Fast and reliable robot deployment for substitution networks

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ABSTRACT

In this paper, we propose an algorithm to efficiently (re)-deploy the wireless mobile routers of a substitution network by considering the energy consumption, a fast deployment scheme and a mix of the network metric. We consider a scenario where we have two routers in a fixed network and where a robust connection must be restored between those two routers with a wireless mobile router. The main objective of the wireless mobile router is to increase the communication performance such as the throughput by acting as relay node between the two routers of the fixed network. We present a fast, adaptive and localized approach which takes into account different network metrics such as Received Signal Strength (RSS), Round-Trip Time (RTT) and the Transmission Rate, between the wireless mobile router and the two routers of the fixed network. Our method ameliorates the performance of our previous approach from the literature by shortening the deployment time, increasing the throughput, and consuming less energy in some specific cases.

Categories and Subject Descriptors

C.2.4 [**Distributed Systems**]: [Distributed applications]

Keywords

substitution network; robot deployment; energy efficiency

1. INTRODUCTION

We define a *substitution network* as a rapidly deployable backup wireless solution to quickly react to network issues due to failures or flash crowd effects on an existing fixed network. Unlike other ad hoc and mesh solutions, a substitution network does not attempt to provide new services to customers but rather to restore and maintain at least some of the services available before the failure of the existing fixed network. Furthermore, a substitution network is not deployed directly for customers but it is used to help the existing fixed network to provide services to customers. Therefore, a substitution network is not, by definition, a stand-alone network. In this paper, we consider a network composed of a set of wireless mobile routers used to restore a robust connection/service between routers of the fixed network. The wireless mobile routers are the cores of the substitution network. They work cooperatively to preserve the fixed network connectivity, to provide Quality of Service (QoS) or Quality of Experience (QoE) under a dynamic and evolving wireless environment to satisfy application-specific requirements.

The implementation of substitution networks poses several challenges since in the case of fixed network failures, the optimal wireless mobile routers locations or the optimal network topology is unknown. Therefore optimally placing the wireless mobile routers is a fairly complex node placement/deployment problem and constitutes the focus of this paper. The goal of the algorithm described in this paper is to deploy a wireless mobile router between router and the fixed network, without prior knowledge of the optimal location, and to improve the network performance by moving the wireless mobile router depending on network conditions. Moreover, energy constraints should also be considered since wireless mobile routers are autonomous and must survive until the fixed network is repaired.

Surprisingly, such a fundamental problem has received very few attention in the literature. In [12, 13], the authors propose an adaptive deployment algorithm to deploy the wireless mobile routers based only on local information, and they evaluate their algorithm through extensive simulations. In these papers, Miranda *et al.*, do not consider the energy consumption of the wireless mobile routers and provide only fixed stepwise deployment algorithm. Moreover, the authors of [12, 13] only consider individually different network metrics such as Received Signal Strength, Transmission Rate and Round-Trip Time.

In this paper, we go a step further than Miranda *et al.* in [12, 13] by considering the energy consumption, a fast deployment scheme and mix of the network metric to (re)-deploy the wireless mobile routers. In order to carry out

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the decision making process, our algorithm relies only on local information. For example, let us assume without loss of generality that we have two routers in the fixed network and that connectivity must be restored between these two routers (let us name them S and D) with a wireless mobile router. Let us assume that the Received Signal Strength is measured between the wireless mobile router and the S and between the D and the wireless mobile router. Based on these values, the wireless mobile router will move closer to D if the Received Signal Strength between the wireless mobile router and S is greater than the Received Signal Strength between D and the wireless mobile router.

The rest of this paper is organized as follows: Section 2 presents the state of the art of rapidly deployable networks. Section 3 describes our deployment algorithm while Section 4 provides the performance evaluation results. Section 5 is dedicated to the conclusion and the future work.

