

# Performance–Cost Trade-Off Strategic Evaluation of Multipath TCP Communications

Stefano Secci, *Member, IEEE*, Guy Pujolle, *Senior Member, IEEE*,  
Thi Mai Trang Nguyen, *Member, IEEE*, and Sinh Chung Nguyen

**Abstract**—Today’s mobile terminals have several access network interfaces. New protocols have been proposed during the last few years to enable the concurrent use of multiple access paths for data transmission. In practice, the use of different access technologies is subject to different interconnection costs, and mobile users have preferences on interfaces jointly depending on performance and cost factors. There is therefore an interest in defining “light” multipath communication policies that are less expensive than greedy unconstrained ones such as with basic multipath TCP (MP-TCP) and that are strategically acceptable assuming a selfish endpoint behavior. With this goal, we analyze the performance–cost trade-off of multi-homed end-to-end communications from a strategic standpoint. We model the communication between multi-homed terminals as a specific non-cooperative game to achieve performance–cost decision frontiers. The resulting potential game always allows selecting multiple equilibria, leading to a strategic load-balancing distribution over the available interfaces, possibly constraining their use with respect to basic MP-TCP. By simulation of a realistic three-interface scenario, we show how the achievable performance is bound by the interconnection cost; we show that we can halve the interconnection cost with respect to basic (greedy) MP-TCP while offering double throughputs with respect to single-path TCP. Moreover, we evaluate the compromise between keeping or relaxing strategic constraints in a coordinated MP-TCP context.

**Index Terms**—MP-TCP, multihoming, load-balancing, network coordination, routing games.

## I. INTRODUCTION

**I**N the recent few years, mobile terminals have been equipped with several network interfaces. 3G terminals have integrated Wi-Fi and bluetooth antennas. Laptops often have Wi-Fi, Ethernet and 3G accesses. 4G terminals are going to have LTE-A and WiMax interfaces. Indeed, multihoming for mobile terminals becomes a desirable feature because it can provide users with ubiquitous access, enhanced Quality of Experience (QoE) and application performances.

At the Internet Engineering Task Force (IETF), novel protocols such as Stream Control Transmission Protocol (SCTP) [2], Level 3 Multihoming Shim Protocol for IPv6 (SHIM6) [3],

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The authors are with Sorbonne Universites, 75005 Paris, France (e-mail: Stefano.Secci@upmc.fr; Guy.Pujolle@upmc.fr; Thi-Mai-Trang.Nguyen@upmc.fr; Sinh-Chung.Nguyen@upmc.fr).

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Host Identity Protocol (HIP) [4], multiple Care-of Addresses registration in Mobile IPv6 (mCoA) [5] and Multipath Transmission Control Protocol (MP-TCP) [6], [7] have been proposed as possible solutions. Among them, SCTP can be considered as the first transport protocol supporting multihoming. Many studies based on SCTP, especially the proposition of Concurrent Multipath Transfer (CMT) [8], have been carried out to enable the simultaneous data transmission over multiple end-to-end paths. SHIM6, HIP, and mCoA are multihoming IP-level protocols for end-hosts. More recently, MP-TCP has been proposed as an extension of TCP to support multihoming, interoperable with the legacy Internet, scalable and with other nice deployment advantages as described in [9].

The concurrent use of multiple interfaces as allowed by MP-TCP can obviously provide users with a better throughput [10]. However, a greedy use of different access technologies may be costly under common per-usage billing schemes. For instance, 3G and 4G accesses are typically more expensive than Wi-Fi or Ethernet ones, due to the use of licensed bands. Certainly, the majority of multi-homed mobile users prefer to use inexpensive technologies as much as possible while maintaining an acceptable performance. The trade-off between performance and cost is therefore subjective, and it seems therefore quite interesting to offer users tools to control it. The specification of such tools is certainly out of scope of the IETF. In fact, the MP-TCP specification and current implementations fully use the available interfaces, which can produce, for example, fast file transfers and better-quality real-time communications. However, in practice, the majority of the users is not willing to greedily use all interfaces concurrently because of performance–cost trade-off preferences.

