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Probabilistic flooding coverage analysis for efficient information dissemination in wireless networks☆

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ABSTRACT

Information dissemination under *Probabilistic flooding* is revisited here in an attempt to realize full coverage in modern wireless networks and at the same time avoid unnecessary transmissions that waste valuable resources. Approaches like traditional flooding, are not suitable in these typically large scale and inherently dynamic environments due to the large number of transmitted information messages. Probabilistic flooding is capable of pruning unnecessary transmissions, while maintaining a large proportion of the network nodes covered. In this paper, an algebraic-based approach is employed to derive an estimation regarding the particular *threshold* probability value that would allow for high network coverage and reduced number of sent information messages. For the analysis' purposes, coverage is studied here and eventually modeled as a polynomial; its higher root being related to the threshold probability. By studying this polynomial's roots, the paper's contribution is twofold: (i) results existing in the open literature are confirmed; and (ii) an algorithm is introduced here to estimate the threshold probability. Simulation results confirm the analytical findings and in addition, they demonstrate that the estimated value derived here regarding threshold probability, is suitable for achieving high coverage and reducing the number of transmitted information messages.

1. Introduction

Modern wireless networks, such as ad hoc, vehicular, sensor and cloud networks, often need to explore certain attributes of the network (e.g., sink node location in sensor networks, nearby vehicles in vehicular networks, cloud management, nanonetworks, underwater broadcasting) and support information exchanges among nodes. The traditional way for *global outreach* employs *traditional flooding* (e.g. [1]), a breadth-first search-based approach that deterministically covers all nodes in any connected network. Although suitable for the wired, small scale network paradigm of the early '80s, this approach is not even an option in nowadays modern network environments that are typically large scale and inherently dynamic. Despite some interesting properties of traditional flooding (e.g., deterministic global outreach, termination time upper bounded by the network diameter) and widespread applicability (e.g., [2–4]), the number of messages sent in the network is significantly large (namely, it is upper bounded by twice the number of links).

An increasing volume of research attention has been observed recently regarding probabilistic flooding (e.g., vehicular networks [5], energy balancing [6], underwater broadcasting [7], advanced probabilistic flooding [8], nanonetworks [9,10]). *Probabilistic flooding* can be seen as a suitable alternative for *pruning* transmissions by employing some fixed probability for message forwarding among neighbor nodes [11]. The basic idea is to employ small values for the previously mentioned *forwarding* probability in order to exclude any redundant links that would not result in *coverage* (i.e., the percentage of nodes that have received the information message) increment. Due to its probabilistic nature, probabilistic flooding cannot deterministically provide a global outreach, rather it guarantees it *with high probability*. Problems start when pruning is more intense than it should (significantly small values for the forwarding probability) and as a result, some nodes never receive the information message. Therefore, the main objective of probabilistic flooding amounts to the derivation of a value for the forwarding probability such that (i) global outreach is achieved; and (ii) the number of sent information messages is minimized. This value of the forwarding probability that sat-

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isfies (i) and (ii) will be referred to hereafter as the *threshold* probability.

There is a close relation between probabilistic flooding and epidemic-based approaches focusing on the epidemic threshold (i.e., the particular value of the spreading over the cure rate for a virus infection to extinguish), e.g., [12–15]. For example, it was shown that the epidemic threshold is inversely related to the *average degree* (i.e., the average number of neighbor nodes) of the network [12] and inversely related to the *maximum eigenvalue* of the network's *adjacency matrix* [13–15]. Motivated by the above mentioned studies, the work presented here considers probabilistic flooding while leveraging tools from the epidemic and graph spectra worlds [16].

The first step is to derive an analytical expression with respect to coverage assuming a certain (even though arbitrary) network topology and a certain *initiator* node (i.e., the particular node that is required to send an information message to the rest of the network nodes). This expression is based on the fundamental observation that only the currently *covered* nodes (those that have just received the information message) may forward the information message during the next time step. Under the assumption that the forwarding probability is small (e.g., smaller than 0.1), the Bernoulli inequality is employed allowing to transform the latter expression into a polynomial (i.e., *coverage polynomial*) of the forwarding probability that captures the number of covered nodes in the network at a specific time instance.

The main contribution of this paper is the subsequent analysis of the *forwarding root* (i.e., the largest and smaller than one root) of the coverage polynomial. Even though analytical results are not available for the general case, it is shown here that the forwarding root converges towards a certain value that is also estimated, indicating the latter as a suitable choice for the forwarding probability or, equivalently, as a lower bound for the threshold probability. These analytical findings are shown to be in accordance with the results in [12,13].

