Power-efficient gossiping in multi-hop ad hoc networks

Benoît Garbinato
Information Systems Institute
University of Lausanne
benoit.garbinato@unil.ch

Denis Rochat
Information Systems Institute
University of Lausanne
denis.rochat@unil.ch

Marco Tomassini
Information Systems Institute
University of Lausanne
marco.tomassini@unil.ch

ABSTRACT

In this paper, we present a novel gossiping protocol for disseminating information in static and mobile multi-hop ad hoc networks. Our protocol exhibits two interesting properties. First, it tends to decrease the power required to disseminate information, by reducing the transmission range each network node uses for gossiping. This property results in a longer life expectancy for the ad hoc network, when running on power-constrained devices. Second, mobility has no negative impact on the performance of our protocol, meaning that it is equally useful in a static context and in a mobile context. Both these properties are shown empirically, via a thorough performance evaluation. It is also noteworthy that our protocol retains the decentralized and stateless nature of traditional gossiping protocols.

Categories and Subject Descriptors

C.2.2 [**Computer-Communication Networks**]: Networks protocols—*Routing protocols*

General Terms

Algorithms, Measurement, Performance

Keywords

ad hoc networks, gossiping protocol, power efficiency

1. INTRODUCTION

Today, wireless networks are increasingly composed of wireless mobile devices with embedded sensing capabilities, contrary to a recent past, when devices were mainly computation-oriented and connected via a wired infrastructure. Smart phones, such as the iPhone with its accelerometer, its GPS[1] capability, and its proximity and ambient light sensors, are good examples of such devices. This change opens new opportunities for context-aware applications but also implies new challenges in order to disseminate context-sensitive information in multi-hop wireless ad hoc networks. That is, protocols must now take into account new parameters, such as the mobility of devices and their constraints in terms of power consumption. In this context, decentralized and stateless broadcast solutions are of particular interest.

When it comes to effectively and efficiently disseminate information, a key factor lies in the topology of the underlying ad hoc network. Besides various uncontrollable parameters, e.g., environmental interferences or device mobility, the topology can to some extent be controlled by modulating the transmission range of each device, possibly by adequately directing their antennas.

1.1 Power-law gossiping

This paper presents a novel decentralized and stateless approach to broadcasting in multi-hop wireless ad hoc networks. Our approach combines the advantage of gossiping, i.e., simplicity and low resource consumption, with the advantages of more structured approaches,[2] i.e., high reliability. That is, devices executing our protocol follow a traditional gossiping protocol but they additionally modulate the range of their wireless transmissions according to a *power-law distribution*; this allows them to control the topology followed by broadcasted messages. More precisely, whenever a device has to wirelessly transmit a message in its neighborhood, it randomly draws the transmission range it will use from a power-law distribution. For this reason, we characterize our broadcast protocol as *power-law gossiping.*

Because the power-law distribution is given a priori to each device, our protocol completely retains the decentralized and stateless nature of a traditional gossiping protocol. The power-law modulation of wireless transmissions produces, for each broadcast, an actual routing topology that exhibits characteristics approaching those of scale-free overlay network. That is, message routing occurs as if we had built an overlay network exhibiting an near power-law topology. Our approach is *power-efficient*, since the transmission range is closely correlated with the power consumption. In addition, our approach has no negative impact on either the number of devices being reached (reliability), nor on the time it takes to reach them (latency).

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[1] Global Positioning System.

[2] By *structured approaches*, we mean broadcasting techniques that rely on some overlay network topology.

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1.2 Scale-free topologies

The starting point of our solution lies in the recurring observation that typical effective communication and information topologies, such as routing paths in the Internet or hyperlinks in the World Wide Web, follow a power-law distribution of degrees, i.e., they are scale-free topologies. This is also true for many other complex systems or phenomena, typically based on *small-world* networks [1, 9], e.g., infection propagation in populations [3].

The most important feature of scale-free topologies is the presence of a significant number of *highly connected nodes*. These so-called *hubs* help reduce the diameter of the graph and thus make these networks small-worlds. Scale-free networks also have a high robustness against random node failures, while they are more fragile with respect to hub failures [9]. Recently, these aspects have been studied in the context of peer-to-peer file sharing systems, such as Freenet or GNUTella [4].