Efficient in lossy wireless access environments [11], the usage of multiple paths in TCP communications has been also considered for wired environments; e.g., it can lead to important performance improvements in multipath datacenter environments [12]. Actually, research on the topic essentially concentrates on multipath transmission performance improvement, for instance, on joint congestion control of the multiple subflows as in [13] and [14], on reordering avoidance in heterogeneous environments as in [15], or stochastic scheduling as in [16]. Opportunistic load-balancing techniques over multiple interfaces with MP-TCP have been proposed in [17] and [18], exploiting end-to-end path delay information to ensure that an efficient load distribution is offered. However, there is no work as of our knowledge that investigates on the performance–cost trade-off, and that proposes strategic multi-homed load-balancing mechanisms to constrain the basic greedy mode of MP-TCP.

Commonly, the methodology adopted to appropriately model multi-decision-maker situations is game theory. In networking, both selfish highly conflicting scenarios, and cooperative scenarios can be modeled with non-cooperative and cooperative game theory. A large number of works have applied game theory principles to networking, for example to topology design [19], network formation [20], Internet routing [21] and wireless access control [22] problems.

In this paper, we adopt a game-theoretic approach to model and control the load-sharing over multiple paths in an MP-TCP communications context. We model the communication between multi-homed endpoints as a non-cooperative game with two independent cost components<sup>1</sup>; a game modeling is appropriate for these situations because each terminal’s utility is not only affected by its outgoing interface decision, but also by the other endpoint’s decision on its incoming interface decision. The game is a combination of an interconnection cost game, built upon access link costs, and a performance game built upon one-way delays; a trade-off coefficient combines the two games. The result is a particular potential game deciding on the load-sharing equilibrium strategy applied over multiple paths; we can explore the trade-off frontier, tuning a minimum-potential threshold, to pass from single-path to multipath solutions, with an increasing path diversity and, therefore, an increasing QoE performance. We present how, in practice, a related application can be conceived. To evaluate different trade-off strategies, we extend an existing MP-TCP implementation. By simulation of a realistic three-interface scenario we show how our strategic load-sharing framework can control the trade-off, highlighting the price to pay (to allow strategic interactions among endpoints) in terms of throughput, and the related savings in terms of interconnection cost, in comparison with greedy MP-TCP and basic TCP. In particular, we can halve the interconnection cost while doubling the throughput with respect to basic TCP. Our model is valid for situations in which the achievable throughput with greedy MP-TCP is more than really needed, with a user modestly requiring a moderate increase of throughput with respect to basic TCP, at a reasonable interconnection cost.

The paper is organized as follows. Section II presents the multihoming game framework. In Section III we propose a policy to control MP-TCP subflow load-balancing. In Section IV, we evaluate the proposition on a three-interface sample setting. In Section V we show the effect of relaxing strategic constraint. Section VI discusses some implementation aspects. Finally, Section VII concludes the paper.

## II. THE MULTIHOMING GAME

In this section, we present how to model the communication between two<sup>2</sup> multi-homed endpoints with non-cooperative game theory, to select coordinated load-balancing decision

<sup>1</sup>The dual modeling approach for single-decision maker situations is often referred to as multi-objective optimization. Game theory modeling multi-decision-maker situations, our framework describes a multi-decision-maker situation with two objective components.

<sup>2</sup>It is worth noting that modeling more than two endpoints in the multihoming game would not make technical sense in MP-TCP communications.

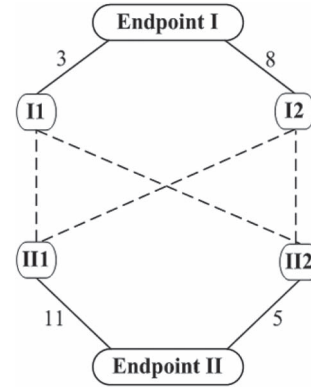


Fig. 1. Example cost setting between two multi-homed endpoints.

strategies. We start with a simple game setting, dealing with interconnection costs only, and then we gradually develop the model.<sup>3</sup> A game modeling is appropriate for these situations because each endpoint’s utility is not only affected by its outgoing interface decision but also by the other endpoint on its incoming interface decision.

