Performance and energy efficiency of position-based routing in IEEE 802.15.4a low data rate Wireless Personal Data Networks

(Invited Paper)

Luca De Nardis, Daniele Domenicali and Maria-Gabriella Di Benedetto
Infocom Department
School of Engineering
University of Rome La Sapienza
Rome, Italy 00184
Emails: {lucadn, dome, dibenedetto}@newyork.ing.uniroma1.it

***Abstract*— The IEEE 802.15.4a standard provides a framework for low data rate communications systems, typically sensor networks, with ranging and positioning capabilities. This work focuses on the analysis of the impact of position information on routing performance in a network of IEEE 802.15.4a-compliant devices. The well known Ad hoc On demand Distance Vector (AODV) routing protocol is compared with the position-based Greedy Perimeter Stateless Routing (GPSR) protocol, taking advantage of the position information provided by a distributed positioning protocol. The comparison is carried out in terms of throughput and consumed energy per bit, and by taking into account all transmitted and received packets, including the additional ones generated by the distributed positioning protocol. Simulation results show that the introduction of position information can lead to significant improvements in both throughput and energy efficiency. Results also show that the energy efficiency of the position based routing protocol is affected by the accuracy of the position information provided by the positioning protocol, in turn depending on the network density.**

I. Introduction

The IEEE 802.15.4a standard provides a framework for low data rate communications systems, typically sensor networks, with ranging and positioning capabilities [1]. The standard includes all the hardware and MAC-layer functionalities required to perform distance estimation. Distance estimates can be then used to build a map of the physical positions of nodes by means of a positioning protocol.

Position information can be introduced in almost all aspects of network organisation and management, from medium access control to node clustering, from scheduling to routing. Although the use of position information is expected to lead to an overall performance increase, a fair analysis of its impact on network performance should also take into account the overhead required to obtain such information, in terms of additional power consumption and interference generated within the network itself.

Routing, in particular, is a network task that can take advantage of the availability of position information. Several position-based routing protocols have been proposed in the past, using position information either to reduce overhead during route search procedures ([2], [3], [4]) or to select the next hop in data packets forwarding ([5], [6]). Performance evaluation of such protocols traditionally assumed that position information was obtained by means of GPS receivers, thus not introducing any overhead on the radio network. This assumption is no longer valid in an UWB network, where devices use the same hardware to communicate and to retrieve and exchange distance and position information.

Moving from this premises, in this work we compare the well known Ad hoc On demand Distance Vector (AODV) routing protocol vs. the position-based Greedy Perimeter Stateless Routing (GPSR) protocol, with position information provided by the Self Positioning Algorithm (SPA), a distributed positioning protocol based on Time Of Arrival distance estimation carried out by network devices. The two protocols are compared in a scenario composed of a network of 802.15.4a devices, using the ranging procedure defined within the standard in order to enable the SPA algorithm and the GPSR routing protocol. Two performance indicators are taken into account: end-to-end throughput and energy per received packet. The latter parameter describes the amount of energy spent in the network (including both data and control packets) for each packet correctly received by the destination node, and measures the overall energy efficiency of each routing solution. Note that this parameter also takes into account the additional energy consumption caused by ranging and positioning in the case of the GPSR protocol.

The paper is organized as follows. Section II describes the 802.15.4a standard, focusing on network organization, medium access and ranging. Section III describes the Self Positioning Algorithm, while Section IV provides a description of AODV and GPSR routing protocols. Next, Section V describes the simulation scenario and results, while Section VI draws conclusions.

II. The 802.15.4a standard

This section provides a brief description of the standard, focusing on the aspects more relevant to the present work. A more detailed description of the standard can be found in [1], [7].

1-4244-0521-1/07/$20.00 ©2007 IEEE

A. Network organization

The 802.15.4a standard defines two classes of devices: Full-Function Devices (FFD), in which all network functionalities are implemented, and Reduced-Function Devices (RFD), that only support a reduced set of functionalities, e.g. sensor nodes that measure a physical parameter and can execute simple commands. RFD and FFD devices organize themselves in Personal Area Networks (PANs). A PAN is controlled by a PAN coordinator, in charge of setting up and maintaining the PAN. The role of PAN coordinator can only be taken by a FFD device, while RFD devices can only join an existing PAN by communicating with the PAN coordinator. A PAN can adopt either of the two following network organizations:

- *star topology* - Devices can only exchange information with the PAN coordinator;
- *peer-to-peer topology* - FFD devices can communicate directly as long as they are within physical reach, while RFD devices, due to their limitations, can only connect with the PAN coordinator.

