On the Impact of Routers' Controlled Mobility in Self-Deployable Networks

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***Abstract*— A substitution network is a temporary network that self-deploys to dynamically replace a portion of a damaged infrastructure by means of a fleet of mobile routers. In this paper, we evaluate the performance of a previous self-deployment scheme, adaptive positioning algorithm (APOLO), for substitution networks and we show the benefit of the controlled mobility in such a network. To that end, we evaluate APOLO in terms of throughput under several scenarios and different metrics. These results constitute a comprehensive evaluation of APOLO and enable to envision new ways of optimization and future paths of research. We prove that APOLO is an efficient deployment and redeployment algorithm for mobile relay networks.**

Keywords–Substitution Networks; Robot deployment; Controlled mobility.

I. INTRODUCTION

A Rapidly Deployable Network (RDN) is a solution to provide communication services in disaster scenarios. Specifically, we focus on a wireless solution named the substitution networks [1]. A substitution network is a temporary network to replace a portion of a damaged infrastructure (called hereafter base network) by means of mobile routers (called substitution routers) capable of moving on demand and connecting to the base network through bridge routers (Figure 1a).

Bridge routers are connected in between the base and the substitution networks, and used to forward the traffic from the base network to the substitution network and vice versa.

Mobile substitution routers are wireless routers of the substitution network, possibly connected to bridge routers, and whose union provides alternative path(s) to the base network.

Figure 1 depicts the complete overview of using a Substitution Network, where the bridge routers are deployed together with the base network (Figure 1a). In this example, the base network operates without the help of the mobile routers. When a failure occurs (Figure 1b), the mobile routers are deployed. In this architecture, the failure detection and the deployment are done autonomously by the base network itself. Mobile routers try to find an optimal position to restore the connectivity service and to ensure Quality of Service (QoS) (Figure 1c). In some cases, the continuous redeployment of the routers may be necessary to adapt to an evolving network and to QoS conditions (see Figure 1d).

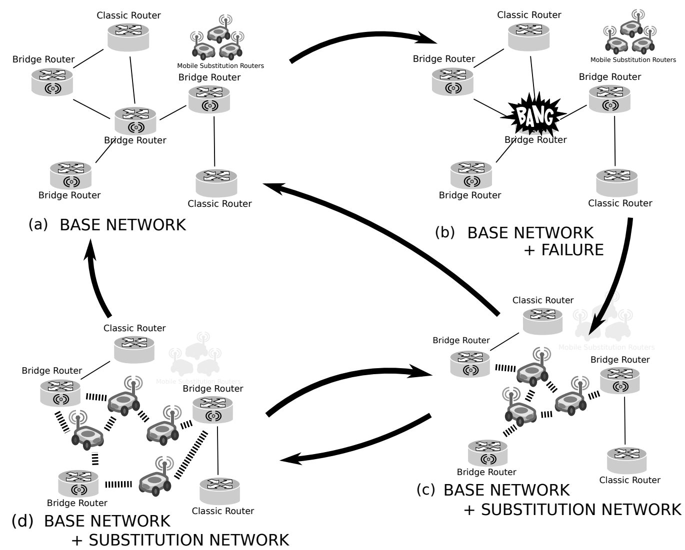

Fig. 1. Typical use case for a base network and a substitution network.

Particularly, our goal is to have an autonomous router deployment, as well as a possible redeployment of the mobile routing devices. Therefore, it is necessary to design algorithms and protocols to deploy and re-deploy such devices [2]. Since the routing devices are autonomously provided with a limited battery, it is also necessary to consider energy constraints during the deployment. Moreover, the deployment computation process does not consider a central entity in the network, hence, this process should be executed in a distributed manner [3]. An efficient router/relay (mobile or static) deployment algorithm must take the link quality into account in order to decide when and where to deploy a relay [4]. For that purpose, the deployment algorithms must be able to measure the wireless link quality. We have presented in a previous work the Adaptive POsitioning aLgOrithm (APOLO) [5].

This paper presents the extended results of APOLO [5] developed for substitution networks obtained under stress and some results under different assumptions, especially regarding channel states. The remaining of the paper is structured as follows. After browsing the literature in Section II, Section III describes the background and the basic concepts used in this paper. Then, Section IV depicts the proposed algorithm APOLO. Section V and Section VI present the simulation settings and results. Finally, we discuss these results and conclude in Section VII.

