Topology-Aware Hybrid Random Walk Protocols for Wireless Multihop Networks

Vasileios Karyotis[1], Fabio Pittalà[2], Maria Fazio[2], Symeon Papavassiliou[1], and Antonio Puliafito[2]

[1] Institute of Communications and Computer Systems (ICCS)
National Technical University of Athens (NTUA)
School of Electrical and Computer Engineering
Zografou, 15780, Athens, Greece
vassilis@netmode.ntua.gr, papavass@mail.ntua.gr
[2] University of Messina
Faculty of Engineering
Contrada Papardo, S. Sperone, 98166, Messina, Italy
fabio.pittala@estudiante.uam.es, mfazio@unime.it, apuliafito@unime.it

Abstract. The proliferation of wireless multihop networks has made various operations, such as search and retrieval of distributed data a significant concern. Various methods have been proposed for performing such tasks efficiently, especially when all network nodes need to be visited at least once. Random walks are probabilistic approaches for performing the aforementioned operations effectively and with relatively small overhead compared to other typically-employed schemes, such as flooding. Recently, a hybrid random walk scheme has been proposed for increasing the desired performance, at the cost of additional consumed resources. In this work, we adopt the paradigm of hybrid random walk protocols and propose two novel hybrid schemes that exploit local topological information, aiming at further increasing the performance of random walk protocols in multihop networks. We consider different jump configurations of the hybrid random walk protocols and various degrees of mobility. Through analysis and simulation, the simple random walk model appears more appropriate for energy-constrained networks such as sensor networks, while the hybrid ones are more appealing for less energy-stringent, performance-oriented multihop networks, such as vehicular and mesh networks. The simple hybrid protocol occupies the middle ground, being appealing for ad hoc networks with medium to low node densities and average energy requirements.

Keywords: hybrid random walks, topology awareness, mobile multihop networks.

1 Introduction

Wireless networks can potentially have large sizes, in terms of the population and/or the deployment region they span. In addition, most of these networks,

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like ad hoc, sensor, mesh and vehicular, are of multihop nature and they are characterized by lack of central infrastructure and dynamic topology. Search in these networks can be rather costly, especially in cases where all network nodes need to be visited at least once, or visited only once, as it is required in the famous Traveling Salesman Problem (TSP) [1].

Various approaches have been proposed for performing search, dissemination and retrieval in large unstructured networks and visiting all nodes of graphs representing such communication networks. Flooding schemes have been used extensively for their optimal performance [2, 3]. However, such schemes suffer from the packet explosion problem, which can be critical for the operation of energy-restricted networks. Alternative methods with comparable performance but significantly less overhead have been devised, most notably the probabilistic random walk [4, 5]. Random walks operate in a state-less fashion requiring only locally available information for their operation.

Random walks have been employed in diverse network types and applications, mainly for performing query search, network sampling and sensor data collection/spreading. In [4] the effectiveness of random walks for searching/ construction of Peer-to-Peer (P2P) networks is analyzed. In the considered framework, random walks achieve improvements over flooding for searching applications in two practical cases, namely in clustered P2P networks and when the same query is re-issued multiple times. In [5], it is shown that the coverage time (i.e. time to visit all network nodes at least once) for a random walk with look-ahead in a power-law graph (frequently used to represent the network graph of autonomous systems (ASs) of the Internet) is sublinear. In [6], constrained and unconstrained random walks over square lattices of sensor networks are studied and a closed-form expression for coverage in unconstrained random walks over the square lattice is obtained. Within this framework and available analytical expression, an optimal lattice form is conjectured and proposed. It is also concluded that constraints on random walks increase their efficiency. In [7] different types of random walks are studied for random graphs, a model commonly used for representing social and other topology-evolving networks.