The peer-to-peer topology provides higher flexibility, and allows more complex topologies, based on multiple clusters; algorithms for the creation and management of such larger networks are however not part of the standard.

B. Access strategies

Medium access within a PAN is controlled by the PAN coordinator that may choose between either *beacon-enabled* or *nonbeacon-enabled* modality.

In the *beacon-enabled* modality, the PAN coordinator broadcasts a periodic beacon. The period between two consecutive beacons defines a superframe structure divided in 16 slots. The first slot is always occupied by the beacon, while the other slots are used for data communication by means of random access, and form the so-called Contention Access Period (CAP). The beacon contains information related to PAN identification, synchronization, and superframe structure.

The beacon-enabled modality is only adopted when the PAN has a star topology. In this case, two data transfer modes are available:

1) *Transfer from a device to the coordinator* - a device willing to transfer data to the coordinator uses either ALOHA or slotted Carrier Sensing Multiple Access with Collision Avoidance (CSMA-CA) to access the medium.
2) *Transfer from the coordinator to a device* - when the coordinator has data pending for a device, it announces so in the beacon. The interested device selects a free slot and sends a data request to the coordinator, indicating that it is ready to receive the data. When the coordinator receives the data request message, it selects a free slot and sends data using either ALOHA or CSMA-CA.

In order to support low-latency applications, the PAN coordinator can reserve one or more slots for those devices running such applications avoiding thus contention with other devices. Reserved slots are referred to as Guaranteed Time Slots (GTS), and they form the Contention Free Period (CFP) of the superframe.

In the *nonbeacon-enabled* modality there is no explicit synchronization provided by the PAN coordinator. This modality is particularly suited for PANs adopting the peer-to-peer topology, but can be adopted in a star network as well.

C. Ranging support

One of the key innovations of 802.15.4a is the accurate ranging capability, although support for ranging in 802.15.4a-compliant devices will be optional.

Distance estimation between two devices is based on a two way ranging approach, without the need for a common time reference.This approach an exchange of at least two packets: a device A starts a ranging measurement by sending a ranging packet to a device B at time t_{start}. Device B replies with a second ranging packet, transmitted after a delay ΔT. The packet is received by device A at time t_{stop}. The knowledge of the time interval $t_{stop} - t_{start}$ and of the delay ΔT allows to determine the propagation time t_{flight}. In [8] a similar scheme was proposed for UWB ranging.

The two way ranging procedure involves time intervals measured by two different devices, using different reference clocks. If neither of the devices involved in a ranging estimation is capable of determining the offset between clocks, a protocol-based solution for compensating such offset is adopted. Such solution, based on the concept of Symmetric Double Sided Two-Way Ranging (SDS-TWR) proposed in [9], consists in repeating the packet exchange twice, inverting the role of the two devices in the second exchange. Furthermore, additional packets are required in order to set-up and finish the ranging procedure, since the ranging function must be enabled and disabled in the receiving device and to enable private (that is, secure) ranging. By the end, in the worst case, ranging can thus require up to eight packets to be exchanged between the two devices. Additional packets are further required when the ranging procedure is requested by a third device, in order to send the ranging command to the initiating device, and to collect time measurements from both devices. The significant overhead introduced by ranging in the 802.15.4a standard should thus be taken into account in the design of applications requiring distance information, e.g. positioning algorithms, to be deployed in 802.15.4a networks.

III. The Self Positioning Algorithm

A. Brief description

The Self-Positioning Algorithm (SPA) [10] has the goal of providing each node in the network with its own position in a common coordinate system. In absence of external reference points (anchor nodes) the nodes are only able to position themselves in a relative coordinate system; in some cases this information is however sufficient for enabling position-based optimizations, for example in routing. It should be noted that the protocol can be easily adapted to the case where anchor nodes are available and provide an external reference system. In this section we will only provide a brief introduction to the protocol, as a background for the performance analysis presented in Section V. A complete description of the algorithm can be found in [10].