2. RELATED WORK

2.1 Wireless sensor network placement

In last years, many works have proposed schemes and solutions to improve network performance by placing wireless relays in specific positions. In [5, 19] static random deployment strategies of wireless nodes are presented. Specifically, in [2, 10, 17] the placement is computed off-line depending on the specific environment and objective to achieve. The reader can find a complete survey in [21]. The most common objectives are the energy consumption and the coverage. For example, in both [14] and [16], authors propose algorithms to place nodes in order to minimize the average energy consumption per node and maximize the network lifetime.

A further development of deployment scheme includes strategies of movement for the nodes that must reach a new location. Authors of [22] consider a flip-based mobility model, where a centralized mechanism is proposed to reposition sensors after the initial deployment, according to the desired density. In [6], authors present a distributed algorithm that first makes sensors determine the best placement and then drives them to the calculated positions. Both these works aim at maximizing sensor network lifetime.

In [23] and [4], authors focus on the usage of nodes controlled mobility in order to optimize QoS parameters, such as the packet delivery ratio and the end-to-end delay. Specifically: In [23] the authors propose a scheme which manages with multiple ferries and is able to meet the traffic demands while minimizing the average data delivery delay; algorithm in [4] deforms the topology of a multi-hop wireless network by moving the nodes to create new links. This leads to a reduction in the mean end-to-end delay of the network, even more effective than the alternative approach of increasing the capacities of the most congested network links. The algorithm is centralized and it takes as inputs: the network topology, the coordinates of the wireless nodes and the network load. In [15] the authors propose a controlled mobility based algorithm to move wireless multimedia sensor nodes towards the optimal positions in terms of energy consumption. Authors study the impact of mobility on the quality perceived by users of a multimedia flow. Finally, in [9] the authors deal with with multi-flows which derive from several sources and end to one destination. The authors present a localized technique to improve network lifetime by moving relay nodes.

To the best of our knowledge, no distributed, localized, scalable and adaptive scheme of placement determination and movement, has been proposed except of our previous work in [12, 13].

2.2 Wireless mesh network deployment

In [8], the concept of rapidly deployable radio network is introduced. The authors describe an infrastructure deployed on-demand for military communications. Following this work, many deployment schemes (military or civil) have been proposed in the literature.

In [3], the authors presents a method to rapidly deploy a wireless ad hoc backbone without any previous planning. The deployment takes into account physical or link quality measurements such as signal-noise ratio and packet loss rate. In their method, no redeployment is proposed.

In [20], the authors propose an algorithm based on a quick evaluation of the physical layer performed by the mobile radio. The mobile radio relay establishes one-hop communication by constantly broadcasting probe packets to previous relays, when some relays in the range respond with a probe acknowledgment packet, the mobile radio measures the Received Signal Strength through acknowledgment reception, if the Received Signal Strength value falls below a given threshold level, then a new relay must be dropped.

A spreadable connected autonomic network (SCAN) is presented in [18]. SCAN is a mobile network that automatically maintains its own connectivity by moving constantly its nodes. The authors present the SCAN algorithm capable to deal with environments where the pre-deployment mapping is expensive or infeasible without any previous information of the environment. This protocol proposes an online distributed process where each node uses two-hop radius knowledge of the network topology and each of them determines when to stop its movement if the decision criterion indicates risk of dividing or disconnecting the network. This work does not take into account the energy consumption nor the deployment performance.

3. FAST ADAPTIVE POSITIONING ALGORITHM

In this section we present F-APA (Fast-Adaptive Positioning Algorithm) a localized algorithm which is capable of adapting router's position using only neighboring information. F-APA is built above our previous work, APA [13], and its objective is to equalize the link quality between a router and two other wireless interfaces in the minimum possible amount of time. Based on the link quality measurements, the mobile robot, acting as a mobile device, tries to equalize the metrics for both the source (S) and the destination (D) by moving on a straight line, towards the one or the other station. Note that finding a position where the two measurements are equals, the throughput may not be maximized, since the correlation between link parameters and position is based on several environmental changes. However, the throughput can be significantly improved.

