Computer Networks 93 (2015) 342–358

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet

# Time series analysis to predict link quality of wireless community networks

Pere Millan[a], Carlos Molina[a], Esunly Medina[b], Davide Vega[b], Roc Meseguer[b,*], Bart Braem[c], Chris Blondia[c]

[a] Department of Computer Engineering, Universitat Rovira i Virgili, Tarragona, Spain
[b] Department of Computer Architecture, Universitat Politècnica de Catalunya, Barcelona, Spain
[c] Department of Mathematics-Computer Sciences, University of Antwerp – iMinds, Antwerpen, Belgium

ARTICLE INFO

*Article history:*
Received 15 February 2015
Revised 1 June 2015
Accepted 16 July 2015
Available online 9 October 2015

*Keywords:*
Community networks
Link quality tracking
Link quality prediction
Time series analysis

ABSTRACT

Community networks have emerged under the mottos "break the strings that are limiting you", "don't buy the network, be the network" or "a free net for everyone is possible". Such networks create a measurable social impact as they provide to the community the right and opportunity of communication. As any other network that mixes wired and wireless links, the routing protocol must face several challenges that arise from the unreliable nature of the wireless medium. Link quality tracking helps the routing layer to select links that maximize the delivery rate and minimize traffic congestion. Moreover, link quality prediction has proved to be a technique that surpasses link quality tracking by foreseeing which links are more likely to change its quality. In this work, we focus on link quality prediction by means of a time series analysis. We apply this prediction technique in the routing layer of large-scale, distributed, and decentralized networks. We demonstrate that it is possible to accurately predict the link quality in 98% of the instances, both in the short and the long terms. Particularly, we analyse the behaviour of the links globally to identify the best prediction algorithm and metric, the impact of lag windows in the results, the prediction accuracy some time steps ahead into the future, the degradation of prediction over time, and the correlation of prediction with topological features. Moreover, we also analyse the behaviour of links individually to identify the variability of link quality prediction between links, and the variability of link quality prediction over time. Finally, we also present an optimized prediction method that considers the knowledge about the expected link quality values.



## 1. Introduction

Community networks are distributed, large-scale and decentralized networking infrastructures composed of several nodes, links and services where the resources are made available to a group of people living in the same area. Networks of this kind are extremely diverse and dynamic because they are composed of decentralized nodes and mix wired and wireless technologies, several routing schemes and diverse services and applications [1]. The network is managed using an open peering agreement, which avoids barriers for the participation in the network. Governance, knowledge and ownership of the network are open. These networks are, therefore, not only decentralized but also owned and managed by community members. In addition, they grow dynamically with regards to the number of links, their capacity and services provided. Some relevant examples of community networks include guifi.net [2] or FunkFeuer [3].

* Corresponding author. Tel.: +34 934137102.
*E-mail addresses:* pere.millan@urv.net (P. Millan), carlos.molina@urv.net (C. Molina), esunlyma@ac.upc.edu (E. Medina), dvega@ac.upc.edu (D. Vega), meseguer@ac.upc.edu (R. Meseguer), bart.braem@uantwerpen.be (B. Braem), chris.blondia@uantwerpen.be (C. Blondia).

http://dx.doi.org/10.1016/j.comnet.2015.07.021
1389-1286/

These large, decentralized, dynamic and heterogeneous structures raise challenges that can be of interest to researchers, both as a source of inspiration and as a field in which apply their research findings [4]. One of the most important challenges is the effect of the unreliability and asymmetrical characteristics of wireless communications on routing protocols and network performance. Many metric-based routing protocols for mesh networks that track link quality (LQ) and select higher-quality links have been proposed to maximize delivery rate and minimize traffic congestion [5–7]. Hence, LQ tracking is a key method to be applied when routing packets through an unreliable network. Moreover, it has been shown that routing algorithms should avoid weak links whenever possible [8], and as soon as possible [9].

LQ estimation (or prediction) [10,11] is an approach that increases the improvements in routing performance achieved through LQ tracking. Typically, real-time metrics do not provide enough information to detect the degradation or activation of a link at the right moment. Therefore, prediction techniques are needed to foresee LQ changes in advance and take the appropriate measures.

