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Decorrelation of networked communication flow via load-dependent routing weights

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Abstract

Clever assignments of link weights are able to change communication routes in such a way that loads are distributed almost evenly across a network. This is achieved by weight assignments based on the link load. As demonstrated for scale-free as well as synthetic Internet networks, they decorrelate the loads of the nodes and links from the network structure and increase the transport capacity of the network. For various Internet scans the increase of transport capacity amounts to a factor of around five when compared to shortest-path routing.

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1. Introduction

The Internet is a complex networked system. It is not necessarily the many tiny operational details on a protocol level [1,2], which are of interest to the physics community, but getting the big picture right, where complexity reduction and coarse graining are needed to increase our understanding of its generic functioning [3]. The scale-free discovery of the Internet topology at the autonomous system (AS) level represents a fine generic example [4]. It helped to trigger the Statistical Physics of complex networks [5–7], which in turn has refined the network-structure description of the Internet and has led to the development of sophisticated topology generators [8–14]. Another example of the physics impact on the understanding of the Internet is the cellular-automata-like modelling of packet traffic, which has allowed one to describe phase-transition-like behaviour on firmer grounds [15–19] and which has led to the development of new, dynamical routing concepts [20–24]. More physics-driven network performance analysis has concentrated on the increase of the overall network performance. The modification of network structure [25,26] and

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the introduction of additional bandwidth [27] are suited to reduce the end-to-end time delay and to increase the transport capacity. Such approaches are of obvious interest to engineers, Internet service providers and users.

The increase of transport capacity is also possible by other means. By using the given network layout, a routing metric cleverly assigns certain weights to the nodes and links of the network. The resulting communication routes reduce the loads of those nodes and links, which restrain the overall network performance. Current Internet routing protocols [28] can use various different metrics based on hop-count, bandwidth, actual load and round-trip time, and reliability as well as cost. However, current implementations come with drawbacks. For example, the actual load fluctuates over time and often leads to unstable routes. Moreover, implemented routing protocols like RIP (Routing Information Protocol) [29], EIGRP (Enhanced Interior Gateway Routing Protocol) [30] and OSPF (Open Shortest Path First) [31] are confined to the intra-AS level. The most commonly used inter-AS routing protocol, the BGP (Border Gateway Protocol) [32], is mainly based on the simple hop metric. Exactly here there is room for improvement. This is another chance for a physics-driven approach, this time with weighted networks [33–35], to design new efficient weights for inter-AS Internet routing.

Inspired by the properties of the underlying nearly scale-free network structure, Ref. [36] has proposed to use the node degree as a routing weight. This leads to a load reduction of the most-loaded nodes. More load reduction has been pointed out in Refs. [37–40], which have coupled the routing weights directly to betweenness-centrality-based loads. In detail, Refs. [37,38] have proposed an iterative scheme which turns a heterogeneous load distribution into a homogeneous one. Refs. [39,40] have proposed an extremal-optimization algorithm which minimizes the maximum node betweenness by iteratively assigning additional weight to the most-loaded node.

The weight assignments of Refs. [36–40] have all been node-based. In this form they are not directly appropriate for today's AS-level Internet. Since each full-duplex router can simultaneously transmit and receive data packets on all its links, it is not the capacity of the nodes themselves, but the bandwidths of the links, which limit the overall transport capacity. Consequently, weights should not be assigned to nodes, but to links.

We want to discuss various link-based weight assignments and find out which of them are most efficient with respect to the transport capacity of Internet-related networks. In Section 2 we list several routing weight assignments for links, which are straightforward generalizations of their node-based precursors [36–40]. Section 3 focuses on synthetic scale-free networks and discusses first consequences like load distributions and decorrelation effects between loads and degrees. Based on an analytic expression for the transport capacity of the network, the different routing weight assignments are rated according to their efficiency. Section 4 sends a clear warning when trying to carry over the previously obtained results to synthetic Internet topologies at the AS level, and forces us to improve on the routing weight assignments. Real AS-level Internet topologies are discussed in Section 5, and it is shown that compared to BGP-like shortest-hop routing the most efficient new routing weight assignments are able to improve the overall transport capacity by a factor of about five. A conclusion and an outlook are given in Section 6.

2. Routing weight assignments

In a communication network, the routes are determined by the routing metric. It assigns weights $w(n)$ and $w(l)$ to all N_n nodes and N_l links of the network. They define the distance

$$d(i,f) = \sum_{n=1}^{N_n} w(n)\mathrm{route}(i,f;n) + \sum_{l=1}^{N_\mathrm{l}} w(l)\mathrm{route}(i,f;l) \quad (1)$$

between an initial and final node i and f along a specific route. The index function $\mathrm{route}(i,f;x)$ is equal to one if the node $x=n$ or link $x=l$ belongs to the route, and is equal to zero else. The shortest route

$$\mathrm{sroute}(i,f) = \arg(\min d(i,f)) \quad (2)$$

between nodes i and f comes with the minimum distance. Those define the load of a node and a link,

$$L(n) = \sum_{i,f=1}^{N_n} \mathrm{sroute}(i,f;n), \quad (3)$$