The proposed algorithm works in rounds and three phases take place in each round (see Algorithm 1). During the first phase the router sends requests to the two stations (S, D) including a sequence number and its MAC address. Each station replies to this request with a reply message that contains the MAC address and information regarding the link parameter. The router maintains a table of the sending times of each packet and it does not consider replies that have been received t_{exp} time units after their sending. At the end, it calculates the average value of the link quality parameter for the packets it has received. It is important to notice that request and reply packets are sent with higher priority and they are placed at the head of line in the link layer queue.

In the second phase, the router computes the new position by taking into account the average values of the link parameter it computed in the previous phase. In each round, F-APA adjusts the movement step of the router using the difference between the two average link parameter values (ΔLPV). The router moves more when the gap between the two values is high, while the traveling distance is small when this gap is low. In more detail, F-APA computes α that is used to compute the movement step afterwards.

$$\alpha = \frac{LPV_{avg}^{S} - LPV_{avg}^{D}}{|\max(diff)|} = \frac{\Delta LPV}{|\max(diff)|}, \qquad (1)$$

where $\max(diff)$ is the maximum difference that has been recorded so far between LPV_{avg}^{S} and LPV_{avg}^{D}.

Using α the router computes the movement step and decides if it will move forward or backward. The movement step is given by:

$$step = \alpha \frac{\overline{RT_n}}{2}, \qquad (2)$$

where $T_n = \{S, D\}$ and $\overline{RT_n}$ is the distance between robot (R) and the target node (T_n). If α is positive the router will move forward (i.e., towards D). On the other hand, it will go backwards if α is negative. We also assign a lower bound μ for *step* in order to avoid useless back and forth small movements. If *step* is below this bound, the router is not moving. μ is a static value and stabilizes the robot movement by making it tolerant in small link changes.

In the last phase, the router travels the distance it has computed in the previous phase. It is worth pointing out that the router will have traveled the half of the maximum distance at the end of the first round.

The link parameter cannot be changed in a single deployment. However, multiple metrics can be used at the same time to evaluate the link quality. Our aim is to take advantage of the each parameter's strengths and try to reduce their disadvantages, resulting in a more robust algorithm. In this case, Formula (1) must be changed accordingly:

$$\alpha = \frac{\frac{\Delta LPV_1}{|\max(diff_1)|} + \frac{\Delta LPV_2}{|\max(diff_2)|} + ... + \frac{\Delta LPV_k}{|\max(diff_k)|}}{k}, \qquad (3)$$

where k corresponds to k different link quality metrics. Examples of the link parameters are the Received Signal Strength (RSS), the Round-Trip Time (RTT), and the Transmission Rate (TxRate). It is also important to notice that all these parameters can be obtained locally and are directly available on commercial wireless cards.

We consider that all the values got by the net card are positive. Please note that, unlikely RSS or TxRate, if the RTT is higher between the source and the router, than between the destination and the router, the wireless mobile device will move towards the source. For the Transmission Rate parameter we assume that the wireless mobile device uses

Algorithm 1 A round of Fast-Adaptive Positioning Algorithm

Phase I: Capture link quality

for $i = 1$ **to** n **do**
  send packet p_i;
  t_i^{tx} = `CLOCK_TIME_NOW`;
end for
set expire time t_{exp};
$LPV_{avg} = 0$;
while true do
  receive packet p_j;
  t_j^{rx} = `CLOCK_TIME_NOW`;
  if $t_j^{rx} - t_{exp} > t_i^{tx}$ **then**
    drop packet;
    $n = n - 1$;
  else
    $LPV_{avg} = LPV_{avg} + LPV_j$;
  end if
end while
$LPV_{avg} = \frac{LPV_{avg}}{n}$;

Phase II: Compute new position:

Require: S, D
compute α using Formula (1);
compute *step* using Formula (2);
if *step* > 0 **and** *step* $> \mu$ **then**
  will move *step* units towards D;
else if *step* < 0 **and** $|step| > \mu$ **then**
  will move $|step|$ units towards S;
else
  $step = 0$;
end if

Phase III: Deployment

Require: S, D, *step*
travel $|step|$ units towards S or D;

an 802.11b wireless card. The possible transmission rates for each packet is 11, 5.5, 2 and 1 Mbps. These transmission rates are automatically adapted depending on network conditions in order to increase link reliability [11].