The SPA algorithm is logically organized in two phases.

Phase 1 – During this phase each node attempts to build a node-centered coordinate system, called Local Coordinate System (LCS) centered on itself. In order to build its own LCS, each node i performs the following actions:

1) Detect its set of one-hop neighbors K_i; in the original definition of the protocol this phase is accomplished by using beacons, in order to maintain an up-to-date map of one-hop neighbors;
2) Evaluate the set of distances D_i from its neighbors K_i; it is assumed that the distance measurement from each one-hop neighbor is obtained by means of TOA estimation;
3) Send D_i and K_i to its one-hop neighbors. As a consequence of the above steps, each node i will know directly its distances from all its one-hop neighbors, the IDs of its two-hop neighbors, and a subset of the distances from its one-hop neighbors to its two-hop neighbors.

The determination of the local coordinate system in a 2D scenario requires the selection of two additional terminals p, q in the K_i set. p and q must satisfy two requirements:

1) They must not lie on the same line with i;
2) Their distance d_{pq} must be known to i.

In the coordinate system defined by i, p and q, i can determine the position of each neighbor k for which the distances d_{pk} and d_{qk} are known.

Phase 2 – At the end of Phase 1, each node that was able to obtain enough ranging information to build a coordinate system occupies the position (0, 0) of its own LCS: in order to define a global network topology, all node-centered systems of coordinates must be linearly transformed in order to have a unique orientation (i.e. the same direction for x and y axes of all nodes) and thus converge to a Network Coordinate System (NCS). This is obtained by exchanging information between nodes in a peer-to-peer fashion: whenever a node receives information on the coordinate system of a neighbor, it decides if harmonizing its own coordinate system to the received one based on a predefined criterion, such as the node ID number.

B. Enhancements to the SPA

The SPA was originally proposed as a solution for providing coarse positioning information to be used by a position-based routing protocol in large scale ad-hoc networks. In the process of adapting this algorithm to the application scenarios foreseen within the 802.15.4a standard, several modifications and enhancements were introduced in the protocol:

- The original beacon-based solution for detecting one-hop neighbors was modified in order to take into account the characteristics of the underlying MAC ranging procedure: in the protocol that we implemented, each terminal transmits a broadcast packet for neighbor discovery; each terminal receiving such packet starts an 802.15.4a ranging procedure after a random delay, required to avoid systematic collisions of ranging packets on the channel.
- In the original version of the algorithm the transmission of the D_i and K_i sets from a generic node i to its one-hop neighbors triggered an immediate update of distance and neighbor databases in each neighbor; this approach would lead to a high number of packets sent almost simultaneously in the same area of the network, causing a high number of packet collisions on the common channel. This behavior was modified in the implementation by forcing each node to introduce a random delay before sending its own update, thus avoiding systematic collisions.
- The SPA was originally defined as a mean for providing each node with its own position in a unique coordinate system, without providing the node with information on the position of all other nodes in the network. In most of the scenarios foreseen in 802.15.4a, however, the capability of a node to determine the position of other nodes is an important additional feature. As a consequence, in our version of the protocol, when a node i sends information on its LCS, it also sends position information about all known nodes. In this way, when a node receives a LCS and harmonizes its own coordinate system to the received one, it also learns about the position of nodes farther than two hops away, eventually leading to a full knowledge of the network map in all nodes in the network.

IV. Routing protocols

A. Ad-hoc On demand Distance Vector

The Ad-hoc On demand Distance Vector (AODV) routing protocol is an on demand protocol, meaning that a route is only searched and established when requested by a source node, and it is only maintained while data transfer along the route is being carried out [11]. When a route is needed, the source node starts a path discovery procedure by broadcasting a Route Request (RREQ) packet. Each node receiving a RREQ packet has three possible choices: a) discard the packet if a copy of the same RREQ packet was already received and processed; b) satisfy the request with a Route Reply (RREP) packet containing the information originally requested by the source node, if this information is available; c) forward the RREQ packet to its neighbors, in case the node has no up-to-date information on the requested route.