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II. State of the art

A self-deployable network is composed of several mobile routers. Such mobile routers perform the same tasks as their static similars distributing the data traffic; however, the mobile routers must self-position in a given area. We can find in the literature few proposals to self-deploy a network. In [2], the authors present the Spreadable Connected Autonomic Network (SCAN) algorithm where the mobile routers move to expand the covered area. In order to maintain connectivity, mobile routers are allowed to move as long as there is no risk of disconnection, if a possible disconnection is detected, the mobile routers must stop moving. A different strategy is presented in [3], where the mobile routers follow a leader router on a straight-line formation, once the leader reaches the desired point it stops and the rest of the routers start stopping as well. Finally, Kim et al. [6] propose a string-type formation to deploy the mobile routers, all with identical characteristics. Each mobile router seeks and adjusts its position according to the packet delivery ratio or bandwidth. These approaches differ from ours in the sense that they do not consider link quality. Such proposals have succeeded to autonomously deploy a network; nevertheless, an efficient self-deploy algorithm should adapt dynamically to the environment changes, for example, different zone sizes, changes on mobile users' distribution, or changes on the channel conditions.

III. Preliminaries

We consider a wireless network composed of mobile routers that are located and may move on the two-dimensional Euclidean space. We use "node" as a generic term for any device in the simulation neighborhood, for instance, the mobile or classic routers. For the sake of simplicity, we assume that the transmission range R of a node u is the area in which another node v can receive/send messages from/to u, i.e., $d(u,v) < R(u)$, where $d(u,v)$ represents the Euclidean distance between u and v, and therefore, it exists a link X between u and v. We assume that two nodes are "neighbors" when they are within the communication range of each other.

In the following, we use X_{prev} and X_{next} to refer to the links of the previous and next hops, respectively, of a mobile router. Likewise, we assume that some of the devices are fixed, that traffic needs to be transferred between two fixed devices, and that the wireless routers dynamically move in the scenario and act as relays, regardless of the routing protocol. And, as many link layer protocols, we assume that each node is equipped with a timer and an 802.11 wireless card, as well as with an identifier that is unique in the network (MAC address).

We define the quality of a communication link, or just "link quality", as the probability that a message transmitted on the link is successfully received, that is, the reliability of the link [4]. The link quality can be assessed as a function of the received signal strength (RSS) or the signal-to-noise ratio (SNR) [7], for example. In general, higher SNR leads to lower probability of error in the packet. Hence, a link with high SNR is considered a high-quality link [8]. We use the RSS, SNR, RTT, and TxRate as values to measure the link quality because their values retrieve insight of the performance of a wireless network [9]. Therefore, we call RSS, SNR, RTT, and TxRate "link metrics" or "link parameters" in general.

We use the term "broadcast" to refer to the message propagation in a router's neighborhood in order to obtain the link measurements. Also, we refer to the control packets of routing protocols as "hello" messages or beacons and to the packets used in active measurements as probe packets. Finally, we define the term *controlled mobility* as the ability of some nodes to move by themselves to a specific destination or with a specific goal, i.e., the opposite of randomly [10].

In this paper, we use the Dynamic Source Routing (DSR) [11] protocol for our set of simulations. The DSR protocol is a self-maintaining routing protocol designed for multi-hop wireless networks composed of mobile nodes. DSR uses on demand routing allowing each source to determine the route used to transmit its packets to the corresponding destinations.

IV. Adaptive Positioning Algorithm

A new quality-of-service-based architecture for substitution networks, presented in [1], envisions a wireless network composed of mobile routers/relays that provide alternative paths to the base network. Such substitution routers are able to move on demand, so, they can self-deploy and adapt to the network topology accordingly to the environment conditions.

Previously, we have presented APOLO for self-deploying mobile routers in a substitution network [5]. During the substitution network lifetime, APOLO is executed in each mobile router to determine whether it has to move by using the feedback of the link quality coming from one-hop neighbors. APOLO consists of three major stages. Firstly, APOLO measures the link quality by means of one link parameter, e.g., RSSI, SNR, or delay. Secondly, APOLO computes the gathered data and makes the movement decision, i.e., if the router needs to move or not to improve the link quality. And finally, APOLO determines direction of the movement and the router moves accordingly.