Interestingly, because our solution implies that a different transmission range is chosen each time a device has to forward a message, no nodes assumes the role of hub permanently, i.e., each node acts as hub only for a small subset of broadcasts. For this reason, our solutions is resilient to any coordinated attack trying to focus on hubs.

1.3 Mobility and geographical constraints

In [2], we have shown that the topology plays a significant role in the dynamics of gossiping protocols in purely relational and static networks, i.e., in networks with neither geographical nor mobility constraints. Yet, the relationship between *mobile ad hoc networks* and *scale-free topologies* is still widely an open issue. The research presented here precisely aims at further investigating this relationship, by extending our approach towards Euclidean topologies and by adding mobility to communicating devices.

1.4 Roadmap

Section 2 specifies our model and precisely states the research questions we address. Section 3 then describes our decentralized power-law gossiping protocol, while Section 4 presents and discusses its performance analysis. In particular, we show that our protocol is efficient in a static context and in a mobile context, and under various broadcast loads. Finally, Section 5 discusses related work, and Section 6 places our results into perspective and discusses ongoing and future work.

2. MODEL DEFINITION

We model a multi-hop ad hoc network as a set of distributed mobile devices communicating by low-level broadcasting with their direct neighbors, via the MAC sublayer.[3] We make no assumptions about the time it takes for devices to execute and for messages to be transmitted, meaning that the system is considered to be asynchronous. The low-level broadcasting is modeled by a `mac-broadcast()` primitive and a corresponding `mac-deliver()` callback. Devices can modulate their transmission range by passing a `range` parameter to the `mac-broadcast()` primitive.

The notion of transmission range allows us to abstract our model from the underlying signal propagation model, from the influence of potential interferences and from the actual transmission power used to perform low-level broadcasting. Indeed, given a signal propagation and interference model, the transmission range easily translates to a transmission power, which is then directly correlated with power consumption. Therefore, we can control the power consumption of our gossiping protocol by adequately modulating transmission ranges.

Regarding mobility, we assume the *random way point* model, in which each device moves on a straight line to a randomly selected position in the deployment field [6]. Once a device reaches that point, it waits for a predefined amount of time, before it selects a new position to move to. In addition, we assume the deployment field to be toroidal, which ensures that the initial uniform distribution of devices remains stationary throughout the execution of the protocol.

2.1 Problem statement and approach

In [2], we show that purely *relational* scale-free topologies have a positive impact on the performance of gossiping in *static* ad hoc networks. In the present paper, we take this approach one step further, by addressing the following question: do scale-free topologies immersed in an *Euclidean space* have a positive impact on the performance of gossiping in both *static* and *mobile* ad hoc networks?

Intuitively, with our power-law gossiping protocol each device individually sets its transmission range according to a power-law distribution function, depicted in Figure 1, whenever it has to forward a message. As suggested by the figure, most of devices choose a low transmission range (between 50 to 55 meters), while few devices will choose a high transmission range (over 65 meters).[4] Since devices choose a potentially different transmission range for each broadcast in which they participate, the decrease in power consumption generated by our protocol benefits to all devices. Figure 2 shows the same distribution function but on logarithmic scale, which naturally translates into a straight line. The small fluctuations at the end of the line can be explained by the cut-off in the distribution function, due to physical constraints imposed on the maximum transmission range.[5]

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[3] Medium Access Control.

[4] These values correspond to a standard WiFi network.

[5] Such physical constraints are typically related to the wireless technology being used, the available battery power, etc.

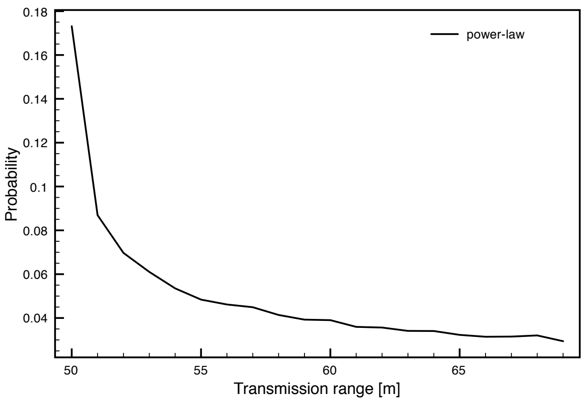

Figure 1: Power-law function distribution of the transmission range (linear scale)

It is also important to note that with our power-law gossiping protocol, it is possible for some device A to reach some other device B, while B is unable to reach A (because it chose a transmission range shorter than the distance between A and B). Besides our power-law gossiping protocol, others routing protocols also consider uni-directional links, e.g., the commonly used AODV protocol [11], which is able to run on networks with some uni-directional links.

