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A MDP Approach to Fault-Tolerant Routing

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This paper defines a theoretical framework based on Markov Decision Processes (MDP) to deal with fault-tolerant routing algorithms in heterogeneous networks, which are realized through the integration of assorted wired and wireless telecommunication technologies. Such kinds of networks are characterized by fast dynamics of link availabilities, mainly due to the extensive use of wireless technologies. The novelty of this paper is the formulation of the fault-tolerant routing problem as a MDP, which is used to compute the optimal re-routing policy. As in existing fault-tolerant algorithms, when a path becomes unavailable, the traffic flows transmitted over that path are re-routed on another available path; the novelty is that the new selected path is the one that minimizes re-routing occurrences, since it is selected taking into consideration the probability that also the alternative paths can become unavailable in the future. As a by-product, the optimal path selection for new traffic flows is also obtained. Simulations show the effectiveness of the proposed approach.

Keywords: Markov decision processes, routing, fault-tolerant, communication networks, stochastic control.

1. Introduction

To support a variety of high capacity demanding applications (data, audio, video), next generation networks will be realized through the integration of heterogeneous wired (e.g., Ethernet, Power Line Communication (PLC), Optical Fiber (OPT)) and wireless (e.g., Wi-Fi, Ultra Wide Band, WiMAX, LTE) telecommunication technologies. In hybrid (i.e., meshed wireless and wired) networks, frequent topology changes occur due to the scarce robustness of some technologies, which cause the link availability to be time-varying. In fact, due to their nature, wireless and also wired technologies (e.g., PLC) are characterized by high probability of link faults (i.e., links becoming unavailable): for example, PLC systems suffer from interference due to the use of electrical power by home appliances [16]; Wi-Fi communication systems suffer from interference due to other communication systems using the same frequency spectrum [9].

The objective of these high-capacity networks is to provide new multimedia services (such as high-definition TV (HDTV) on-demand or high-quality video-conference) characterized by large bitrate, long flow duration and tight Quality of Service (QoS) constraints (e.g., in terms of delay and delay variation). To guarantee the required QoS to these flows, they are subject to an admission control procedure, in charge of deciding if the flow can be supported by the network based on current traffic and network conditions, and to a routing protocol, which decides the path to be used for the transmission. Other services, such as web browsing, emails, P2P, are low-bitrate services and/or 'elastic' services (i.e., they adapt their transmission bitrate to the available capacity), and do not have strict QoS requirements; thus, they are less impaired by link faults, and are regarded as background traffic with lower priority with respect to the high-quality flows.

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In the case of home networks, taken as reference example due to their actual evolution from mono-technological networks to multi-technological next generation networks, the number of high-quality flows is likely to be small (at maximum, 5–10 simultaneous flows). Therefore, given the scarce robustness of wireless and PLC technologies, the link availability dynamics due to link faults become even faster than the high-quality traffic dynamics (i.e., birth and termination of high-quality flows). In the case of wider networks supporting QoS, analogous considerations are relevant as flows with similar QoS are usually combined in a small number of aggregated flows.

In this scenario, the routing algorithm has to be fault-tolerant, in the sense that it should be able to rapidly re-route on-going flows as soon as a link become unavailable in the path: in fact, as a link becomes unavailable, all the flows crossing that link have to be re-routed on other paths. This re-routing event should be avoided as far as possible, because i) during the re-routing process, some packets are likely to be lost (affecting the QoS of the flow), and ii) the re-routing process involves additional control communications, which reduce the capacity available to data communications. If the network supports classes of service to offer QoS guarantees, decisions upon the re-routing of flows should be based also on their classes of service. For instance, re-routing a flow is likely to cause jitters in the flow transmission (i.e., a variation in the transmission delay of flow packets): such jitters are insignificant in case of data flows, whereas in case of video flows they affect the quality experienced by users.

1.1. State of the Art

Existing routing algorithms are classified either as proactive (e.g., [3, 14, 33]) or as reactive (e.g., [12, 25]). The former algorithms continuously update path information, which is then available at algorithm decision time; the drawback is that these algorithms require the knowledge of the topology of the whole network. Reactive algorithms performs a route discovery procedure on-demand, i.e., only at routing decision time: on the one hand, they generate less control information since they must not continuously update topology information; on the other hand, they delay the actual data transmission until the path is discovered.

Clearly, the proactive approach is preferred in the considered scenario due to the fast re-routing requirements. Proactive routing problems have been successfully modeled as Markov Decision Processes (MDP[1]), with the objective of maximizing the number of on-going flows supported by the network (e.g., [6, 13, 18, 19, 20]). However, in the MDP formulations introduced so far, the topology of the network is considered as static, and the dynamics of the MDP is driven by traffic events (e.g., acceptance of new flows, flow terminations, flow variations); the routing problem is then to decide the optimal paths of the on-going flows. As topology events such as link faults occur, the MDP must be re-defined and the optimal policy must be re-computed. This approach is then not suitable to provide fast re-routing.

Fault-tolerant routing algorithms have been proposed in the mobile ad-hoc networks scenario. In [15, 17, 31, 32, 34], robustness is achieved by redundancy: the source node sends the same packets along all the different paths available between the source and the destination; these multipath routing mechanisms are not suitable for the scenario considered in this paper, since sending multiple copies of high-bitrate flows over different paths would rapidly flood the network. Also in [35], a multipath routing algorithm is proposed, which is capable of significantly reducing the packet overhead by dynamically identifying unavailable paths via end-to-end path performance measurements. In [22], a stochastic learning-based weak estimation procedure is used to minimize the overhead while guaranteeing a certain level of packet delivery. By the way, since also [35] and [22] use duplicate packets to achieve robustness to faults, they are not efficient in case of high-bitrate flows: the algorithms would flood the network with packets before convergence to the new paths. Finally, in [24] an adaptive distributed routing algorithm is presented. By maintaining several paths between the source and the destination, this algorithm allows to reduce the delay introduced to perform the re-routing in case the used path fails, since the new path to be used is already set up, but it does not optimize the choice of the new path to be used. In conclusion, all the algorithms proposed so far are not aimed at minimizing re-routing events, which, as already discussed, can lead to a degradation of the QoS of the provided services in highly variable networks.

1.2. Innovative Fault-Tolerant Routing Concept

Up to the authors' knowledge, all the fault-tolerant algorithms in the literature deal with the fast provision of alternative paths in case of link faults, but no algorithm is concerned about the optimality of the selection of the new path. Therefore, the aim of the proactive algorithm developed in this paper is to set up an optimization framework for the selection of alternative paths in case of link faults. In this respect, the algorithm objective is to select these alternative paths in such a way that re-routing occurrences are minimized. Recalling that, in the considered network scenario, topology dynamics are faster than traffic

[1] MDPs are stochastic control processes, and provide a mathematical framework for optimization problems involving both random events and decision makers [7].