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Network nodes play a game – a routing alternative in multihop ad-hoc environments☆

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ABSTRACT

A key aspect to consider in delivering data from one node to another in a communication network is finding a suitable path through the relaying nodes, i.e., routing. The standard routing solutions work well in the reliable networks, but do not achieve acceptable performance in low-power, noisy, and dynamic environments due to the high overhead associated with establishing a consistent view of the network. The paper presents a different solution to the problem of data delivery based on an evolutionary game between the network nodes. In the proposed approach, instead of forming a fixed path, the nodes take independent forwarding decisions. The set of nodes participating in the data transfer self-adjusts to the current networking conditions by playing the game, without involvement of a control plane. As a result, a low-overhead alternative to routing is obtained. The proposed solution is particularly well suited for the ad-hoc wireless networks serving time-sensitive data, e.g., it can provide an efficient communication platform for low-cost networked control systems.

1. Introduction

Recently, a growing interest can be observed in the environmental, military, and industrial applications that require cooperation of a set of independent devices to perform a desired task. The devices communicate using a wireless network, typically operating in a centralized topology. However, also the self-organizing architectures without a designated node are considered. Depending on the objectives and physical technology involved, the considered class of networks encompasses the ad-hoc, sensor, BAN, VAN, radio, and acoustic ones, jointly refereed here as non-govern networks (NGN). Due to economical reasons, the devices in NGN are equipped with low-end processors and have installed limited amount of memory, that is usually insufficient to queue the relayed messages. While problematic for the delivery of streaming data, the NGN-based communication platform is suitable for the transfer of real-time data, e.g., in networked control systems (NCS) where both the latency and jitter need to be limited even at the cost of an increased drop ratio (that is inevitable anyway and requires handling at a higher level [1–3]). In fact, the application of NGN in NCS is quite common today and broadens in scope encompassing, e.g., security and safety systems, or autonomous control settings [4–6].

In the centralized topologies, e.g., 802.11, or 802.16, all the nodes communicate through a designated one that governs the network. However, the systems formed in this way are susceptible to the central node faults and bottlenecks. The centralized solution also suffers from the detrimental effect of delays which downgrade the application-level experience, e.g., they reduce the control quality in NCS [7–9]. Another issue to consider is the overhead associated with the communication control plane. In the high-performance networks, the volume of control traffic (media access, routing, reservation, etc.) is negligible when compared to the total network throughput. However, when the overall network performance related to serving the actual user data decreases, the communication control plane does not scale proportionally. In effect, the throughput-to-bandwidth ratio diminishes, which is hardly acceptable for the low-end devices in NGN.

Alternatively to the centralized one, a distributed solution, where the traffic is relayed from a source to its destination along a chosen data path, can be applied. The selection of the set of nodes forming the path is typically performed by a routing protocol. However, the existing routing solutions for NGN [10] (some even standardized [11]) are subject to serious constraints, like fixed topology, or a limited number of intermediate nodes. Moreover, the routing procedures themselves may result prohibitive in terms of the consumed resources at low-end devices.

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Therefore, in this paper, a different approach is investigated. The idea is to replace the communication control plane by a dynamic game played by the network nodes, implemented in a decentralized manner.

Each node (player) participating in the game takes an independent decision whether to forward a received message or not, and is accordingly awarded (or penalized) for its actions. The decision is based on the observation of the environment (noise), result of previous attempts, and success of neighboring nodes. The information related to the environment is acquired from the fields in the data frame only. By removing the need for routing, small protocol footprint and low resource consumption are ensured. In the paper, a protocol for message exchange among the nodes is developed and methods of node activity adjustment so that high throughput is achieved are formally explored. Moreover, guidelines for the practical assessment of node behavior in the physical, data link, and network layer are provided.

The paper is organized in the following way. Section 2 gives a brief account on the game theory achievements in the analyzed class of applications. In Section 3, the fundamental problems and design challenges are discussed, with specific theoretical considerations given in Section 4. The description of the proposed message exchange protocol is provided in Section 5 and the game formal analysis in Section 6. The results of simulation experiments are presented in Section 7. Finally, Section 8 comprises the conclusions.