The results presented in [5][12] are restricted to only one propagation model (two-ray ground) and three simulation scenarios. In this paper, we extend these results with extra propagation models and scenarios. First, we present the results obtained when the router's initial position is random. Second, we study the behavior of our algorithm when there exist multiple mobile routers between the source and the destination. Then, we evaluate the redeployment capacity of the mobile router when a new node arrives. Finally, we compare the deployment performance of each link parameter under three different propagation models (two-ray ground, shadowing, and ricean).

V. Simulation environment

We present an extension to the experimental performance evaluation of APOLO. Our main goal is to present the effectiveness of the algorithm to deploy wireless mobile routers in a given area. To that end, we evaluate our proposal by using the

TABLE I. SIMULATION PARAMETERS.

Physical	Propagation	Two Ray Ground
	Error Model	Real [15]
	Antennas Gain	$G_t = G_r = 1$
	Antennas Height	$h_t = h_r = 1$ m
	Min Received Power	$P_{r-thresh}$=6.3 nW
	Mobile Router Energy	50 J
	Communication Range	240 m
MAC	802.11b	Standard Compliant
	Basic Rate	2Mbps
	Auto Rate Fallback	1, 2, 5.5, 11 Mbps
LLC	Queue size	50 pkts
	Policy	Drop Tail
Routing	Static	Dijkstra [16]
	Routing Traffic	None
Transport and Application	Flow	CBR / UDP
	Packet Size	512 B/1 MB
Statistics	Number of samples	$k = 10$
	Broadcast period	$t = U(0.1)$
Mobility	Movement step	$d = 2m$

NS-2 network simulator [13]. In our previous work [12], we have chosen three scenarios proposed in [14] as a result of the study on relay wireless networks. We propose three additional scenarios plus a propagation model comparison.

Since our goal is to assess the impact of controlled mobility in wireless routers, we use the DSR protocol for our simulations, although, APOLO is not tied to any routing particular protocol. Table I summarizes the basic parameters used in our simulations in NS-2. In this paper, we use the instantaneous throughput (TH_{ins}) defined as he number of bits transferred to the final destination in any given instant to assess the performance of our deployment algorithm.

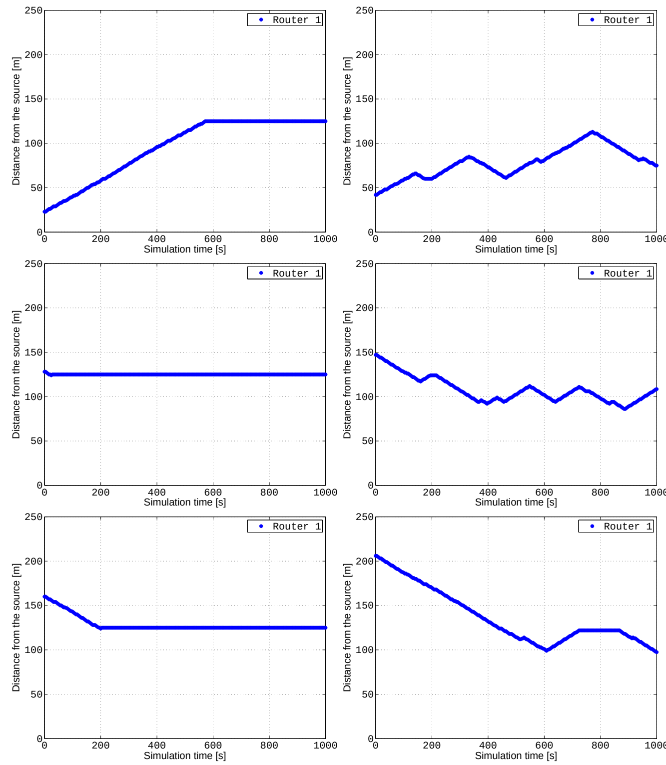
VI. Results

A. Random initial position

In our previous work, the basic scenario is composed of one mobile router, one source node (S), and a destination node (D). The source and the destination are placed 250 m away from each other, i.e., the source is placed at coordinates (0,0) and the destination at coordinates (250,0). Finally, at the beginning of the simulation, the router node is placed 10 m away from the source node, that is, at coordinates (10,0), as depicted in Figure 2. Then, the router starts moving based on APOLO. Nevertheless, the mobile router may reach the position that equalizes the parameter values regardless of its initial position.