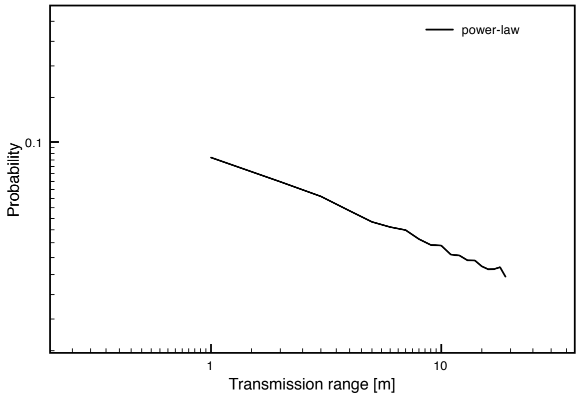

Figure 2: Power-law function distribution of the transmission range (logarithmic scale)

3. POWER-LAW GOSSIPING PROTOCOL

A gossip-based communication layer is typically modeled via a broadcast() primitive and a deliver() callback. A *gossiping* (or *epidemic*) dissemination protocol then works as follows: each device that receives a message (resulting from some broadcast) forwards the message to its neighbors with a certain probability, called hereafter the *gossip ratio* (*gr*) and then delivers the message. Algorithm 1 presents the generic structure of such a gossiping protocol, where the *msgSent* set helps to avoid forwarding the same message forever. The protocol stops when no more device that received the message have to forward it.

Algorithm 1 - Generic gossiping protocol

```
Initialization:
    $msgSent \leftarrow \emptyset$
    $gr \leftarrow ...$                                {gossip ratio}

To execute broadcast($msg$) do:
    gossip($msg, gr$)

deliver($msg$) occurs as follows:
    when mac-deliver($msg$) $\wedge$ $msg \notin msgSent$
        $msgSent \leftarrow msgSent \cup \{msg\}$
        gossip($msg, gr$)
        deliver($msg$)
```

The actual gossiping strategy is then encapsulated in the gossip() function presented in Algorithm 2, which in turn relies on function f. Hereafter, Equation 1 defines a constant distribution function f that turns Algorithms 1 and 2 into a traditional gossiping protocol, whereas Equation 2 defines a power-law distribution function f that turns Algorithms 1 and 2 into our power-law gossiping protocol. In those equations, c_1, c_2, c_3 and α are all constants; α defines the shape of the power-law distribution. Function random() simply returns a random value between 0 and 1.

$$f(x) = c_1 \quad (1)$$

$$f(x) = c_2 + c_3 \times x^{\alpha} \quad (2)$$

Algorithm 2 Function gossip(msg, gr)

```
function gossip($msg, gr$)
    if random() < $gr$ then
        $x \leftarrow$ random()
        $range \leftarrow f(x)$                {range distribution}
        mac-broadcast($msg$, $range$)
```

Note that these distribution functions have to return a value between a minimal value strictly greater than 0, to ensure an effective physical broadcasting, and a maximal value given by the technology constraints, e.g., around 10 meters for Bluetooth and 100 meters for WiFi. Note also that the power-law gossiping protocol based on Algorithms 1 and 2, and on Equation 2, is not optimized. An simple improvement could for instance consist in making each device that initiates a broadcast use the maximum transmission range, i.e., to systematically force any broadcast initiator to be a hub for that broadcast. This improvement would also positively impact the latency of our protocol.

