1** - Store in the packet the DODAG root with the smallest angle to the source-destination line.

**Step 2** - Start with greedy step of GOAFR until: (case I) finding a void node (i.e. a node where GOAFR would switch to face routing (OAFR)) or (case II) delivering the packet. In case I, store the current position in the packet and go to step 3.

**Step 3** - If the destination node is closer to the DODAG root (stored in the packet) than the current node or the DODAG root is closer to the destination node than the current node, forward to the next hop in the DODAG towards the root (i.e. upward route). If neither condition is satisfied, go to step 4. Whenever the current node position is closer to destination than the position stored in the packet in step 2, go to step 1.

**Step 4** - Execute face routing mode of GOAFR until delivering the packet or returning to step 1.
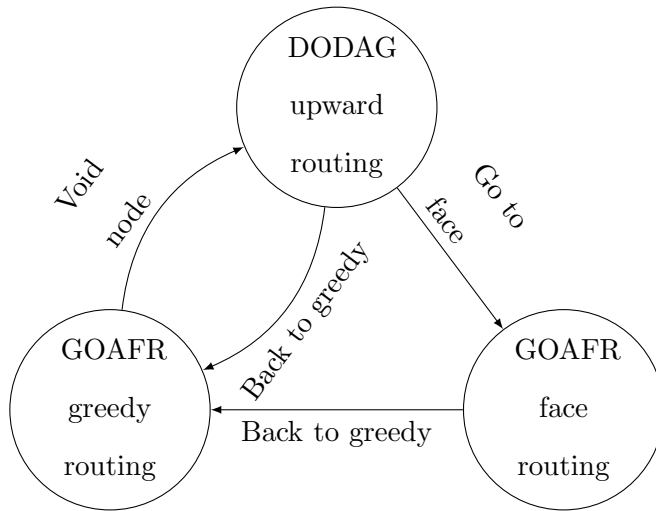
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Figure 4: GeoRank operation

## 5. Simulation Results

In order to evaluate the proposed technique, simulations were performed in scenarios based on real street maps exported from the OpenStreetMap (OSM) data set, which is an open collaborative mapping project (Haklay and Weber, 2008). The scenarios have been chosen to cover a wide range of possible street layouts. They have been populated with nodes with an average distance of $40m$, in order to simulate a real street lighting system, with network sizes ranging from 100 up to 400 nodes. A sample of the chosen scenarios are shown in figure 5.

For every scenario, there were generated 1000 random source-destination pairs, giving a coverage of up to 10% of the possible source-destination combinations. Also, every simulation was performed for 10 different (random) positions of the DODAG root in every scenario, which gives a good coverage of the 5 possible root placements (i.e. center and top/bottom-right/left cor-

16

Figure 5: Sample of simulated scenarios with nodes populated.

ners). Then, for the each source-destination pair, the route was determined by each algorithm under test (RPL, GOAFR, *GeoRank* and Dijkstra' algorithm for shortest path) and length of each route was measured in number of hops. The average length of the routes was computed and the results are shown in figure 6.

*5.1. Remarks*

The results shown that, for large radio ranges, where the average connectivity is high, the geographic routing is able to find near optimal routes. The reason for this is that with larger radio ranges the number of links that provide shorter paths are increased and the geographic routing is able to use them for routing, while RPL is constrained to the longer DODAG paths. By other hand, when the radio range is decreased, the network approaches the critical density, where geographic routing starts to reach more voids in the network and needs to resort more often to the face routing mechanism for circumventing the voids. Thus, the overall effect is that the use of geographic routing results in longer paths than RPL in lower link density conditions.