Hence, we take again this basic scenario. We run a set of simulations choosing the initial position of the router randomly. We use the 802.11b standard along with the two-ray ground model. Figure 3 plots the x coordinates along time to illustrate the movement evolution. Figure 3(a) presents the results while using the RSS as link metric and Figure 3(b) presents the results while using the SNR as link metric. In Figure 3(a) the router's initial coordinates are (23,0), (128,0), and (160,0), respectively. The theoretical position that equalizes should be (125,0) where the router is placed at exactly

Fig. 2. Basic scenario composed of one mobile router, one source node, and one destination node.



(a) Results by using the RSS as link metric (b) Results by using the SNR as link metric

Fig. 3. Simulation results for random initial position of the mobile router.

the middle point between the source and the destination, and therefore, the link values of X_{prev} and X_{next} should be the same. We observe in Figure 3(a) that the router reaches such a position regardless of its initial position, an expected result since the two-ray ground model calculates the RSS as a function of the distance. Similarly, in Figure 3(b), the router's initial coordinates are (42,0), (147,0), and (206,0), respectively. Despite the router does not reach a steady position, this behavior corresponds to the previous simulations where the router's initial position is (10,0), in other words, the initial position of the router does not affect the movement behavior by using SNR as link metric. We believe that such a behavior is due to the propagation model we have used. In order to corroborate this, we perform a set of simulations with different propagation models. The results are presented in Section VI-E.

B. Multiple routers scenario

In [12], we studied the performance of APOLO by considering a scenario with two routers. In such a scenario, there is a source and a destination communicating though two mobile routers, so, we extend this scenario by considering three and four intermediate routers between the source and the destination, as shown in Figure 4.

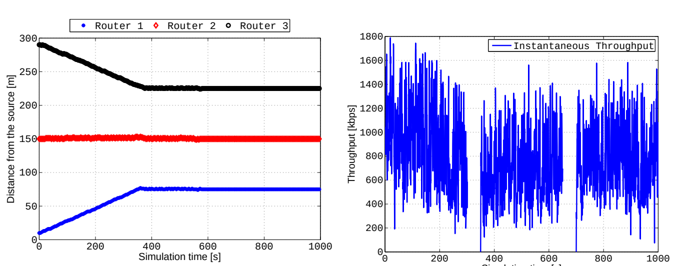
1) Three routers: Regarding the three router scenario, the source, once again, is placed at coordinates (0,0) and the destination at coordinates (300,0), that is, 300 m away from each other. At the beginning of the simulation, Router 1 is placed at coordinates (10,0), Router 2 is placed at (150,0), and Router 3 is placed at (290,0). Then, the routers execute APOLO to adjust their position using the RSS as link metric, the results are presented in Figure 5. The deployment evolution is plotted as x coordinates as function of simulation time where we observe that the behavior of the routers follows the results obtained with the two router scenario (Figure 5(a)). The routers travel the corresponding distance to equalize the values of the link metric. In this case, Router 1 and Router 3 travel a similar distance. The routers reach their final position after 550 s, which are, Router 1 at 75 m, Router 2 at 150 m, and Router 3 at 225 m from the source, that means a distance of 75 m between each node. Figure 5(b) plots the instantaneous throughput obtained during the routers deployment.

2) *Four routers:* Regarding the four router scenario, the source is placed at coordinates (0,0) and the destination at coordinates (400,0), that means, 400 m away from each other. At the beginning of the simulation, Router 1 is placed at coordinates (10,0), Router 2 is placed at (140,0), Router 3 is placed at (260,0), and Router 4 is placed at (390,0). Subsequently, each router adjusts its own position by executing APOLO using RSS as link metric. Figure 6(a) shows the routers deployment through the simulation time. Once again, the final position of the routers equalize the link metric and it is equidistant between nodes. These results, three and four routers, show that the behavior experienced with only one mobile router is duplicated, and therefore, APOLO is a scalable solution and it is able to deal with multiple router scenarios.