4. PERFORMANCE ANALYSIS

To compare our power-law gossiping with traditional (constant) gossiping, we use three different measures. First, we measure the *delivery ratio*, which assesses the reliability of each protocol. The main objective is of course to reach a high delivery ratio. Then, we measure the *cumulated transmission range* used during the lifetime of the mobile ad hoc network. This value gives an indication of the power consumption induced by each protocol. For this measure, we consider the worst-case scenario: if a device has to forward several messages in a short period of time, it always sends them independently.[6] Finally, we measure the *latency* as the longest path, in number of hops, that the broadcast message is going through, until the gossip process terminates.

4.1 Measurement settings

We consider a 600 × 600 m^2 map, where 1000 devices are initially placed at random following an uniform probability. This setting roughly corresponds to the downtown of a typical European city. To avoid boundary problems, the map is a torus. The minimal transmission range is 50 meters and the maximal transmission range is 70 meters. Those values correspond to WiFi capabilities, considering a reasonable level of interference. For the random way point mobility model, we consider a Gaussian speed distribution with a mean of 10 meters/second and a variance of 20 meters/second, while the waiting distribution follows a Poisson distribution, with a lambda coefficient of 10 seconds. These values roughly correspond to people walking pseudo-randomly in the downtown of some city.

For our measurements, traditional gossiping is based on a constant function that always return 60 meters as transmission range, i.e., $c_1 = 60$ in Equation 1. As for our power-gossiping protocol, it relies on the power-law function given by Equation 1, with $c_2 = 50$, $c_3 = 20$ and $\alpha = 2.3$. That is, this function returns values between 50 and 70 meters. Finally, three gossip ratios are tested: $gr = 0.6$, $gr = 0.8$ and $gr = 1.0$, the latter corresponding to a flooding protocol.

In the following, we start by presenting performance results obtained in a static context (no mobility), for both a single-source scenario (only one device is allowed to broadcast) and a multiple-source scenario (all devices are allowed to broadcast). We then present performance results in a mobile context, again for single-source and multiple-source scenarios. For multiple source scenarios, we consider various *broadcast loads*, expressed in the percentage of nodes that are actually broadcasting; for this parameter, we use the following values: 0.1%, 0.2%, 0.5% and 1%. Finally, we compare results obtained in a static context with those obtained in a mobile context. Our performance measurements were performed using Sinalgo [10], a simulation framework specifically aimed at simulating communication algorithms in wireless networks.

4.2 Static context - Single source

Hereafter, all curves represent the average of 100 independent simulations. Figure 3 shows the cumulated transmission range when executing one broadcast with a gossip ratio of 0.6. We can observe that our power-law gossiping protocol decreases the cumulated transmission range by 10% with respect to traditional gossiping, passing from about 380'000 meters to about 340'000 meters. Translated to power consumption, a 10% gain is clearly interesting. For critical applications, this difference can even be decisive.

Figure 4 shows that the delivery ratio of the two gossiping protocols are not statistically different: with a gossip ratio equal to 0.6, the delivery ratio is about 98% of the devices for both protocols. In addition, none of them terminates faster. That is, the 10% gain in cumulated transmission range (or power) observed for the power-law gossiping does not decrease its reliability, nor increase its latency.