In our work, we focus on hybrid random walk schemes in wireless multihop networks, where nodes perform either single or multiple hop jumps in successive steps of the walk. The main idea is inspired by [8], in which a two-state Markov chain is employed for performing multihop jumps or single hop visits. The proposed scheme achieves fewer node revisits and in general it is found that longer average jump lengths lead to higher performance at the expense of increased energy consumption. We propose two novel hybrid random walk protocols that attempt to improve the performance of the walk by exploiting local topological information. We then compare the performance of these protocols with that of the basic hybrid random walk protocol and the typical random walk, in order to obtain the most appropriate technique for different network application scenarios.

The rest of the paper is structured as follows. In section 2 the network model and random walk framework are described, while in section 3 the adopted and proposed hybrid random walk protocols are presented and analyzed. In section 4 comparative numerical results are presented and based on them conclusions are drawn on the suitability of each protocol for the considered networks and application environments.

2 Random Walk Framework

In this work, we consider a wireless, mobile, multihop network consisting of a set $V = \{1, ..., N\}$ of N nodes. The network can be modeled as a graph $G = G(V, E)$, where E is the set of links representing reliable wireless channels between communicating nodes. Without loss of generality, each node is considered to have the same initial available energy reserves E_{init}, transmission power P and corresponding transmission radius R. A deterministic wireless channel, in which the receipt power decays with respect to a specific power of the distance between the transmitter-receiver is considered (the decay factor being the path loss constant γ). Thus, for deterministic channel conditions, two nodes are considered neighbors if each one lies within the other's transmission range. Nodes are initially randomly and uniformly deployed in a planar region, which is considered to be square of size A. Essentially, the considered network model is a Random Geometric Graph (RGG) [9] in two dimensions.

The adopted graph model is able to accurately represent any type of wireless multihop networks, like ad hoc, sensor, mesh or vehicular. In Table 1 we summarize the macroscopic features of such networks according to the parameters of node density, network size, degree of mobility and energy constraints. Variations of such characteristics, that however do not significantly affect the generality of the analysis, may be identified in several cases.

In probability theory a Random Walk (RW) is a Markov process $\{X_i\}_{i\geq 0}$ in which X_i denotes the state of the process at step i and the next state is randomly and uniformly chosen among all the possible next states of the process.

Table 1. Wireless multihop networks' features

	node density	**network size**	**degree of mobility**	**energy constraints**
ad hoc networks	low/medium	small/medium	medium	medium
sensor networks	high	medium	none/low	high
mesh networks	medium	large	none/low	none
vehicular networks	medium/high	large	high	none

In our study the objective of the walk is to visit all network nodes at least once in some sequential random order. An accurate representation of the visiting process is for the state of the walk to denote the vertex of the graph visited in each time step, so that in the i-th step of the walk $X_i = v$, $v \in V$ being the label of the currently visited node. In the basic version of a RW on a network graph, transitions are allowed only between neighboring nodes. Each neighbor is chosen with equal probability. In this work we refer to the plain version of a RW as Simple Random Walk (SRW). If d_v denotes the degree of node $v \in V$, then the transition probabilities between states (i.e. neighboring vertices) are $P_{u,v} = \begin{cases} \frac{1}{d_u} & \text{if } (u,v) \in E \\ 0 & \text{if } (u,v) \notin E \end{cases}$ and the stationary probabilities, i.e. the probability for the walk to be in state u is $\pi_u = \frac{d_u}{2|E|}$.

Several quantities of interest may be defined for the SRW. In this paper we will focus on the expected number of steps required to visit all network nodes at least once, denoted by the term Cover (Coverage) Time, C. We also take into account the number of revisits before all nodes are covered, used to acquire the total energy required to cover the network.

SRWs have been used extensively in wireless sensor networks, P2P and ad hoc networks for performing the aforementioned tasks with simplicity, exploiting locality of computation and at the same time provide increased robustness to failure [4, 5, 6, 7]. Owe to their stateless fashion, mobility-induced topology and channel variations do not significantly affect (if at all) RW operation, as the only information required is locally available at the current state-node.