We choose three link parameters: Received Signal Strength, Transmission Rate and Round-Trip Time to evaluate the performance of our algorithm at different layer of the OSI model. Namely, Received Signal Strength is a Physical layer metric, Transmission Rate is a Link Layer metric and Round-Trip Time is a routing layer metric. It is worth noting that the upper layer metrics include the performance in its value. That is, the Transmission Rate parameter strongly depends on the Received Signal Strength and the value of the Round-Trip Time is directly linked to that of Transmission Rate.

4. EVALUATION & DISCUSSION OF THE RESULTS

In this section we provide the simulation results of our algorithm. We first describe the simulation parameters and then we provide individual simulation results with Round-Trip Time, Transmission Rate, Received Signal Strength and a hybrid version. We also compare our algorithm to the algorithm described in [12, 13] called hereafter APA.

4.1 Simulation parameters

We present simulation results derived by multiple scenarios using NS-2. We used the Received Signal Strength (RSS), the Round-Trip Time (RTT), and the Transmission Rate (TxRate). A hybrid metric using multiple parameters was also used. For all those metrics we plotted the position of the robot throughout the process, the throughput in bits per second and the energy consumption in Joules.

Both algorithms were implemented in version 2.29 of Network Simulator with patches that reflect a wireless propagation model, a wireless physical layer, and the adaptive autorate fallback (AARF) mechanism for 802.11b [11]. A realistic channel propagation and error model was also added [7] in order to provide the effect of interference and different thermal noises to compute the signal to noise plus interference ratio (SINR) and accounting for different bit error rate (BER) to SINR curves for the various codings employed. Moreover, we used the CSMA/CA medium access of 802.11b to reduce the collisions between packet replies at the robot. Table 1 summarizes the parameters used in the simulations.

Physical	Propagation	Two ray ground
	Error model	Real
	Antennas gain	Gt = Gr = 1
	Antennas height	ht = hr = 1 m
	Min received power	P = 6.3 nW
	Communication range	240 m
MAC	802.11b Basic rate Auto rate fallback	Standard compliant 2 Mbps 1, 2, 5.5, 11 Mbps
LL	Queue size Policy	50 pkts Drop tail
Routing	Static Routing traffic	Dijkstra None
Transport & application	Flow Packet size	CBR/UDP 512B
Statistics	Number of samples Simulation time	10 3000s
	Broadcast period	0.1s
Mobility	Movement step	see Formula (2)

Table 1: Simulation parameters

Figure 1 depicts the scenario we used to evaluate the two algorithms. In this topology, the two stations are 250 meters away and the mobile router is placed 10 meters away from the source (S), while it is able to communicate with both the source and the destination (D).

Figure 1: Our scenario

4.1.1 *Energy model*

In order to abide the principles of wireless communications, it is crucial to account with an accurate simulation model. NS-2 applies a linear battery model by default, for this reason we obtain the energy consumed by real mobile devices. Hence, the energy consumption and the speed of the mobile robot was experimentally calculated by using wifibots [1], and we consider these values for our simulation model.

The energy consumption E_c of the router in Joules was calculated using the following formula:

$$E_c = \begin{cases} 25d + 2 & \text{if the router is moving,} \\ 8 & \text{if the router is not moving,} \end{cases} \quad (4)$$

where d is the traveling distance (step) in meters and 2 Joules were added for the robot acceleration. The speed of the robot was 0.9 m/s.