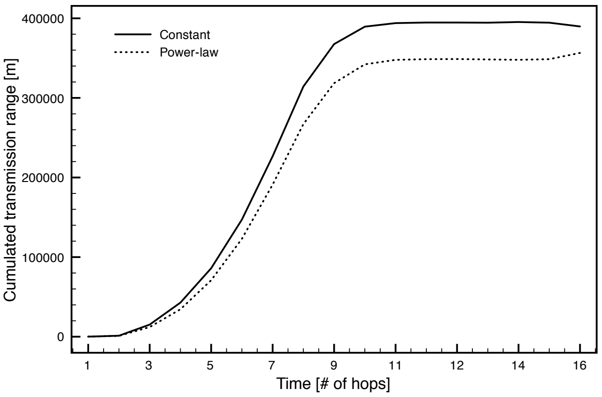

Figure 3: Cumulated transmission range, gossip ratio = 0.6

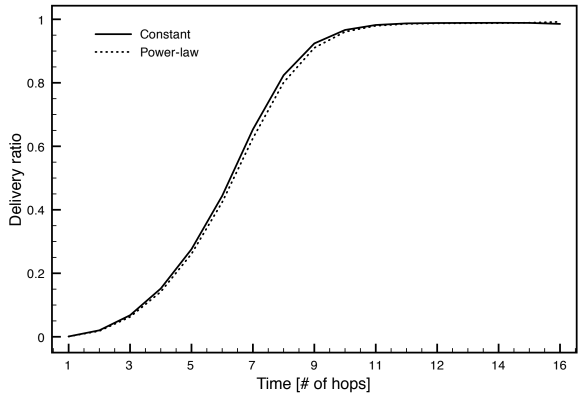

Figure 4: Delivery ratio, gossip ratio = 0.6

Figure 5 shows the latency of both gossiping protocols, i.e., the longest paths, in number of hops, that messages are going through, until the gossip processes terminate. We can observe that there is no significant difference.

4.3 Static context - Multiple sources

Hereafter, all curves represent the average of 50 independent simulations. Figure 6 shows the cumulated transmission range when executing 1000 broadcasts with four different broadcast loads and a gossip ratio of 0.8. Taking the curves clockwise, the latences increases as the broadcast load decreases, i.e., the more gossip processes running simultaneously, the more power-efficient our protocol. Interestingly, the advantage in power efficiency of our protocol increases together with the broadcast load The fluctuations at the end of the curves result from the fact that, as gossip processes asynchronously terminate, the data used to plot the curves because more and more scarce.

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[6] A more favorable scenario would consist in packaging several messages and in sending them together, hence decreasing the cumulated transmission range.

Gossip ratio	standard	power-law
0.6	13.94	14.29
0.8	12.07	12.17
1.0	10.07	10.17

Figure 5: Latency (in number of hops) to execute gossiping protocols with different gossiping ratios

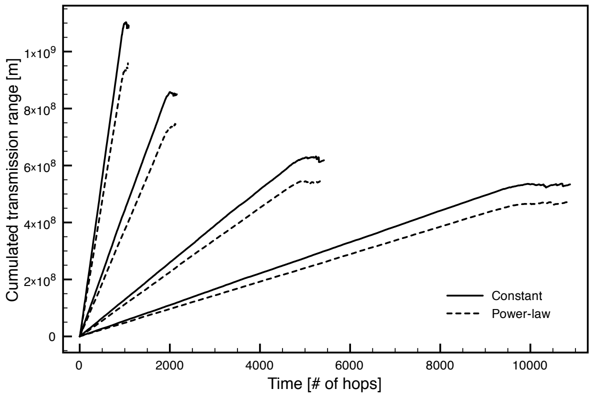

Figure 6: Cumulated transmission range, gossip ratio = 0.8. Clockwise, the broadcast load decreases

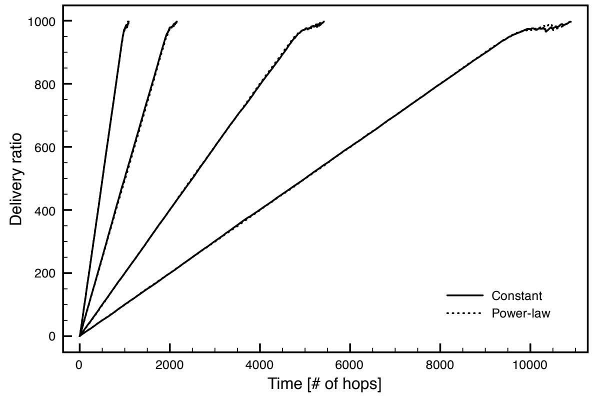

Figure 7: Delivery ratio, gossip ratio = 0.8. Clockwise, the broadcast load decreases

Figure 7 shows that broadcast load has no impact in the final delivery ratio. Again, curves are similar for standard gossiping and power-law gossiping. In conclusion, we observe that a gain in transmission range (hence in power efficiency) has no impact on the delivery ratio nor on the latency.

4.4 Mobile context - Single source

Hereafter, curves represent the average of 100 independent simulations with a gossip ratio equals to 0.6. Figure 8 describes the performance of the two protocols in a mobile context. The figure describes the same observations as in a static context: our power-law gossiping protocol is power-efficient in comparison to the standard gossiping protocol.