3 Hybrid Random Walk Protocols

In this section we present analytically the adopted and proposed hybrid Random Walk protocols for wireless multihop networks. Each of the proposed three strategies performs either simple one-hop jumps, or multihop jumps, the latter implemented as a sequence of one-hop jumps. For instance, if the random walk is currently at node 4 in Fig. 1 and performs a one-hop jump it can potentially transition to nodes $\{1, 2, 3, 5\}$. However, if it performs three-hop jumps it will transition to node 7. In the latter case, the walk will pass through nodes 5 and 6 in order to visit 7. However this passage is not counted as visits of nodes 5 and 6 because such visits were not decided by the walk in this step. Nevertheless, the consumption for intermediate links needs to be accounted for, since it represents actual transmissions taking place.

More formally put, the walk constitutes a permutation of the set of node labels $V = \{1, 2, \ldots, N\}$ (visit sequence) determined by the specific protocol and network topology. In the case of SRW, the permutation is determined by the uniform distribution. On the contrary, in the event of a long jump in hybrid RWs, the permutation is decided by the nodes residing that many hops away as the length of the jump. The hybrid protocols aspire to improve the performance of the process by deciding proper sequences that yield small Cover Times. However, this happens at the cost of increased energy consumption, since a single

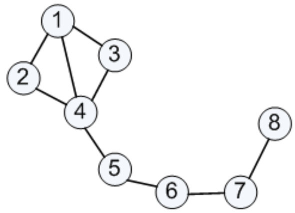


Fig. 1. Example of protocol operation

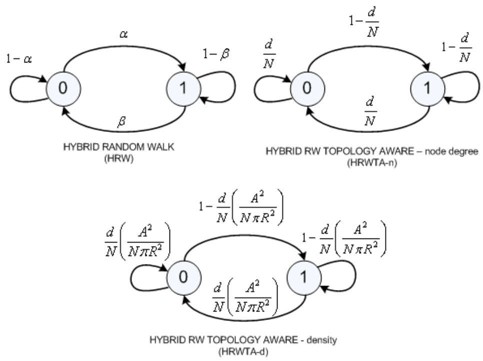


Fig. 2. Markov chains of the Hybrid Random Walk protocols

visit might require more than one transmission. Clearly, there exists a tradeoff between performance and consumption that the hybrid protocols need to balance. The main focus of this study is to specifically quantify this tradeoff and utilize it according to the application network.

3.1 Simple Hybrid Random Walk Protocol (SHRW)

In Simple Hybrid Random Walk protocol with parameters α, β, denoted by SHRW(α, β) [8], the random walk process has two states. When in state 0 (Fig. 2), the walk operates as a simple random walk, performing one-hop jumps out of each node it currently visits. When the walk is in state 1, it proceeds with multihop jumps. The multihop jumps in state 1 can be of fixed or variable length. In the latter case, the jump length is a random number uniformly distributed in the interval $[2, \ell_{\max}]$, where $\ell_{\max}$ is the maximum allowable jump length in hops. For compatibility purposes, $\ell_{\max} \leq D$, where D is the diameter of the network graph. In this work and in order to demonstrate the operation of the protocols in a simple way, we employ the uniform distribution for selecting the jump length. The direction of the jumps can be selected in various ways, and we choose again the uniform distribution direction among the available outgoing edges of a node.

The state transition probabilities of SHRW(α, β) are deterministic and remain fixed for the duration of the walk. More specifically, if at state 0, the process switches to state 1 with probability α and remains in state 0 with probability $1-\alpha$. Similarly, when the process is at state 1, it transitions to state 0 with probability β and remains in state 1 with probability $1-\beta$ (Fig. 2). State changes (if decided) take place at each step of the walk.

As it will be demonstrated by the numerical results, the addition of long jumps to the conventional operation of SRW is expected to improve performance with respect to Cover Time. The intuition behind this is that long jumps potentially avoid local revisits caused in highly clustered areas of a multihop network. Furthermore, several spatially distinct nodes are covered quickly by means of the long jumps.