In AODV nodes store information on active routes in routing tables. When a node processes a RREQ packet it creates a table entry related to the source node that generated the request, which is deleted after a timeout. If the node receives a RREP packet related to the request before the table entry timeout expires, the node will forward the RREP to the previous node on the reverse path to the source, and will refresh the table entry, setting a new timeout waiting for data packets.

AODV also foresees procedures in order to deal with link failure and node mobility. When a node on an active route becomes unreachable the node just upstream to it on the route will trigger a route maintenance procedure in order to either search an alternative route to the destination or, at least, communicate to the source that the route is no longer available. A link failure is identified by detecting long periods of inactivity by a node: in order to avoid false alarms, a node that has been inactive for a long time will periodically emit hello messages so that neighboring nodes can refresh their local topology information.

It should be noted that a correct set-up of timeouts is fundamental in optimizing AODV performance. Short timeouts can in fact lead to excessive overhead due to incorrect link failure detection, while long timeouts can cause a slow reaction to topology variations and node mobility, causing a high number of packet losses. In our simulations we used the implementation of AODV provided within the AdHocSim simulation framework developed on the basis of the Omnet++ simulation environment [12], implementing version 10 of the AODV IETF draft.

B. Greedy Perimeter Stateless Routing

The Greedy Perimeter Stateless Routing (GPSR) protocol was originally proposed in [5]. The protocol uses positional information as the key metric in packet forwarding, using a simple "greedy" forwarding strategy:

1) Each packet is marked by the source terminal with the information about the location of the destination.
2) Each intermediate node forwards the packet to the neighboring node closest to the destination.

The above strategy by itself does not guarantee that a path between source and destination is always found, as situations may occur in which a terminal is closer to the destination than any of its neighbors. In these situations the protocol switches from a greedy forwarding strategy to a perimeter forwarding one, in which a terminal is allowed to forward the packet to a neighbor which is farther than itself from the destination, in order to solve the deadlock caused by greedy forwarding. The perimeter forwarding, based on planar graph theory, guarantees that a path between source and destination is always found.

The main advantage of GPSR is in the reduction of the state information in each terminal, if compared to traditional table-driven algorithms. In fact, each node only needs to maintain information about its one hop neighbors locations, which is exchanged by means of periodic beacons broadcasted by each terminal. This means that the amount of routing information is only dependent on the network density (average size of neighbors for each terminal) and not on the network size. It should be noted however that the algorithm only works if all nodes share the same coordinate system, that is if the position of the destination attached by the source in a packet is coherent with the positional information available to the intermediate nodes.

In the implementation of GPSR used in this work the following modifications were introduced:

- The perimeter forwarding approach was replaced by a simpler flooding solution: whenever a node is closer to the destination than any of his neighbors it falls back to flooding, and broadcasts the packet to its neighbors. Packet forwarding is carried out by flooding until the local deadlock is solved, as much as it was done with perimeter forwarding in the original GPSR protocol;
- Since the SPA protocol cannot guarantee that all nodes share the same coordinate system, such coordinate system is explicitly included in the data packet, so that each intermediate node can evaluate if it can use position information to forward the packet. Whenever position information is either not valid or not available nodes switch to flooding in order to proceed with packet forwarding;
- The distance information is used to scale down the transmit power when transmitting data packets in greedy forwarding mode; packets transmitted in flooding mode are always transmitted at full power.

TABLE I
MAIN SIMULATION SETTINGS

Parameter	Value
L	5
N	25
Area A	150 m × 150 m
User bit rate	10 kb/s
Transmission rate	966 kb/s
Power	36.5 μW (FCC limit for a 0.5 GHz bandwidth)
DATA packet length	1224 bits (+ 64 bits for Sync trailer)
Physical layer settings	N_s = 16, T_s = 64.1 ns, T_m = 2 ns