### A. Modeling Scenario

Let us consider the case where two multi-homed MP-TCP endpoints exchange an equivalent amount of data via multiple available paths. For the sake of modeling generality, it is worth noting that, while the multi-homed endpoints can be both mobile endpoints (peer-to-peer situation), more generally, the model we introduce in the following can also encompass situations with multi-interface server endpoints with, or without, performance–cost preferences (for instance, servers translating network-level preferences over egress paths into server-level preference over egress interfaces, e.g., enforced by different VLANs in a data-center environment). These paths use different interfaces, such as physical Ethernet interfaces, virtual Ethernet interfaces, as well as wireless Wi-Fi, 3G, 4G, and bluetooth interfaces, which have various characteristics in terms of connection cost, bandwidth, and delay. Aiming to improve their connection performance while considering the user interests, endpoints can announce to each other their respective interface preferences. For example, an endpoint may prefer Ethernet to 4G because the Ethernet interface is faster and less expensive.

As a first step, let us model the interaction between the two endpoints as if they did not coordinate the interface path decision. In this case, an endpoint autonomously decides on the destination endpoint’s incoming interface, impacting an interconnection cost to the destination endpoint for the incoming flow. For the moment, we do not consider the outgoing interface selection to emulate, therefore, the basic MP-TCP behavior, which fully uses the outgoing interfaces without considering their possible interconnection cost. For example, in Fig. 1 the endpoints I and II have two interfaces each, with associated interconnection costs. Taking into account the interconnection cost impacted by the other endpoint decision, we have the

<sup>3</sup>Note that we voluntarily set the first base games as partially unrealistic, but it is useful to introduce them as such to ease the understanding of the complete game modeling.

TABLE I  
FIG. 1 GAME WITH INCOMING INTERCONNECTION COST ONLY  
(UNCOORDINATED SUBFLOW ROUTING)

I \ II	I1	I2
II1	3,11	8,11
II2	3,5	8,5

TABLE II  
FIG. 2(a) GAME EXAMPLE WITH TWO-SIDE BIDIRECTIONAL  
INTERCONNECTION COSTS (COORDINATED SUBFLOW ROUTING)

I \ II	$S_1D_1$	$S_1D_2$	$S_2D_1$	$S_2D_2$
$S_1D_1$	6,22	11,22	<b>6,16</b>	<b>11,16</b>
$S_1D_2$	6,16	11,16	<b>6,10</b>	<b>11,10</b>
$S_2D_1$	11,22	16,22	11,16	16,16
$S_2D_2$	11,16	16,16	11,10	16,10

strategic game of Table I.<sup>4</sup> It is easy to notice that all the profiles in Table I are (pure-strategy) Nash equilibria, i.e., for each player there is no preference over the available strategies [23]. Indeed, the game can be considered as a “dummy” game, since it highlights that unilaterally selecting the destination’s incoming interface without a unilateral performance improvement is a decision rationally not motivated. Therefore, it is necessary to define coordination mechanisms to benefit strategically and not greedily from the multihoming capabilities.

The two endpoints can agree in jointly routing their flows following implicit coordination equilibria of the multihoming game. This means accounting not only for the (incoming) cost that the other player decision impacts on its own network, but also for the (outgoing) cost of its own decision. For the moment, let us suppose that for each interface incoming and outgoing interconnection costs are the same.

