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Game-theoretic model of asymmetrical multipath selection in pervasive computing environment

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ABSTRACT

In order to transfer the ever increasing multimedia data we need to make use of multiple paths to realize the bandwidth aggregating. In pervasive computing environment, the combination of ubiquitous overlay networks and the capacity of multihoming can provide the possibility of exploiting plentiful available paths. Thus, we introduce a Pervasive Multipath Architecture (PEMA), in which we use the game theory to investigate the selfish strategic collaboration of multiple heterogeneous overlays when they are allowed to use the massively-multipath transfer. Overlay networks are modeled as "players" in this multipath selection game, and we study the asymmetric case where all overlays have different Round Trip Times (RTT) and different degrees of waste. We demonstrate the existence and uniqueness of Nash equilibrium (NE). In addition, we find that overlays differing only in their *RTTs* still receive proportional throughput shares and utilities at the NE. However, if overlays differ only in their degrees of waste, a more wasteful overlay has a larger utility and a larger throughput (bandwidth) share than a less wasteful overlay. Since maintaining connected paths consumes resource, we further consider a more generalized cost function where an overlay's total resource consumption includes both transferring data packets and maintaining path connections. In this general game, we find that the overlay is more conservative, which opens smaller number of paths and obtains smaller efficiency loss at the NE than in other simplified games. Our simulations confirm the effectiveness and friendliness of multipath transfer for a range of path numbers and in the presence of multi-overlay traffic.

1. Introduction

By using the ubiquitous and overlapping access networks, our world has been interconnected as a pervasive computing environment consisting of massive intelligent network devices, which can process and transport information to adapt to the associated context and activity. It is challenging to enable multiple access networks to cooperate autonomously to realize the ubiquitous access and multipath transfer between any two end hosts. In this environment, the multipath transfer technologies [1,2] have gained more and more attention from academy and industry, which could maximize the use of network resources and multiply the available bandwidth. On the other hand, traditional routing policies are restrictive, which limits the communication between source–destination pairs to only one path, although there often exist more than

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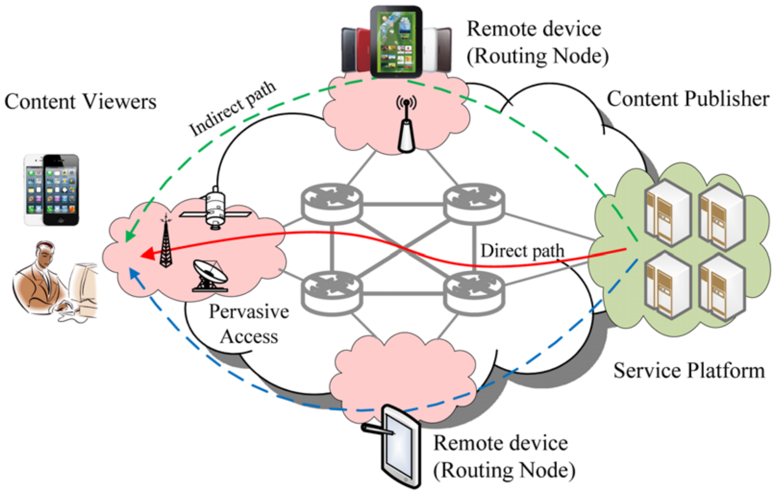

Fig. 1. A multi-homing and overlay network with multiple path support.

one indirect paths through the overlay routing via overlay peer(s). Earlier studies [3,4] have demonstrated the benefits of overlay multipath transfer to achieve high available bandwidth, good loss patterns and bounded delay in the best-effort Internet environment. As the last mile bandwidth has been set to increase dramatically over the last few years, as shown in Fig. 1, we expect that bottlenecks will be shifted away from the network edges and the end-to-end data transfers will be constrained by the capacity of core links. Thus, we will have the opportunity to exploit path diversity and use multiple routing paths concurrently to fully saturate the available core link bandwidth for high-volume data transfers, e.g. video streaming or inter-datacenter bulk transfers.

In this system, end users are effectively provided with a large set of potential paths from which they choose a small subset of paths to improve the performance. As the selected paths may negatively affect each other and the underlying network, there is a need for the management system that controls and adapts their behaviors to meet their specific demands and those of the network and service providers. The following questions arise naturally: How many paths are required? How can we design a multipath selection mechanism that only opens the necessary and sufficient number of paths to exploit the multipath transfer capability? One of the main objectives of the multipath selection is to establish a number of rules guaranteeing that common resources are fairly shared among all the overlays. In most prior models, it has been assumed that each flow is assigned a single path between its source and destination. However, in multipath models each flow can be split into multiple paths simultaneously by a unified control. As using excessive paths can degrade the overall system performance, we should select the number of paths as small as possible. Selfish overlay networks are often accused to be unfriendly when they share network resources with traditional or other overlay flows. As the paths are shared between many flows, the greedy selection behavior can easily lead to unstable network state. The cooperation is hard to maintain due to the characteristics of selfish overlays. Even if Nash equilibrium (NE) appears, it may not be optimal. The number of paths used by each application is determined by the multipath selection according to the observed qualities of total networks.

In this paper we analyze a scenario where multiple selfish overlays deliver their traffic in a shared multipath network infrastructure between the common source and destination. By using a game-theoretic framework, we study the impact of selfish behaviors of overlays when multipath transfer is allowed. One of our motivations comes from the observation that more and more users use Peer-to-peer (P2P) applications (e.g., PPLive, BitTorrent) to construct the overlay network to realize the efficient multipath transfer. For example, PPLive maintains 4 active paths and an additional path periodically chosen at random according to the throughput measured. In our scenario, a number of overlays compete for the capacity of a single bottleneck link. Overlays are modeled as "players" in the game, where each player has infinite amounts of data to send and is allowed to open a number of concurrent paths. The criterion of optimality is trying to maximize each player's utility function, which is a combination of a payoff and a cost.

We assume that the payoff received by a player is a continuous, concave and increasing function of its received data throughput. Regarding the cost, the player is concerned with the number of its paths. This cost accounts for the cost of maintaining the paths opened, which is specific to the overlay. In this game, a pure-strategy Nash equilibrium [5] is a vector of the numbers of paths of all overlays, and each player cannot benefit from unilaterally deviating from this NE.

We investigate the effect of the number of TCP paths on the network performance with a focus on a game-theoretic study of selfish player behaviors. We assume that each player uses "standard TCP" and is allowed to choose the number of concurrent paths. Our result for multipath networks presented in this paper is consistent with the following conclusion drawn in the traditional unipath networks [6]: when the users use TCP New Reno loss-recovery [7] in combination with drop-tail queue management, the equilibrium strategies of the users are quite efficient for fair resource allocation. Although playing NE is fair, it does not guarantee that each player be given the best possible reward. When the players are non-

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