In this work, we present a LQ analysis and prediction of the FunkFeuer wireless mesh community network [3]. To the best of our knowledge, no previous work explores LQ prediction in the routing layer of large-scale, distributed and decentralized systems. The main contributions of this work are the following:

- The use of time series analysis to estimate LQ in the routing layer for real-world wireless mesh community networks.
- Clear evidence that LQ values computed through time series algorithms can make accurate predictions in wireless mesh community networks.
- A detailed global analysis of links to identify the best prediction algorithm and metric, the impact of lag windows on it, its accuracy some time steps ahead into the future, its degradation over time and its correlation with topological features, showing the potential of time series to estimate LQ.
- A detailed analysis of individual links to identify the variability of LQ prediction between links and over time, showing the potential of time series to estimate LQ.
- A hybrid prediction approach that combines a number of prediction algorithms along with a value saturating technique.

This paper is structured as follows. Section 2 gives an overview of prediction in computer networks focusing on link quality. Section 3 presents the experimental methodology used in this work. Sections 4 and 5 describe our proposal and analyse the results globally and locally, respectively. Finally, in Section 6 we provide some concluding remarks and future work.

## 2. Link quality prediction in wireless networks

LQ tracking has been previously applied in several scenarios in different ways [5–7,8,12] to select higher quality links that maximize delivery rate and minimize traffic congestion. LQ prediction/estimation is used in addition to LQ tracking to determine beforehand which links are more likely to change their behaviour. As a result, the routing layer can make better decisions at the appropriate moment. LQE (Link Quality Estimators) [10,11] are in charge of measuring the quality of the links between nodes based on physical or logical metrics. Physical metrics focus on the received signal quality and logical metrics focus on the percentage of lost packets. LQE with metrics like LQI (Link Quality Indication) [13], SNR (Signal-to-Noise Ratio) [14] or RSSI (received signal strength indication) [15] fit in the former category, whereas metrics like RNP (required number of packets) [16], ETX (expected transmission count) [17,18] or PSR (packet success rate) [5] fit in the latter. It is also important to notice, as is shown in [10], that a slight variation in SNR may affect the link quality, changing it from good to bad in a bursty way. All these metrics can be used by LQE in isolation or as a combination of some of them [10,11,19] to select the more suitable neighbour nodes when making routing decisions.

The Four-Bit Wireless Link Estimation method [13] collects information of several layers (physical, link and network) to make LQ predictions that can be decoupled from particular layer implementations while remaining efficient and accurate. A Kalman Filter approach [15] estimates the received signal strength (RSS), then takes this value to evaluate the SNR and finally approximates the Packet Success Rate (PSR) in a way that can adapt fast enough to the temporal dynamics of the links. There are some other studies [14] that conclude that including SNR information significantly improves wireless LQ prediction. The Holistic Packet Statistics (HoPS) [19] approach applies EWMA (Exponentially Weighted Moving Average) filters to calculate several metrics that help evaluate the short-term and long-term quality link, its variation and evolution over time. On the other hand, the WMEWMA estimator (Window Mean with Exponentially Weighted Moving Average) [5] predicts LQ of sensor networks based on the Packet Success Rate (PSR) in a simple, memory efficient and fast reacting way.

The analysis of the most important network properties for the design of efficient routing protocols leads to the conclusion that the required number of packets (RNP) that must be sent before a packet is received is a precise LQ estimator [16]. Based on this metric, distributed and centralized routing algorithms are proposed to improve efficiency of networks with low power links. ETX has also been proved to be a good metric for LQ estimation [17], particularly with larger networks with longer paths. For instance, when the DSDV and DSR routing algorithms are adapted to include the ETX metric, the overall performance of the network is significantly improved. The ETX_ANT algorithm [18] is a simple approach that predicts ETX values a few seconds in advance. This estimation assumes a linear regression method, which is applied to a variable number of last ETX measurements.

Special attention must be paid to the MetricMap mechanism [20]. MetricMap is fundamentally a routing protocol for wireless sensor networks that uses a learning-enabled method for LQ assessment. Based on the observation that high traffic rates make tracking link qualities more difficult, this protocol uses prediction methods to estimate them in advance. In a first stage, a machine-learning algorithm is applied to classify link qualities. Two types of classifiers are