4.2 Simulation results

4.2.1 *Evaluation of the lower bound (μ)*

μ is one of the most important parameters of our algorithm. Indeed, its value can increase the energy consumption if μ is too small but it can also modify the behavior of the algorithm by refraining movements if μ is too large. In order to find the appropriate value of μ, we ran some simulations and we found out that the best value for μ is 3 meters. We do not show these results here since they do not provide any interesting insight but we proceed by testing all the values of μ between $[1; 20]$m with a step of 0.5m for all the link parameters studied in this paper.

4.2.2 *Static deployment*

In order to find an upper bound of the achieved throughput we manually placed the router in different static positions without moving it throughout the process. Five different positions where tested and the results are illustrated in Figure 2. The best throughput is achieved when the router is close to the midpoint (i.e., 125 meters) or closer to the destination (i.e., 200 meters), while the performance worsens when the router is placed closer to the source (i.e., 20, 40 meters). In all the following figures, we use the midpoint as a benchmark for our algorithm.

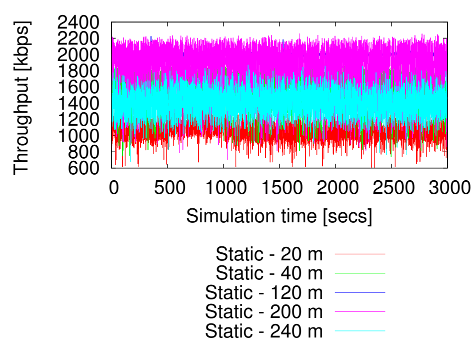

Figure 2: Throughput achieved using different static positions

4.2.3 *Results with Received Signal Strength*

Figure 3(a) illustrates the progress of the mobile relay throughout the simulation using Received Signal Strength. We can observe that both algorithms reach the middle of the distance, but with F-APA the deployment is much faster.

The fast deployment also leads to an improved throughput performance (see Figure 3(b)) which converges quickly to the rate obtained by the static deployment. F-APA's better performance is achieved by consuming similar energy to APA (see Figure 3(c)). With this metrics, it is not surprising that the router finds the middle point between the source and the destination since Formula (1) tries to equalize the value of LPV^S_{avg} and LPV^D_{avg}. Indeed, the Received Signal Strength is strictly linked to the distance since power used for transmission is constant and the propagation model is the same for all the wireless entities.

It is important to notice from Figure 3 that the effect of Formula (2) leads to a speed gain of around 500 seconds. From a data transfer perspective, the gain of F-APA is around 375000KB more data transfered than APA after 700 seconds.

4.2.4 Results with Transmission Rate

Figures 4(a), 4(b) and 4(c) illustrate the corresponding results with the Transmission Rate metric. F-APA reaches the midpoint very fast but the robot does not stay at a specific point since the transmission rate continuously changes. This is due to the fact that the Transmission Rate is impacted by different network condition such as the number of collisions. Despite the fluctuation the overall throughput is better than that of APA. However, the continuous movement of the robot increases the energy consumption.

It is also important to notice from Figure 4 that despite the constant movement of the wireless mobile router the obtained throughput is fairly stable with F-APA. This behavior shows how the algorithm rapidly adapts to changing network conditions while maintaining the throughput constant.

4.2.5 Results with Round-Trip Time

The next simulation was run using Round-Trip Time (RTT). Figure 5(a) indicates that the robot's movement is similar to that of Transmission Rate. The only difference is that APA fails to reach the midpoint, since the round-trip time remains more or less constant throughout the process. It is worth pointing out that the use of F-APA can help the wireless mobile router escape from a local deadlock such as with APA. It is also interesting to see from this figure that the layer 3 metrics exhibit such poor performance regarding throughput since it takes implicitly into account the metrics of the other layers. This is mainly due to high variability of this metrics which provides less stability than the other metrics.

The robot's movement for both algorithms consists of many back and forward steps which are larger in case of F-APA due to the larger step. Since F-APA is able to avoid deadlocks, it significantly increases the throughput (see Figure 5(b)), while it consumes little more energy than APA (see Figure 5(c)).