Simulation results support the analytical part. It is shown that the analytical expression regarding coverage, successfully captures the behavior of probabilistic flooding for each individual node. Also, it is illustrated that the forwarding root is actually a lower bound for the threshold probability. If this value is employed as forwarding probability, then high coverage (larger than 95%) is assumed, for all considered topology scenarios. The relevance to the epidemic threshold is also demonstrated to be in accordance with the analytical findings. In addition, the effectiveness of the approach for various topologies that the forwarding probability does not satisfy the Bernoulli inequality (i.e., values greater than 0.1) is also investigated.

In the following, Section 2 presents past related work in the area and Section 3 describes the basic definitions and explores the basics of probabilistic flooding. Section 4 includes the core analysis and threshold probability is studied in Section 5. Section 6 presents simulation results and the conclusions are drawn in Section 7. A table of the main notations as well as the proofs are included in the Appendix.

2. Past related work

Probabilistic flooding is a suitable alternative for traditional flooding for numerous applications and it is still under consideration as new networking paradigms emerge. Stauffer and Barbosa [11] compare its performance against a heuristic flooding approach that changes the (otherwise fixed) forwarding probability. Crisóstomo et al. [17] consider various topologies of stochastic nature in order to derive suitable values for the threshold probability. The case of random graphs is further studied by Oikonomou et al. [18] and asymptotic expressions are derived, while Gaeta and Sereno [19] consider generalized random graphs. Banaei-Kashani and Shahabi [20] perform a criticality-based analysis considering unstructured peer-to-peer networks. In this environment, Tsoumakos and Roussopoulos employ an adaptive probabilistic search [21].

Besides the traditional flooding schemes, there are many approaches that are based on gossip algorithms for information dissemination in ad hoc networks [22]. Gossip-based techniques are widely used in wireless sensor network environments (e.g., [23]) using a flooding-like concept. Chang et al. propose a probabilistic and opportunistic flooding algorithm, where each node chooses a subset of its neighbors to broadcast the information message [24]. A recent work on probabilistic information emission in random geometric graphs is described by Hu in [25], where the emphasis is given on gossip or epidemic algorithms for information broadcasting.

In the area of mobile ad hoc networks, Sasson et al. [26] have proposed a probabilistic broadcast for flooding, while Li et al. [6] present a balanced probabilistic flooding algorithm for wireless sensor networks. Wang et al. [27] propose a link correlation based probabilistic flooding algorithm and Drabkin et al. [28] propose a variation of probabilistic flooding for reliable dissemination. Reina et al. combine various flooding schemes, proposing a probabilistic approach with adaptive probability to ensure low overhead [29]. They also compare their method against traditional and probabilistic flooding. An adaptive probabilistic broadcast strategy based on the wave propagation is proposed by Palmieri [30] and an energy efficient routing algorithm using probabilistic flooding is proposed by Agarwal et al. [31].

Saeed et al. [9,32] propose probabilistic flooding for nanonetworks [10]. Probabilistic flooding is also investigated in underwater environments by Koseoglu et al. [7], whereas vehicular networks have also been the focus by Xeros et al. [33] and Mylonas et al. [5]. An adaptive version for multi-path routing purposes is presented by Betoule et al. [34]. Margariti et al. [8] propose an advanced probabilistic flooding taking into account both the popularity of resources and the hop distance from the initiator node. Lichtblau and Dittrich [35] present a method for evaluation of network-wide broadcast protocols, while Badreddine and Butucaru [36] use probabilistic flooding in their broadcast protocol for wireless body area networks.

An important aspect revealed in this paper is the close relation between probabilistic flooding and epidemic-based approaches focusing on the epidemic threshold. In particular, the work by Wang et al. [13] that relates the maximum eigenvalue of the network adjacency matrix with information dissemination, has been the main motivation for the work presented here. As already mentioned, Kephart and White [12] relate this threshold to the inverse of the average node degree in the network. Pastor-Satorras and Vespignani [37] study epidemic thresholds in scale-free networks, while van Mieghem et al. [14] introduce intertwined Markov chains expanding the previously mentioned results. A thorough analysis and presentation of important results in the area is given in [16]. Lately, Socievole et al. [15] assess network robustness by relating the largest eigenvalue to the viral conductance metric.

As already mentioned, the work presented here confirms the analytical findings from the area of graph spectra [16] and proceeds even further by deriving an approximate value regarding the threshold probability. An earlier version of this paper was presented in [38] that is extended here by both analytical and simulation results that shed further light on probabilistic flooding.

The differences and the similarities of the presented past related works are summarized in Table 1.

An earlier version of this paper was presented in [38] that is extended here by both analytical and simulation results that shed further light on probabilistic flooding. An important improvement