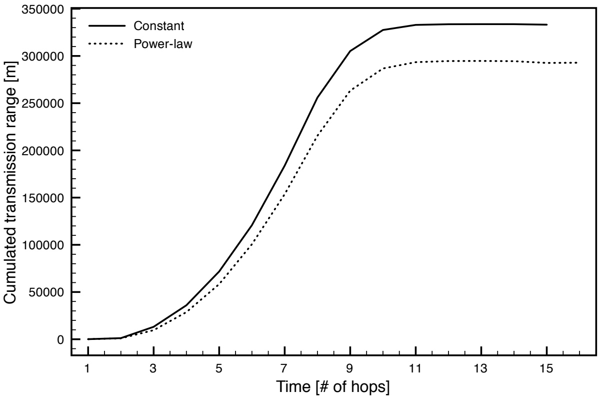

Figure 8: Cumulated transmission range, gossip ratio = 0.6

Figure 9 shows that, as in a static context, the delivery ratio is statistically equivalent for standard gossiping and for power-law gossiping. In Figures 8 and 9, the power-law gossiping process seem to take longer, i.e., 16 hops *vs.* 15 hops for traditional gossiping. This difference is however no significant and probably due to one or two longer simulations. Indeed, in Figure 10, we can see that there is no real difference between the two protocols when it comes to latency. To conclude, devices mobility does not change the observation made in a static context: our protocol is still more power-efficient when compared to standard gossiping.

4.5 Mobile context - Multiple sources

Hereafter, curves represent the average of 50 independent simulations with a gossip ratio equals to 0.8. Figure 11 shows that, again, our power-law gossiping protocol is more power-efficient that standard gossiping. And again, the difference increases together with the broadcast load. Figure 12 shows that the delivery ratio and the latency are negatively impacted by a lower cumulated transmission range.

To conclude, in a more realistic context with mobility and more than just one gossip process, our power-law protocol is more power-efficient than traditional gossiping and the higher the broadcast load, the more efficient the transmis-

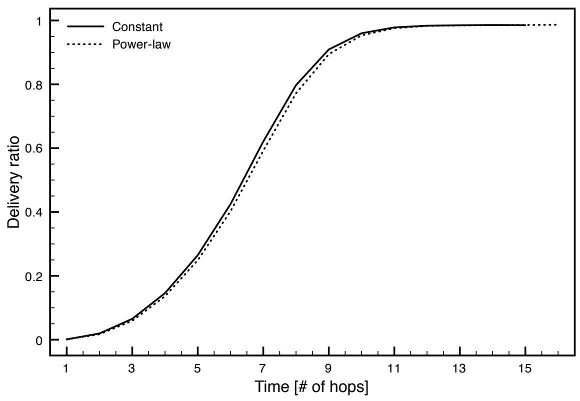

Figure 9: Delivery ratio, gossip ratio = 0.6

Gossip ratio	standard	power-law
0.6	14.02	14.07
0.8	12.06	12.12
1.0	10.09	10.36

Figure 10: Latency (in number of hops) to execute gossiping protocol with different gossip ratios