4.2.6 Results with Hybrid

The previous simulation results showed that only RSS is a reliable measurement because the robot movement is stabilized and the throughput is constant once the robot reaches the midpoint. But, on the other hand, since NS-2 assumes that all the nodes in the network have an identical range, the received signal power is the same at the same distance. Due to this, when the mobile robot uses RSS as parameter, it achieves exactly the middle between the source and the destination. This actually means that the RSS performance presented here may not be the same in a real experiment.

Since a single metric may not be adequate to provide a reliable behavior, we present simulation results using a hybrid parameter that includes multiple metrics. Three metrics were used in total; one metric from the physical layer (Received Signal Strength), Round-Trip Time as a network layer metric, and Transmission Rate as a link layer metric.

The results are presented in Figures 6(a), 6(b) and 6(c), and they show that the movement fluctuation is reduced, the throughput is more stable and the energy consumption is decreased. In more detail, we can observe that the robot's movement ranges between 110 and 200 meters, values which provide the best throughput as it has been discussed in Section 4.2.2. The energy consumption is lower than with the Round-Trip Time and Transmission Rate and higher than with the Received Signal Strength, but it is comparable to those obtained by APA in the previous experiments.

5. CONCLUSION

In this paper, we improved our previous work, APA, by introducing a dynamic computation for the movement step of the router. Through extensive simulation we showed that the new algorithm shortens the deployment time and increases the overall throughput, while it exhibits comparable energy consumption to its predecessor. Moreover, we provided a new cost function to evaluate the link quality between the two static stations. The new hybrid function may exploit multiple metrics and provides more adequate results compared to the single-based function. Due to the nature of the problem (i.e environmental changes, simulator restrictions, presence of interference) our simulation results must be further validated by real experiments with different types of traffic and different MAC layer protocols. Our current research focuses exactly to this direction; to create a real substitution network scenario on real mobile routers.

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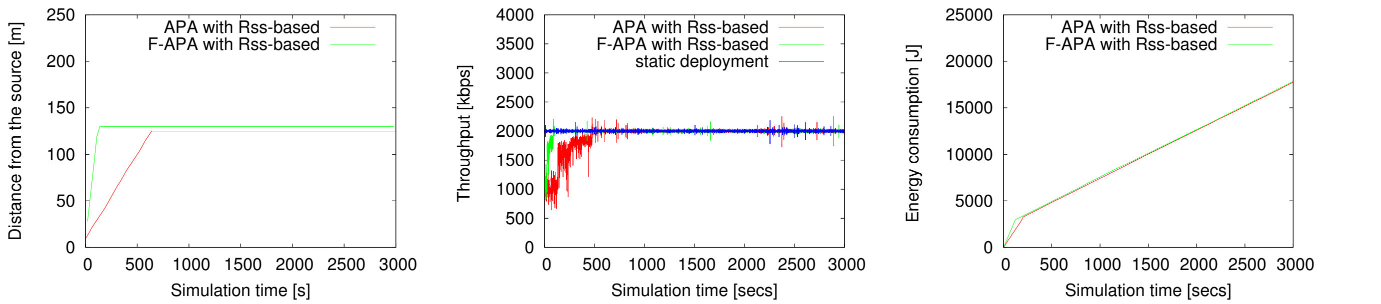
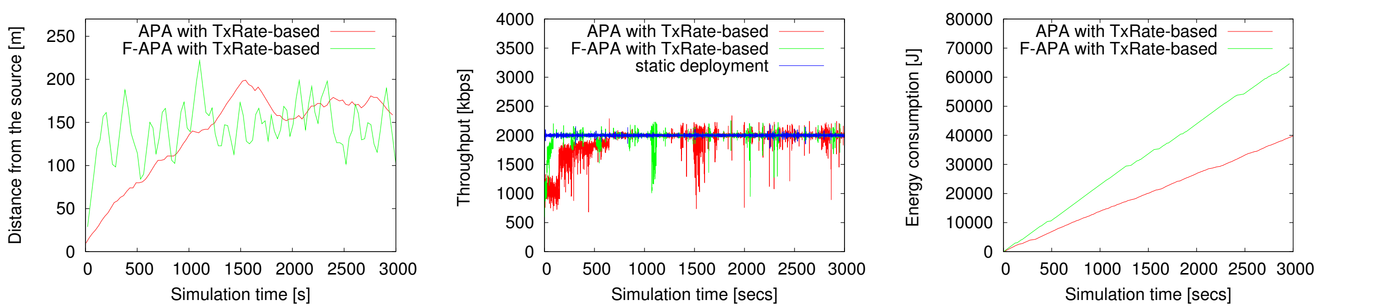