V. Simulation Results

We compared the AODV protocol vs. the combination of SPA and GPRS protocols by means of simulations. Simulation results were averaged over L different simulation runs. In each simulation run, N 802.15.4a-like devices were randomly located inside a square region with area A. Propagation was modeled by using the CM5 and CM6 scenarios defined by the IEEE 802.15.4a channel subcommittee, corresponding to outdoor propagation in residential environments in LOS and NLOS conditions. At the beginning of each run the path loss model between each pair of nodes was selected to be NLOS with a probability P_{NLOS}. By varying the value of P_{NLOS} between 0 and 1 different degrees of network connectivity were simulated. The selected channel model between each pair of nodes was also taken into account by the interference module for introducing errors on the received packets, according to the MUI model described in [13]. Furthermore, ranging errors were introduced on each distance measurement depending on the nature (LOS vs. NLOS) of the link. Ranging error was modeled according to the model described in [14] and originally proposed in [15].

The main simulation settings are presented in Table I.

Figure 1 presents the values of throughput as a function of the probability of NLOS links in the network, corresponding to different degrees of network connectivity and ranging errors, while Figure 2 shows the required energy for each end-to-end received packet. The combination of GPSR and SPA protocols achieves better throughput results than AODV

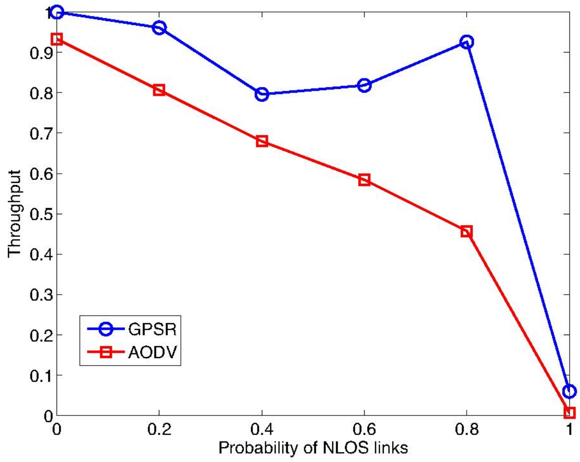

Fig. 1. Throughput as a function of the probability of NLOS links (Squares: AODV, Circles: GPSR).

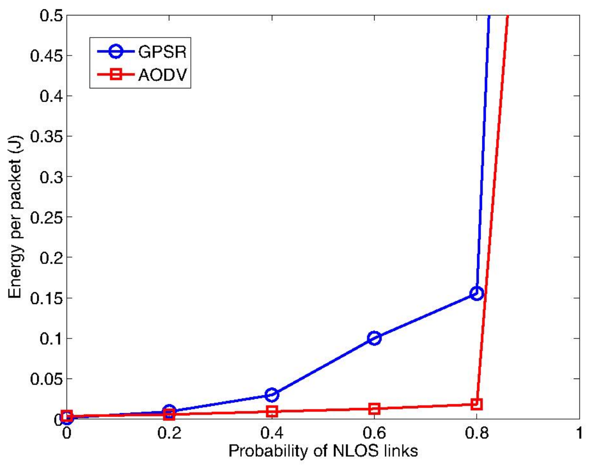

Fig. 2. Consumed energy per received packet as a function of the probability of NLOS links (Squares: AODV, Circles: GPSR).

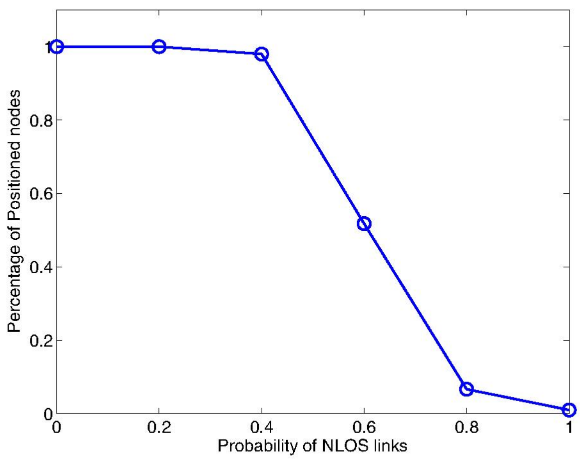

Fig. 3. Percentage of nodes sharing a common coordinate system as a function of the probability of NLOS links.