In Table II, the strategies have now the notation  $S_iD_j$ , where  $i$  and  $j$  indicate the source’s outgoing interface and the destination’s incoming interface, i.e., a MP-TCP subflow. In fact, now the decision is not simply on the destination interface where to send the traffic, but also on the source outgoing interface; in MP-TCP, subflows are natively identified and therefore this strategy set seems appropriate to the technology context. Table II indicates in bold the four Nash equilibria of the corresponding balancing game. For example,  $(S_1D_1, S_2D_2)$  is a Nash equilibrium but the equal-cost  $(S_2D_2, S_1D_1)$  strategy profile is not; indeed, for  $(S_1D_1, S_2D_2)$ , both the players have no incentive to change their strategies, while for  $(S_2D_2, S_1D_1)$  player II has incentives to change to a strategy with a lower unilateral cost such as  $(S_2D_2, S_2D_1)$ . In addition, among the four (pure-strategy) equilibria of Table II, the italic one  $(S_1D_2, S_2D_1)$  is the efficient one (more precisely, Pareto-superior to the others).

An assumption made above is that the incoming cost is equal to the outgoing cost for a given interface. In practice, they may not be the same for a number of cases, as commonly in access networks you have asymmetric service levels (e.g., different upstream and downstream bandwidths). Therefore, a

<sup>4</sup>In the table, endpoints I and II have as strategies the endpoint II’s and I’s incoming interface, respectively, identified with I11 and I12, I1 and I2 (respectively): each cell, corresponding to a strategy profile, indicates the costs for players I and II for that strategy profile, on the left and on the right, respectively.

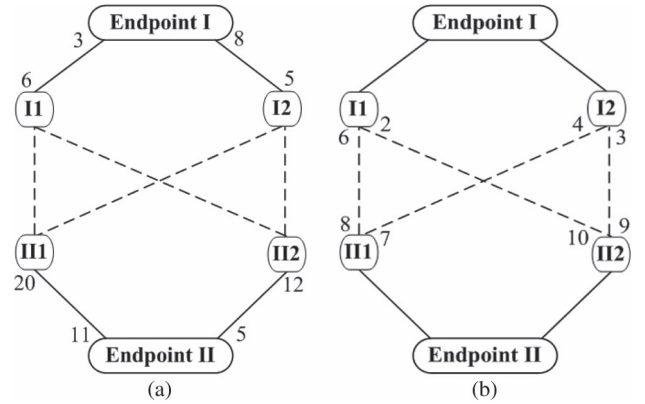


Fig. 2. Multihoming example with eight subflows. (a) Interconnection costs. (b) Path delay costs.

TABLE III  
FIG. 2(a) GAME EXAMPLE WITH TWO-SIDE UNIDIRECTIONAL  
INTERCONNECTION COSTS (COORDINATED SUBFLOW ROUTING)

I \ II	$S_1D_1$	$S_1D_2$	$S_2D_1$	$S_2D_2$
$S_1D_1$	(9, 31) <sup>9</sup>	(14, 31) <sup>9</sup>	(9, 23) <sup>1</sup>	(14, 23) <sup>1</sup>
$S_1D_2$	(9, 25) <sup>9</sup>	(14, 25) <sup>9</sup>	(9, 17) <sup>1</sup>	(14, 17) <sup>1</sup>
$S_2D_1$	(8, 31) <sup>8</sup>	(13, 31) <sup>8</sup>	<b>(8, 23)<sup>0</sup></b>	<b>(13, 23)<sup>0</sup></b>
$S_2D_2$	(8, 25) <sup>8</sup>	(13, 25) <sup>8</sup>	<b>(8, 17)<sup>0</sup></b>	<b>(13, 17)<sup>0</sup></b>

more generic game setting has different incoming and outgoing costs. For instance, in Fig. 2(a), for each interface, the incoming cost is close to the endpoint while the outgoing cost is near the interface; we obtain the new strategic form of Table III. Also for this case we have four Nash equilibria, with one Pareto-superior to the others. The meaning of the exponent in Table III, as well as the presentation of the resulting game properties need a preliminary mathematical formalization.