3.2 Hybrid Random Walk Topology Aware Protocol-Node Degree (HRWTA-n)

Hybrid Random Walk Topology Aware-node degree (HRWTA-n) works similarly to SHRW(α, β), but state transitions are now functions of the node degree of the currently visited node. More specifically, the normalized degree (node degree over the total number of network nodes, $\frac{d}{N}$) of the specific node is used as a transition probability. With probability $\frac{d}{N}$ the walk remains in the state with one-hop jumps, i.e. state 0, and with probability $1-\frac{d}{N}$ it transitions to the state with multihop jumps, i.e. state 1. On the contrary, if at state 1, HRWTA-n transitions to state 0 with probability $\frac{d}{N}$ and remains in state 1 with probability $1-\frac{d}{N}$ (Fig. 2).

The intuition behind the HRWTA-n scheme is that if the currently visited node has large node degree, i.e. large number of neighbors or equivalently large $\frac{d}{N}$, then it is more efficient to spent some steps of the walk in this neighborhood utilizing one-hop jumps in order to cover as many nodes as possible. On the contrary, if the ratio $\frac{d}{N}$ is small, i.e. the node degree is small, it will be more convenient to perform a long jump and move to a different neighborhood that it is not potentially already visited.

3.3 Hybrid Random Walk Topology Aware Protocol-Density (HRWTA-d)

The Hybrid Random Walk Topology Aware-density (HRWTA-d) protocol is similar to HRWTA-n. The state transition probabilities depend again on the topological information available at the node. Each currently visited node is able to measure the local density by dividing its node degree by its nominal coverage transmission area $\frac{d}{\pi R^2}$. The local density can be divided by the total network density $\frac{N}{A^2}$, since both the total number of nodes and coverage area are known to the nodes (design parameters). Division of the two densities yields the normalized local node density. Direct employment of this quantity was found to yield very abrupt transition probabilities, i.e. the transitions were very biased towards one of the two states. For this reason the normalized local density is multiplied by a scaling factor, that depends on the total number of nodes $K = K(N)$. In this work, we employ the factor $K(N) = \frac{1}{N}$.

Combining the aforementioned quantities the state transition probabilities from state 0 will be $\frac{d}{N}\left(\frac{A^2}{N\pi R^2}\right)$ for staying in state 0 and $1-\frac{d}{N}\left(\frac{A^2}{N\pi R^2}\right)$ for transiting out of state 0. On the contrary, the latter is the probability to remain in state 1 if already there and the first is the probability to transition to state 0 if in state 1 already (Fig. 2).

4 Numerical Results

In this section we present and discuss some results on the performance of the presented protocols, SHRW, HRWTA-n and HRWTA-d and SRW under several working conditions. The analysis has been performed through a simulative study, by implementing our own simulator in the MATLAB environment. Simulation scenarios have been built with the following settings: the network area was considered as an $A \times A$ square, with $A = 1000m$. Over this area, $N \in [100, 250]$ nodes were deployed according to a uniform distribution, which allowed the study of protocol behavior for increasing node densities. For simplicity, in Table 2 we summarize all the settings used in simulations.

Table 2. Simulation settings

Network size	$A = 1000m$
One-hop transmission power	$P = 1mWatt$
SHRW parameters	$\alpha = 0.3$ and $\beta = 0.7$
Communication range	$R = 150m$
Fix length jumps	$FixJump = 3$
Variable length jumps	$MaxJump = 5$
Low mobility	$Speed = [0; 2]$, $PauseTime = [0; 10]$
Medium mobility	$Speed = [0; 4]$, $PauseTime = [0; 7]$
High mobility	$Speed = [0; 8]$, $PauseTime = [0; 4]$

Multihop jumps in the network have been implemented in two ways: 1) fixed-length jumps, 2) variable-length jumps. We denote the first variation for hybrid modes of RW protocols with jumps by the term FixJump. In our simulations FixJump is set to 3 hops. The second variation is characterized by the MaxJump ($\ell_{\max}$) parameter, so that the length of each jump in hops, when the protocol operates in the multihop jump mode (state 1), is determined uniformly and randomly in the range $[2, MaxJump]$.