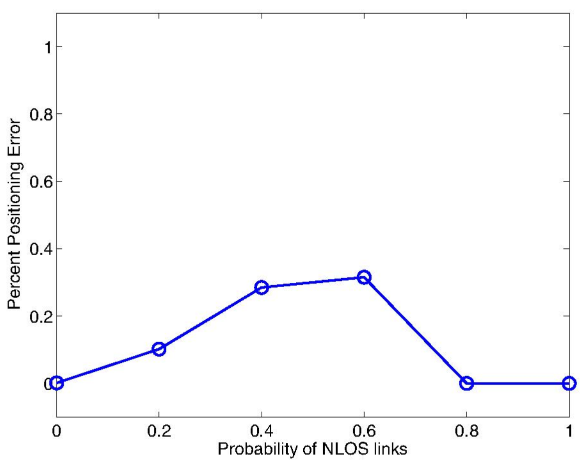

Fig. 4. Percentual positioning error as a function of the probability of NLOS links.

in all scenarios where $P_{NLOS} < 1$, while both protocols fail completely for $P_{NLOS} = 1$ due to lack of connectivity. It is interesting to note that the throughput obtained by using the AODV protocol decreases monotonically with the network connectivity, while the throughput obtained by using the GPRS protocol has a local minimum for $P_{NLOS} = 0.4$ and then grows again before dropping abruptly. This behavior can be explained by observing the results of positioning accuracy obtained in the same simulation runs, shown in Figures 3 and 4. Figure 3 shows the percentage of positioned nodes, that is the percentage of nodes which are able to join a common reference system. It can be observed that such percentage remains quite high until $P_{NLOS} \leq 0.4$ while it drops for higher percentages of NLOS links due to insufficient connectivity. At the same time Figure 4 shows that the percentual positioning error grows steadily with P_{NLOS}, and it cannot be evaluated for $P_{NLOS} > 0.6$. For $P_{NLOS} = 0.4$ the network connectivity is still high enough to allow almost all nodes to join a common coordinate system, but the ranging error introduced by NLOS links is large enough to significantly affect the overall positioning accuracy. As a consequence, almost all nodes rely on position information which is not accurate, leading to wrong path selections and inefficient transmit power values. On the other hand, for larger values of P_{NLOS} a significant percentage of the nodes is no longer able to connect to a coordinate system and stops using position information, relying more and more on flooding. This behavior helps increasing the network throughput, as shown in Figure 1, at the price of an increased energy consumption (Figure 2), and thus eventually a shorter network lifetime.

It should be noted that the results were obtained in a static network, where the positioning refresh interval could be set arbitrarily large without significantly affecting the accuracy of the position estimation. Such interval was set to 30 seconds in the case of the results presented above. In the case of a network of mobile nodes the interval should be optimized by taking into account the degree of mobility of the nodes. A shorter interval could lead to increased energy consumption due to the local broadcasts of distance and position estimations required by the SPA protocol. Figure 5 shows the impact of the positioning refresh interval on the consumed energy per received packet in a highly connected network (P_{NLOS}=0) and highlights that this parameter plays a key role in determining the actual energy efficiency of the position-based routing solution.

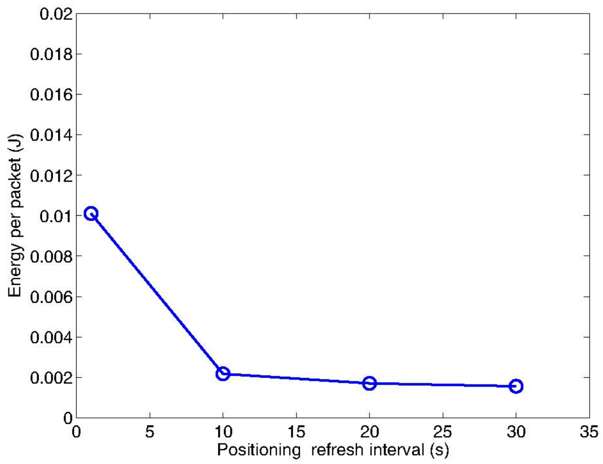

Fig. 5. Consumed energy per received packet as a function of the positioning refresh interval.