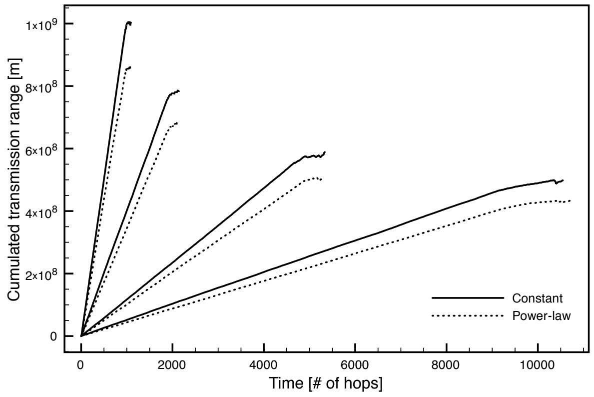

Figure 11: Cumulated transmission range, gossip ratio = 0.8

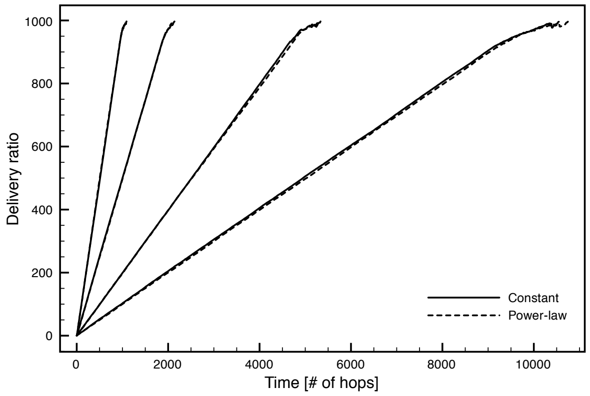

Figure 12: Delivery ratio, gossip ratio of 0.8

sion range modulation.

4.6 Static context vs. mobile context

Hereafter, curves represent the average of 100 independent simulations with a gossip ratio equals to 1 (flooding broadcast). Figure 13 shows a diminution of the cumulated transmission range needed with mobility compared to the static case. This can be explain by the fact that when devices received a message from another common device, the potential of redundancy is high that these two devices forward the messages to each other. This redundancy is less likely to happen when devices move because devices can move away from each other. The gain due to mobility is the same for both standard gossiping and power-law gossiping. So none of these protocols takes advantage of the mobility over the other. Furthermore, mobility has no negative impact on the delivery ratio, nor on latency.

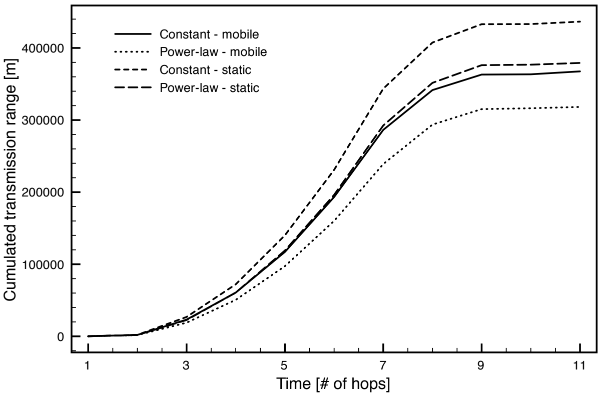

Figure 13: Cumulated transmission range, gossip ratio = 1.0 (flooding broadcast)

Figure 14 shows similar resutls in term of delivery ratios. All curves are superimposed and so, no statistical difference can be observed. Figures 15 and 16 describe the same results as in the two previous figures with different broadcast loads. Again, delivery ratios are statistically similar with the two protocols.

5. RELATED WORK

Two main areas are studied in this paper. First, dissemination in small-world topologies, which inspired our power-law gossiping protocol, and power-efficient protocols in mobile multi-hop wireless networks.

Epidemic information dissemination has been widely studied in the context of peer-to-peer systems. In [14] for instance, the authors discuss their model of information dissemination and membership management in the context of a heterogeneous communication network, consisting of computing nodes, local high-speed links and wide-area links. Interestingly, their networks are small worlds but they are not scale-free. Along the same line, the authors of [5] propose a gossip-based protocol for aggregating information in a peer-to-peer manner. When simulating their protocol on various

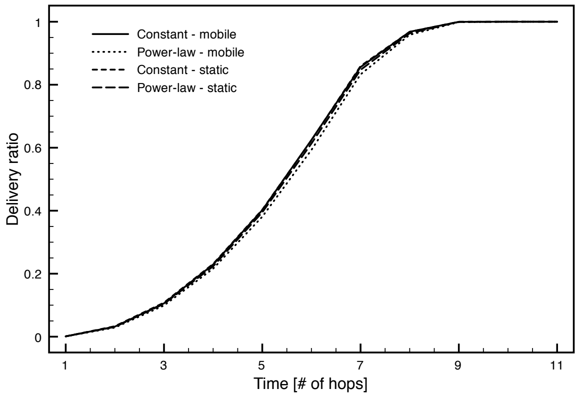

Figure 14: Delivery ratio, gossip ratio = 1.0 (flooding)