We have focused the analysis on two metrics:

- Coverage Time: the Coverage Time of a graph G is the expected time taken by a RW protocol to visit all the nodes in G. In this work, the Coverage Time is estimated as the number of steps in the Markov process.
- Energy consumption: the energy expended to visit all the nodes in G. The energy consumption model was taken as a simplified one, able to bind the

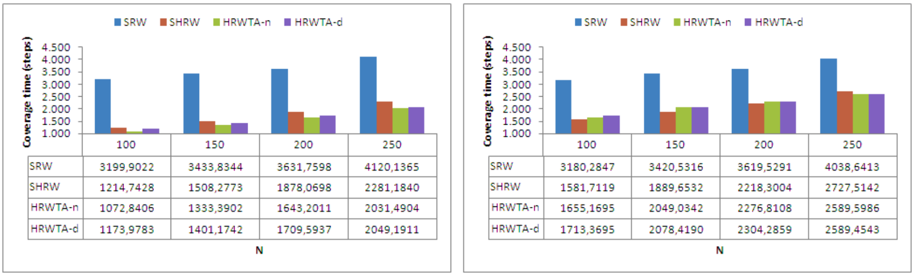
transmission power to the length of jumps. For one-hop communications, the transmitter node was assumed to spend 1 mWatt. Thus, if the protocol works in State 0, the power consumed was 1 mWatt. The power spent from a transmitter to make a jump was equal to the total length of the jump converted in mWatts.

Simulations have been carried out in two stages: at first, we have considered static nodes in order to understand the impact of jumps on the system behavior. Then we have repeated the experiments adding node mobility features, until all nodes are covered again. To provide informative and accurate results, all the simulation measurements have been averaged over 10000 different network topologies for each type of scenario.

4.1 Analysis of Static Environments

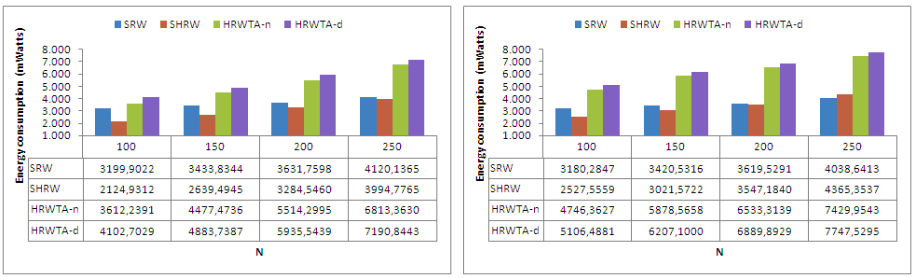
In Fig. 3, we show the various protocol performances with respect to the Coverage Time for static scenarios. We distinguish performances of protocols for the MaxJump and the FixJump configurations. SRW exhibits the worst behavior, exemplifying the importance of jumps in providing desired networking service. By considering simulations with the MaxJump configuration, HRWTA-n presents better results followed by HRWTA-d and SHRW, but the gap in performance among protocols with jumps is narrow. In fact, the gap between HRWTA-n and SHRW is about 12% in all the network scenarios, whereas the gap between HRWTA-n and HRWTA-d depends on the nodes' density. In particular, it ranges from 8% for networks with low density of nodes ($N = 100$) to 1% in networks with high density of nodes ($N = 250$). The transition from the MaxJump configuration to the FixJump configuration results to protocols' performances degradation of about 37%, with a peak of 46% when N is small. In this context, the best protocol is SHRW when the density of nodes is low, while HRWTA-n and HRWTA-d perform better otherwise.

Results on protocol performances with reference to energy consumption are shown in Fig. 4. Simulations show that SRW and SHRW exhibit the best performances in terms of energy consumption. In particular, SRW carries out one-hop communications, thus minimizing the energy consumption for each data transmission. However, the low energy consumption for transmission is at the cost of high Coverage Time. On the contrary, HRWTA-n and HRWTA-d waste a lot of energy due to jumps. This is confirmed by the results on the time spent in State 1 for SHRW, HRWTA-n and HRWTA-d. In fact, nodes that run SHRW spend 30% of time in state 1 against the percentage of 90% if they run HRWTA-n and the percentage of 99% if they run HRWTA-d. The performances of SRW and SHRW are almost identical in dense networks, especially with regard to the FixJump configuration. SHRW performs better than SRW in large networks with low node density. When the density of nodes becomes high, SRW outperforms SHRW. Between HRWTA-n and HRWTA-d, the first always shows a better behavior in terms of energy consumption than the second. The best performances in terms of energy consumption are always under the MaxJump configuration,