VI. Conclusions

The introduction of position information made available by the ranging capabilities of the new IEEE 802.15.4a standard is expected to provide significant performance improvements in several aspects of network organization and management. In this paper the impact of position information on routing was investigated by comparing a traditional solution based on the AODV routing protocol with a position-based solution relying on the combination of the SPA distributed positioning protocol and the GPRS routing protocol. Performance was measured in terms of end-to-end throughput and energy per received packet. Simulation results show that, despite the additional overhead required by the distributed positioning, position-based routing can increase both throughput and energy efficiency. Results also show that more stringent requirements on the positioning refresh frequency due to rapidly changing topologies can have a significant impact on the energy efficiency of the position-based solution.

Acknowledgements

This work was partially supported by the European Union within the Integrated Project n. 506897 - PULSERS.

References

[1] "IEEE 802.15.TG4a official web page," http://www.ieee802.org/15/pub/TG4a.html.

[2] Y. B. Ko and N. H. Vaidya, "Location aided routing in mobile ad hoc networks," in *ACM International Conference on Mobile Computing and Networking (Mobicom)*, 1998, pp. 66–75.

[3] D. Kim, Y. Choi, and C. K. Toh, "Location-aware long lived-route selection in wireless ad hoc networks," in *IEEE Vehicular Technology Conference*, vol. 4, 2000, pp. 1914–1919.

[4] S. Basagni, I. Chlamtac, and V. R. Syrotiuk, "Dynamic source routing for ad hoc networks using the global positioning system," in *IEEE Wireless Communications and Networking Conference (WCNC)*, September 1999, pp. 301–305.

[5] B. Karp and H. T. Kung, "Gpsr: Greedy perimeter stateless routing for wireless networks," in *ACM International Conference on Mobile Computing and Networking (Mobicom)*, 2000, pp. 243–254.

[6] S. Basagni, I. Chlamtac, V. R. Syrotiuk, and B. A. Woodward, "A distance routing effect algorithm for mobility (DREAM)," in *ACM/IEEE International Conference on Mobile Computing and Networking (Mobicom)*, 1998, pp. 25–30.

[7] L. De Nardis and M. G. Di Benedetto, "Overview of the IEEE 802.15.4/4a standards for low data rate Wireless Personal Data Networks," in *4th Workshop on Positioning, Navigation and Communication 2007*, March 2007, pp. 285–289.

[8] ——, "Joint communication, ranging, and positioning in low data-rate UWB networks," in *Joint 2nd Workshop on Positioning, Navigation and Communication 2005 & 1st Ultra-Wideband Expert Talk*, March 2005, pp. 191–200.

[9] R. Hach, "Symmetric Double Sided Two-Way Ranging," IEEE P802.15 Working Group for Wireless Personal Area Networks (WPAN), Doc. IEEE P.802.15-05-0334-00-004a, 2005.

[10] S. Capkun, M. Hamdi, and J. P. Hubaux, "GPS-free positioning in mobile Ad-Hoc networks," in *Hawaii International Conference On System Sciences*, 2001, pp. 3481–3490.

[11] C. Perkins, "Ad hoc on demand distance vector (aodv) routing," 1997. [Online]. Available: citeseer.ist.psu.edu/article/perkins00ad.html

[12] N. Concer, "AdHocSim project," 2005. [Online]. Available: http://www.cs.unibo.it/ concer/adHocSim.html

[13] G. Giancola and M.-G. Di Benedetto, "A Novel Approach for estimating Multi User Interference in Impulse Radio UWB Networks: the Pulse Collision model," *Signal Processing, Special Issue on Signal Processing in UWB Communications*, vol. 86, no. 9, pp. 2185–2197, September 2006.

[14] L. De Nardis and M. G. Di Benedetto, "Positioning accuracy in Ultra Wide Band Low Data Rate networks of uncoordinated terminals," in *IEEE International Conference on UWB 2006*, September 2006, pp. 611–616.

[15] B. Denis and N. Daniele, "NLOS ranging error mitigation in a distributed positioning algorithm for indoor UWB ad-hoc networks," in *2004 International Workshop on Wireless Ad-Hoc Networks*, May-June 2002, pp. 356–360.