C. *Two sources and one destination scenario*

By the same token, we evaluate APOLO in a multiple destination scenario [5]. In addition, we present a topology with multiple sources by using the topology depicted in Figure 7, where we illustrate two sources (`n0`, `n1`) and one destination (`n3`) out of range. Thus, a mobile router (`n2`) is used to connect the sources and the destination. At the beginning of the simulation, the router (`n2`) is placed 10 m away from the source nodes (`n0`, `n1`) on the straight line

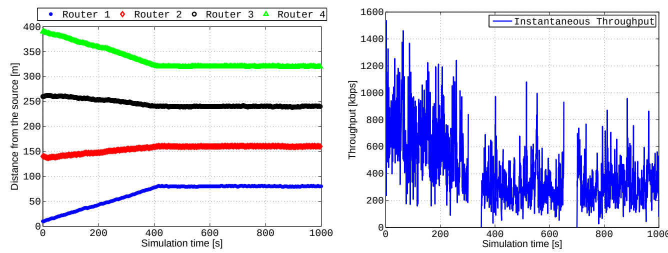
Fig. 4. Multiple routers scenario composed of three mobile routers, one source node, and one destination node.



(a) Movement evolution in time of the mobile routers

(b) Throughput as a function of time

Fig. 5. One source, one destinations, and three mobile routers.



(a) Movement evolution of the routers

(b) Throughput as function of the time

Fig. 6. Multiple routers scenario composed of four mobile routers, one source node, and one destination node.

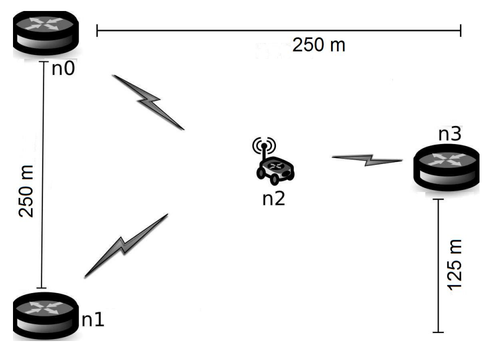


Fig. 7. Two sources, one destination, and one mobile router scenario.

that connects the sources from the middle position between the receiver node (`n3`), and finally, we use User Datagram Protocol packets with a size of 1 MB since UDP is used in most multimedia applications.

In this scenario, two identical CBR/UDP flows are transmitted from the source nodes (`n0`, `n1`) to destination node (`n0`) starting and finishing at the same time. A priori, we assume that the best position is located at the coordinates (83,125), which is the triangle centroid. Then, the router uses APOLO to decide where to move and RSS as link metric. The movement trace is depicted in Figure 8(a). During the first 500 s, the router moves in a straight line from (10,125) to (94,125), i.e., it travels 84 m. After this time, the router moves from left to right (in the y axis domain) in a range of ± 3 m, i.e., from (94,128) to (94,122). This behavior is very different from that one experimented in a similar scenario with two source nodes and one destination. In the latter scenario, the router moves mostly in the x axis range and stops very close to the triangle centroid. Hence, the oscillation experienced in two source scenario is caused by the two flows arriving to the router, that means, the router moves to improve the link quality accordingly to the data flow arriving at the time. In order to avoid wasting energy with short distance movements, it is possible to implement a movement threshold, for example, the router moves if the RSS value drops under certain threshold.

D. *Redeployment*

One issue that remains open is the routers redeployment. The redeployment is specially important in dynamic scenarios. In the following, we present a simulation campaign where the redeployment is needed. As in the previous set of simulations,

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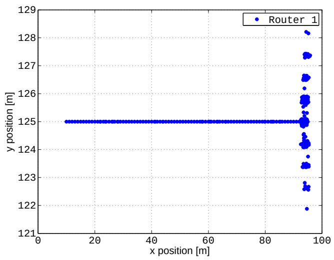
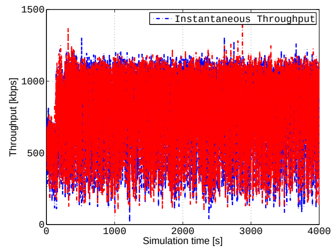


(a) Movement evolution of the router



(b) Throughput as function of the time

Fig. 8. Scenario two sources and one destination. Movement of the mobile router through the time and the corresponding throughput.