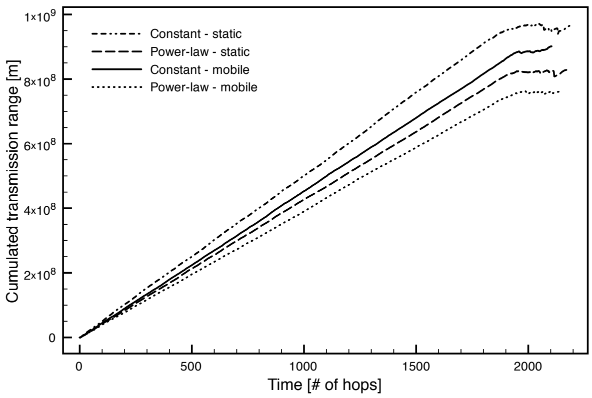

Figure 15: Cumulated transmission range, gossip ratio = 1.0 (flooding)

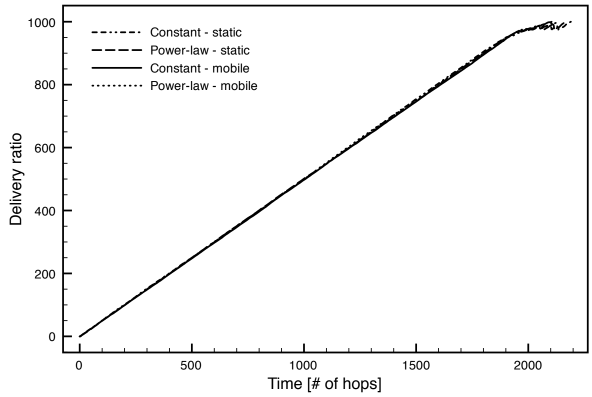

Figure 16: Delivery ratio, gossip ratio = 1.0 (flooding)

topologies, they found out that performance is independent of network size but highly sensitive to the topology. That is, their gossip protocol is efficient on topologies that have a small diameter, in particular on small-world topologies. This concurs with our own findings that scale-free topologies are beneficial to the performance of gossiping protocols. Similarly, in [7] a gossiping strategy is proposed to improve information dissemination in peer-to-peer communities. Intuitively, this strategy relies on a discovery protocol that first identifies highly influential peers. When joining a community, a peer then follows certain rules resulting in the creation of a scale-free gossiping graph, with influential peers as highly connected nodes. As a consequence, a large percentage of peers can be reached in just two hops, by pushing information to only a small number of highly influential peers. Pursuing a slightly different goal, the authors of [17] try to reduce the number of messages necessary to disseminate information in a peer-to-peer network. To that end, they propose a broadcast protocol based on connected dominating sets. When simulated on a scale-free peer-to-peer overlay graph, their protocol drastically reduces redundant messages compared to a flooding protocol, while maintaining the same coverage. This concurs with our own findings, although their study is less systematic.

Power-aware protocols in multi-hop ad hoc networks try to extend the lifetime of the network. MBCR (Minimum Battery Cost Routing) [13] is a good example of a such protocol. The MBCR prevents hosts from being overused. But the selected route can contain nodes with little remaining battery capacity, because only the summation of battery costs is considered. Another one is POAD (Power-aware on-demand routing protocol for MANET) [15], which uses energy status reports exchanged by devices to create routes. Somehow, all these protocols rely on either local or global information to find routes, which constitutes the main difference with our power-law protocol. Indeed, our protocol retains the stateless and decentralized nature of traditional gossiping.

In addition, we can mention two papers which also propose transmission range adjustment but with other goals. First, [12] propose transmit distance adjustment to guarantee the connectivity of the network. Then [16] propose a distributed topology using directional information to increase the network life.

6. FUTURE WORKS AND CONCLUSION

In this paper, we proposed a power-law gossiping protocol in a static and mobile multi-hop ad hoc networks. Our performance analysis shows that our protocol offers a better power-efficiency than standard gossiping, while its reliability (delivery ratio) and latency are equivalent. This observation is true in a static and more important, in a mobile environment. In terms of future work, improvements in the choice of the transmission range could probably be obtained by taking into account the number of hops messages are going through. It would also be interesting to extend the system model with failures and to evaluate how our power-law gossiping protocol performs in such an unreliable environment. Along that line, we could further extend our model towards more realistic mobility scenarios, such as the *Random Trip Model* [8].

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