2. Game-based approach in relevant networking problems

While game theory has been intensively applied in economics for many years, it became recognized and gained popularity in network engineering only recently [12,13]. The commonly addressed problems, treated separately in the literature, are the bandwidth sharing by wireless terminals (the shared spectrum game) [14] and multihop transmission [15]. The reported solutions rely on external knowledge of the network (e.g., the node position) [16]. Some authors also consider the imperfect information game where the nodes are independent of each other [17]. A major drawback of the previous game-based approaches to the networking problems is the difficulty of translating the obtained theoretical results to the resource-constrained physical devices. Due to the substantial resource requirements – complex, usually floating-point, computations, and large memory – the previously reported algorithms can hardly be implemented in low-end nodes, and thus are impractical from the perspective of NGN.

The approach presented here combines the shared spectrum game with the multihop one using an evolutionary strategy for adjusting the node forwarding activity to the dynamically changing networking conditions. By incorporating the measurements provided by the designed message exchange protocol, the imperfect information game turns into a perfect one. As a result, the high-complexity obstacle of game-theory-based solutions in the considered class of problems is overcome.

3. Problem statement

In order to effectuate a successful transmission between a set of nodes using low power and unreliable channels, at least two general issues need to be taken into account: (1) selection of a proper transmission path in a dynamic topology and (2) the influence of noise (interference). Typically, both problems are considered separately [16,18], which is justified in wired networking or a mixed one, when only the first mile is implemented as a wireless link. It may also be suitable for backhaul networks, or when the transmission system is governed by a single controller. In the case of networks with distributed control logic, performing the path selection without taking into account the channel reliability or load is inappropriate [19]. The problem of efficient load balancing within the shared spectrum environment is considered, e.g., in [16,20]. However, these works restrict the problem scope to direct communication, i.e., without involvement of intermediate nodes.

In this work, the issue of finding a suitable data path for balanced NGN performance is addressed with explicit consideration of the noisy environment.

3.1. Application area

The communication solution presented in this paper is primarily intended for the networks that provide the information exchange platform for real-time connectivity, e.g., in the NCS and Internet of Things environments. In such environments, the cost of equipment and energy expenditure should be kept to a minimum, which involves simplified electronics in both the end-points and intermediate nodes (thus characterized by limited amount of memory and small computational power). On the other hand, the considered application area imposes stringent requirements with respect to the latency of message transfer between the communicating parties. Taking as an example NCS, if the relevant information in the feedback loop is not received within specified time limits, the control quality degrades and the regulated system may even loose stability (e.g., as in the cart movement control in an automated warehouse). The late (outdated) messages are not only useless for the control process [7–9], but their delivery consumes the energy and network resources, and in the case of dense networks creates another source of interference for the legitimate transmission.

The standard connectivity solutions for the short-range communication and inexpensive devices were designed with the streaming applications in mind, i.e., for the applications where the completeness of data received at the destination is crucial, and the time of delivery is given secondary importance. In consequence, these solutions often result in long queues at the nodes and require implementation of an ARQ mechanism at each hop (or the transport and application layer acknowledgements), leading to prolonged delays. The real-time applications, including interactive telephony, or the mentioned above NCS, tolerate the occasional disruptions in the continuity of the received data (packet losses), but are sensitive to delay and its variation [21]. The communication solution proposed in this paper responds well to the challenges of real-time data transfer. From the point of view of a typical routing protocol, it resembles the ones based on multiplicative metrics. However, it is free from the defects of the classical routing (e.g., path flapping) discussed in the seminal paper [19]. The price to pay is the occasional data loss.

3.2. Game-based message forwarding

The basic idea behind the proposed communication solution originates from the human perception of the ordinary mail delivery process and the associated game theory concepts. Assume the sender's objective is to deliver a series of packages using an unverified broker. First, a single package is passed to the broker. If the sender sees that the broker is effective in the package transfer, then the broker's reputation grows, and it may be asked for assistance in further deliveries more willingly. Otherwise, the broker's reputation decreases according to the reason of failure – sluggish performance, malfunctioned delivery truck, or, perhaps, dishonesty in stating the reasons of failure. The assessment of broker's (or the next hop in network transmission) reputation determines the sender's strategy.

In the context of communication networks, one may consider the transmission scenario illustrated in Fig. 1. The message deliv-