(a) MaxJump configuration (b) FixJump configuration

Fig. 3. Coverage time in static scenarios



(a) MaxJump configuration (b) FixJump configuration

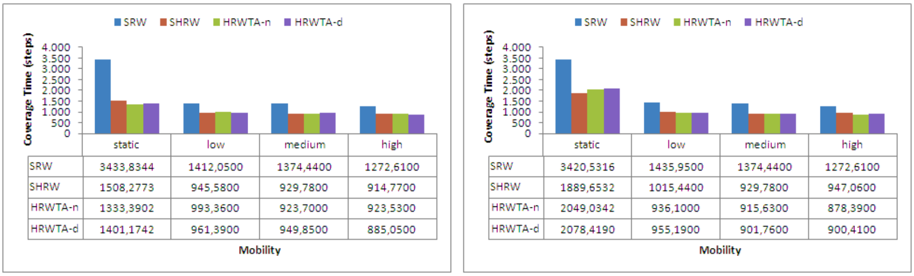
Fig. 4. Energy consumption in static scenarios

with a gap in performances between the two types of configuration in the range of 10-30%. In fact, long jumps reduce the coverage time and, hence, the number of transmissions in the network.

From previous considerations, we can assert that jumps in the RW protocols offer great benefits in the network delivery service. In fact, when we consider the Coverage Time as evaluation metric, protocols with jumps provide improvements of about 60% in the MaxJump configuration and 40% in the FixJump configuration over the SRW performances. Employing protocols like SHRW, HRWTA-n and HRWTA-d, takes place at the cost of higher energy consumption as opposed to the case of SRW. So, in wireless multihop scenarios where energy consumption is not an issue, like wire-powered mesh networks, HRWTA-n can offer the maximum efficiency in the networking services. On the contrary, SHRW is suitable in scenarios where nodes are limited in energy supply, like in sensor networks, since it guarantees a better Coverage service than SRW, but with significantly lower energy consumptions than hybrid protocols.

4.2 Analysis of Mobile Environments

In our simulation scenarios, node mobility has been implemented according to the Random Waypoint (RWP) model [10]. Nodes change their spatial



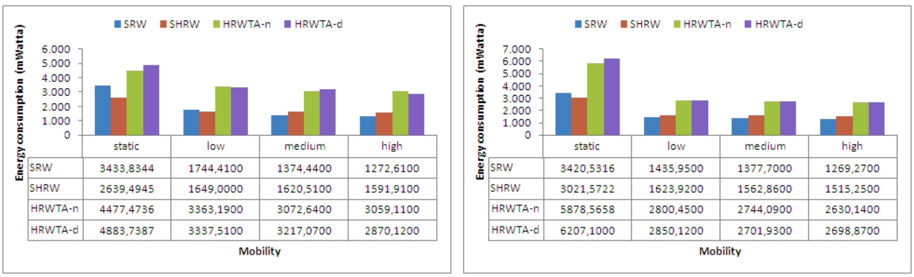
	static	low	medium	high
SRW	3433,8344	1412,0500	1374,4400	1272,6100
SHRW	1508,2773	945,5800	929,7800	914,7700
HRWTA-n	1333,3902	993,3600	923,7000	923,5300
HRWTA-d	1401,1742	961,3900	949,8500	885,0500

(a) MaxJump configuration

	static	low	medium	high
SRW	3420,5316	1435,9500	1374,4400	1272,6100
SHRW	1889,6532	1015,4400	929,7800	947,0600
HRWTA-n	2049,0342	936,1000	915,6300	878,3900
HRWTA-d	2078,4190	955,1900	901,7600	900,4100