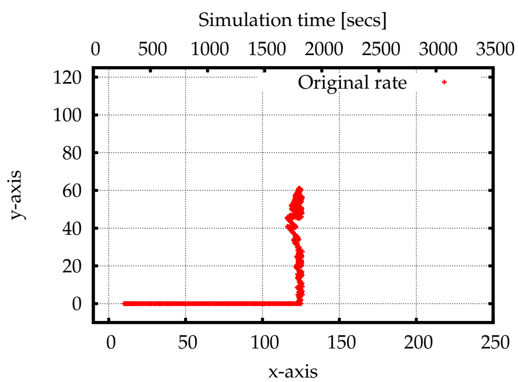


Fig. 9. Redeployment of a mobile router.

the mobile router executes APOLO to redeploy and uses RSS as link metric. At the beginning of the simulation, the scenario is the one depicted in Figure 2, one source node, one destination node, and one mobile router. The source (n0), the router (n1), and the destination (n2) are located at coordinates (0,0), (10,0), and (250,0), respectively. Then, after 650 s a new source node (n3) arrives to transmit data to (n2), and therefore, the router must adapt its position. Node (n3) appears at coordinates (0,125).

Figure 9 plots the movement of the router in the Cartesian space. The first seconds of the simulation, the router follows the same behavior than in the previous simulation, in other words, the router reaches the position at (125,0). Then, when the second source appears, the router starts to move to equalize the quality of the new link between (n3) and (n1). Finally, the router reaches its final position at coordinates (124,60). These results are very interesting for two reasons. Firstly, they prove that APOLO is useful to redeploy automatically mobile routers, and hence, it is well suited in dynamic scenarios. And secondly, the results prove the importance of the hello messages to advertise the eventual changes in the network topology, if the transmission rate of such hello messages is too low, the information gathered may not reflect the changes in the topology over the time. Nevertheless, it is also important to consider the cost of such hello messages in terms of energy and overhead. To overcome this problem, it is interesting to study the optimal transmission frequency of the hello packets [17], as well as the overhead reduction techniques.

E. Propagation model comparison

The propagation models are empirical mathematical formulations to characterize the radio wave propagation based on physical phenomena such as distance, used frequency, or fading effects. In wireless network simulations, the propagation models are used to simulate the wireless channel by computing the wireless signal strength at the receivers for any packet transmitted by a single sender. Particularly, NS-2 simulator provides three propagation models: Free space model, Two Ray Ground model, and Shadowing model. Moreover, it is possible to add a fourth model called Ricean.

Each propagation model computes the attenuation of the signal strength between the sender and the receiver by using a Carrier Sensing Threshold (CSThresh_). If the signal strength is lower than CSThresh_, the packet is discarded at the physical layer. Otherwise, the signal strength is compared to a second threshold at the receiver (RxThresh_) to determine whether the packet is received with errors or not. If so, the MAC layer discards the packet.

Free space model represents the transmission range as a perfect circle around the sender. Basically, if the receiver is within the circle, it will receive all the packets; otherwise, it loses them. Two-ray ground reflection model considers both the direct path and a ground reflection path, a difference from the free space model, which only considers a single line-of-sight path. The two-ray ground model gives more accurate prediction at a long distance than the free space model. Nevertheless, the free space model is used when the distance is small because the two-ray model does not give a good result for a short distance due to the oscillation caused by the constructive and destructive combination of the two rays. It is important to notice that both models represent the communication range as a prefect circle, i.e., the received power is a deterministic function of distance. On the other hand, the shadowing model takes the fading phenomenon into account. Finally, the Ricean model characterizes the effect of small-scale fading (Rayleigh and Ricean). Such a fading is caused by movement of the sender, receiver, or of other objects in the environment. This movement may be characterized by the Doppler spreading.