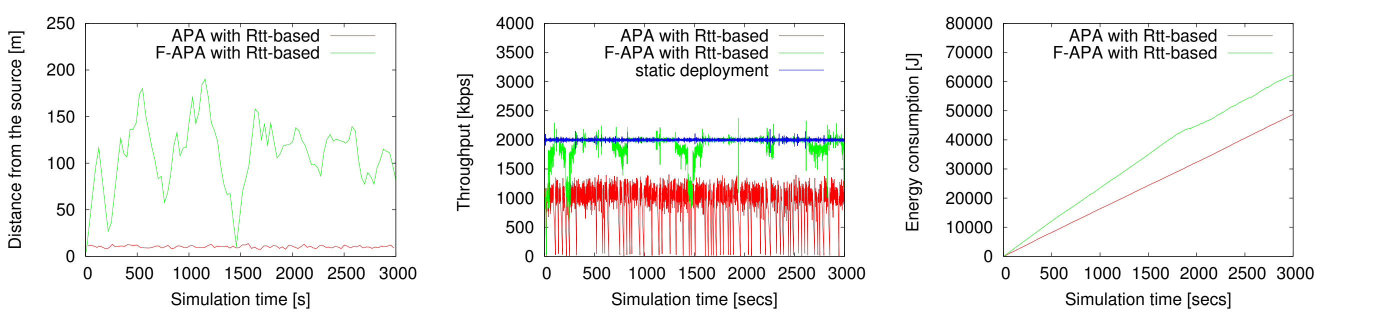
(a) Position (b) Throughput (c) Energy

Figure 3: Received Signal Strength



(a) Position (b) Throughput (c) Energy

Figure 4: Transmission Rate



(a) Position (b) Throughput (c) Energy

Figure 5: Round-Trip Time

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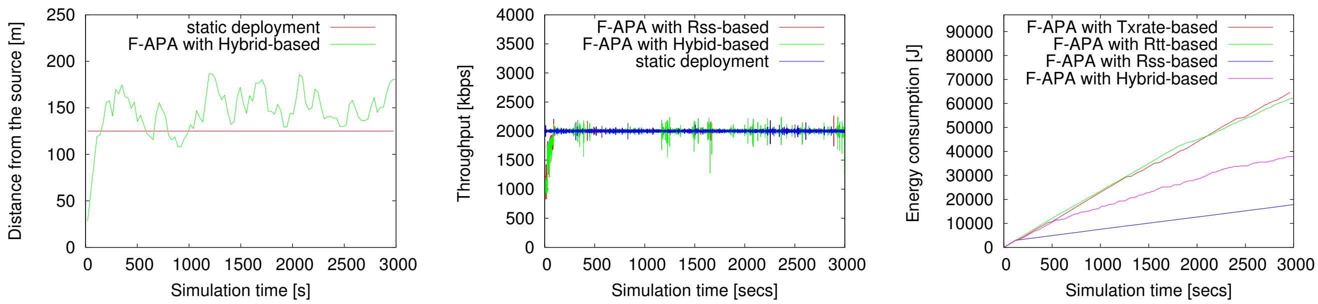

(a) Position (b) Throughput (c) Energy

Figure 6: Hybrid

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