(b) FixJump configuration

Fig. 5. Coverage time in mobile scenarios



	static	low	medium	high
SRW	3433,8344	1744,4100	1374,4400	1272,6100
SHRW	2639,4945	1649,0000	1620,5100	1591,9100
HRWTA-n	4477,4736	3363,1900	3072,6400	3059,1100
HRWTA-d	4883,7387	3337,5100	3217,0700	2870,1200

(a) MaxJump configuration

	static	low	medium	high
SRW	3420,5316	1435,9500	1377,7000	1269,2700
SHRW	3021,5722	1623,9200	1562,8600	1515,2500
HRWTA-n	5878,5658	2800,4500	2744,0900	2630,1400
HRWTA-d	6207,1000	2850,1200	2701,9300	2698,8700

(b) FixJump configuration

Fig. 6. Energy consumption in mobile scenarios

distribution by uniformly and randomly selecting in the network area a destination trip (waypoint). Then, the trip path of a node is a straight line that connects the current node position with the trip destination. Also we have used three mobility degrees: low, medium and high to test protocols under different mobility conditions. Settings regarding the mobility degrees employed are provided in Table 2.

Mobility amplifies the effect of reducing local revisits of nodes, which is effectively, similar in concept to the execution of multihop jumps (different operation, similar outcome). A mobile node changes locations constantly, joining new neighbors and thus increasing the probability to visit uncovered nodes. By intuition, mobility can be considered as a different way to implement jumps in the network. This explains the improvement in the performances of all the protocols when we consider mobility in the network, especially of SRW that was not employing jumps previously.

In Fig. 5 and 6 we show experimental measurements on protocol performances by increasing the mobility degree and setting $N = 150$ for MaxJump and FixJump configurations. In general, the performances are always better in mobile scenarios than their counterparts in the static case both for Coverage Time and energy consumption metrics. Also, increasing the mobility degree, the overall performances increase. The protocol that mostly benefits from mobility in terms of Coverage Time is SRW, since it does not implement any mechanism to avoid local loops and mobility helps in exactly this direction. In particular, it improves its performances by approximately 60%. Protocols with jumps also improve their performances, even at lower degrees than SRW. With reference to Coverage Time, gains of 33% in performances are achieved with MaxJump and of 56% with FixJump configurations respectively. Also, in both configurations, the protocols show very similar behaviors. Regarding the energy consumption metric, the improvement in performance with MaxJump is 36% and with FixJump 53%. Thus, the FixJump configuration allows to draw much more benefits from mobility. Even if SHRW shows the best performances among protocols with jumps, differences diminish by increasing mobility.

4.3 Discussion

In this subsection, we perform an overall assessment of the analyzed protocols. As mentioned earlier, both variations of HRWTA protocols have better performance but higher energy consumption. Consequently, they are more appealing for mesh and vehicular networks, where minimal energy requirements exist, if any. Furthermore, these networks have large sizes and medium to high node densities, calling for increased performance. Mobility degrees vary from very low (mesh) to very high (vehicular), however, the protocol operation will remain satisfactory, as it can only increase in the presence of mobility. Between the two, HRWTA-n is more suitable for vehicular networks and HRWTA-d for mesh networks, as HRWTA-n has a slightly better performance and respective increased consumption.

On the other hand, SRW and SHRW are more appropriate for ad hoc and sensor networks, due to their energy-conserving nature. Between the two, SHRW is more oriented towards medium to low densities, while SRW towards higher densities, in the sense that their performance gap closes towards these density extremes for each case respectively. Consequently, SHRW are better suited to ad hoc networks and SRW to sensor networks. Their energy-consumption fits ideally the corresponding network types, while for the indicated density ranges, their performance will not be significantly lower than the best-performing protocols.

Overall, hybrid protocols are more appropriate for performance oriented networks, while simple RW protocols for more energy-stringent. With respect to the protocols studied in this work, HRWTA-n is suitable for vehicular networks, HRWTA-d for mesh networks, SHRW for ad hoc and SRW for sensor networks.

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