As in the previous sections, we evaluate the performance of APOLO under three different propagation models, Ricean, Two ray ground, and Shadowing. To that end, we use the one source-one destination scenario (Figure 2), the router is placed at coordinates (10,0). Then, we vary the propagation model for each of the link parameters, i.e., RSSI, SNR, RTT, and transmission rate. The results obtained are presented in Figure 10. Figure 10(a) presents the comparison of the router deployment by using all the APOLO variants for each model propagation. The Two-ray ground plot was presented in [5], where router using the RSS variant reaches exactly the middle point between the source and the destination, i.e., at coordinates (125,0) while the router using the SNR and TxRate does not reach a steady point. However, this behavior changes completely when we evaluate APOLO by

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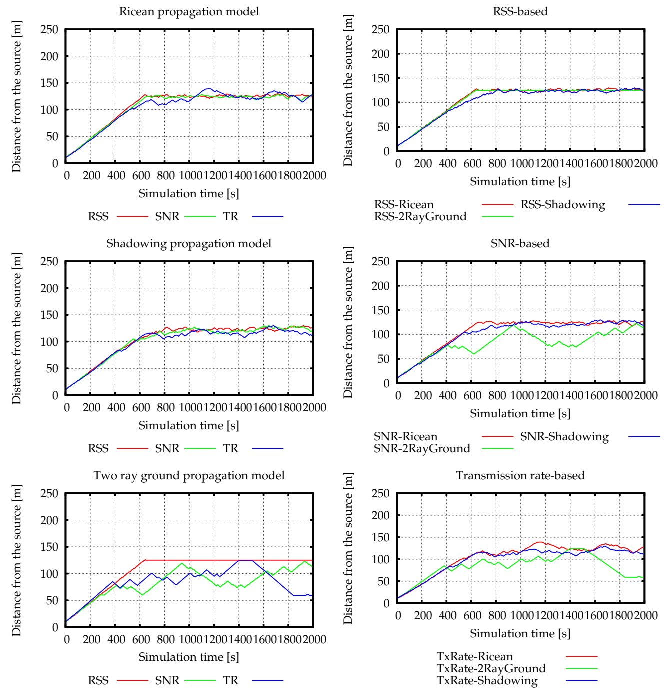

(a) Comparison of the link parameters for each propagation model. (b) Comparison of the each parameter for all the propagation models.

Fig. 10. Evaluation of APOLO under different propagation models. The movement of the mobile router as function of time.

using the Ricean and Shadowing models. Under both models, Ricean, and Shadowing the performance of the three variants is similar. None of the variants reaches a steady point still the router moves ±10 m away from the middle point (125,0). Nonetheless, this behavior confirms our observation about the SNR performance obtained in Section VI-A, that is, since each propagation model characterizes in different way the events at the physical layer, the values of the link metrics correspond to such characterization and behave accordingly. We also include a comparison of each link parameter under all the propagation models to clarify the difference in the behavior (Figure 10(b)). Because the link quality values depend largely on the propagation model, it is important to choose the one that characterizes better our case of study. In general, the NS-2 community uses the two ray ground model but the shadowing model corresponds better to the real scenarios.

VII. Conclusion and Future Work

We have presented the impact of controlled mobility to self-deploy routers in substitution networks. The results provide a wide view of the performance of the Adaptive POsitioning aLgOrithm (APOLO). They prove that APOLO is able to successfully deploy the mobile routers in several scenarios and by using different propagation models. Moreover, APOLO performs well also when router redeployment is needed. The comparison of different deployment algorithms is not a trivial task since each proposal considers different metrics such as coverage, number of nodes, devices connected, delay, or throughput. We believe that a careful election of the performance metrics is the next step to continue on this direction. We have already set the metrics and we are currently comparing several deployment algorithms by means of simulations. Eventually, we will evaluate such algorithms by means of a real implementation with WiFiBots®.

We observed that by using the Ricean and Shadowing models the deployment performance of the SNR and TxRate variants outperform the two-ray ground one even if in the former case the router does no reach a steady point. This disadvantage may be overcome by adding a threshold to avoid useless movements. Thus, we are interested in studying how the threshold choice may (or may not) impact the performance.

VIII. Acknowledgment

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