It is remarkable that the *GeoRank* is able to reduce the length of the route found by geographic routing in lower link densities. It does so by avoiding to circumvent the void with face routing whenever it is possible to use the
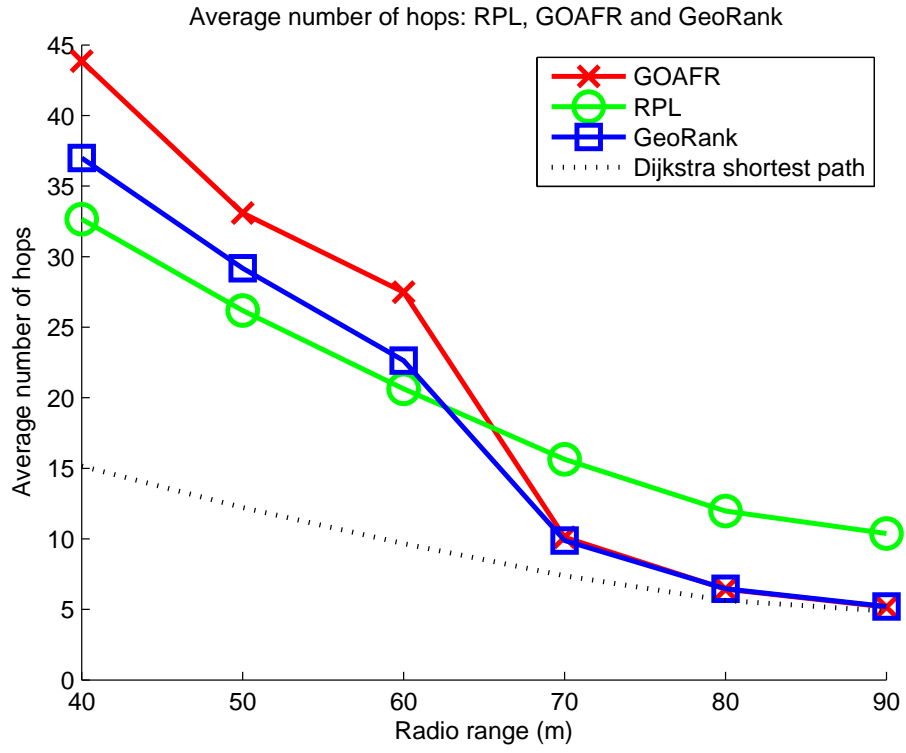
Figure 6: Simulation results of the average route length for the routing algorithms (RPL, GOAFR, *GeoRank*, and Dijkstra' algorithm for shortest path).

DODAG to perform this deviation. Thus, *GeoRank* achieves a significant reduction of the path length when the number of voids is large (i.e. when the radio range is small) compared to geographic routing alone. By the other hand, when the radio range is increased, geographic routing performs better than RPL, and *GeoRank* does not impact negatively its performance. Therefore, *GeoRank* works as a selective method, that is able leverage the best of RPL and geographic routing, and being adaptive to the network density.

In a large scale network, as a smart street lighting, there may be some places where the link density is very low due to obstacles, such as in dense urban environments, while some places may have high link density due to less and lower buildings. Therefore, while in either case RPL or geographic routing alone would not be the best option, the remarkable adaptability of *GeoRank* makes it the well suited to such variable link density case.

## 6. Conclusions

In this paper, a smart street lighting system using a 6LoWPAN-based wireless sensor network was proposed. Moreover, in order to improve the performance and scalability of the network, it was proposed a new routing protocol, named *GeoRank*, which integrates the standardized RPL routing protocol for 6LoWPAN networks with the state-of-the-art GOAFR position-based routing algorithm. The results obtained from simulations on networks extracted from real street maps have shown that *GeoRank* has an improved routing performance over GOAFR in low link density condition, while outperforming the RPL protocol in high link density condition by finding mostly

optimal routes. Therefore, *GeoRank* is an adaptive approach for scenarios with variable link densities.

Further, it is remarked that *GeoRank* is not required to use the highly bandwidth-consuming RPL DAO control messages, and is more scalable than storing-mode RPL according to memory usage. Finally, although *GeoRank* is proposed for a smart street lighting system, it is highlighted that it may find applicability for other large-scale network scenarios where the link density is variable and the scalability of the network is a major concern.

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22

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