### B. Notations and Properties

The resulting multihoming finite game can be described as  $G_{\text{cost}} = (X, Y; f, g) = G_s + G_d$ , the sum of a selfish game and a dummy game, respectively; let  $f$  and  $g$  be the cost functions, and  $X$  and  $Y$  the strategy sets, of endpoint I and endpoint II, respectively. Each strategy  $x \in X$  or  $y \in Y$  indicates the source and destination interfaces. The strategy set cardinality is equal to the product: number of source interfaces  $\times$  the number of destination interfaces.  $G_s$  considers the outgoing cost only, while  $G_d$  considers the incoming cost only impacted by the other endpoint’s interface selection decision.

$G_s = (X, Y; f_s, g_s)$ , is a purely endogenous game, where  $f_s, g_s : X \times Y \rightarrow \mathcal{N}$  are the cost functions for endpoints I and II, respectively. In particular,  $f_s(x, y) = \Phi_s(x)$ , where  $\Phi_s : X \rightarrow \mathcal{N}$  and  $g_s(x, y) = \Psi_s(y)$ , where  $\Psi_s : Y \rightarrow \mathcal{N}$ .

$G_d = (X, Y; f_d, g_d)$ , is a game of pure externality (i.e., it only affects other player’s costs), where  $f_d, g_d : X \times Y \rightarrow \mathcal{N}$ .  $f_d(x, y) = \Phi_d(y)$ , where  $\Phi_d : Y \rightarrow \mathcal{N}$  and  $g_d(x, y) = \Psi_d(x)$ , where  $\Psi_d : X \rightarrow \mathcal{N}$ . For example, to calculate the cost of strategy  $(S_2D_1, S_1D_2)$ :

$$\begin{aligned}
 f_s(S_2D_1, S_1D_2) &= \Phi_s(S_2D_1) = 5 \\
 g_s(S_2D_1, S_1D_2) &= \Psi_s(S_1D_2) = 20 \\
 f_d(S_2D_1, S_1D_2) &= \Phi_d(S_1D_2) = 8 \\
 g_d(S_2D_1, S_1D_2) &= \Psi_d(S_2D_1) = 11.
 \end{aligned}$$

$G_s$  is a cardinal potential game [24], i.e., the incentive to change players' strategy can be expressed with a single potential function,  $P : X \times Y \rightarrow \mathbb{R}$ , for all players. A game is a potential game if the difference in individual costs by an individual strategy move ('individual' means only of player I or of player II for each unilateral strategy move) has the same value as the potential difference. That is, for a game in strategic form  $G = (X, Y; f, g)$ , where  $X$  and  $Y$  are the strategy sets for the two players, and  $f$  and  $g$  are cost functions,  $G$  admits a potential if it exists a function  $P : X \times Y \rightarrow \mathbb{R}$  such that  $\forall x', x'', x \in X, \forall y', y'', y \in Y$ :

$$\begin{aligned} P(x', y) - P(x'', y) &= f(x', y) - f(x'', y) = \Phi_s(x') - \Phi_s(x'') \\ P(x, y') - P(x, y'') &= g(x, y') - g(x, y'') = \Psi_s(y') - \Psi_s(y'') \end{aligned} \quad (1)$$

where  $(x, y)$ ,  $(x', y')$ , and  $(x'', y'')$  represent three different arbitrary profiles. As explicated in (1), the function difference for a unilateral move is equal to the difference of the unilateral  $G_s$  components, not depending on the other player's strategies, hence  $G$  is a potential game, and  $P$  is called *potential function*. Separately to  $G_s$ ,  $G_d$  can be seen as a potential game too, but with null potential, so that  $G_{\text{cost}} = G_s + G_d$  is a potential game, as the sum of potential games. In Table III and the following table examples, the exponent to a strategy profile indicates the corresponding potential value. It is worth mentioning that the basic structure of the defined multihoming game is similar to the peering game proposed in [21] (to cooperatively manage IP aggregate flows across the peering links between Internet carriers). Both games are potential games, composed as the sum of an endogenous game and of a pure externality game, hence both share the following equilibrium computation property that drastically eases the equilibrium computation.

Generally, in non-cooperative games, the Nash equilibrium existence (in pure strategies) is not guaranteed. As a property of potential games, the  $P$  minimum corresponds to a (pure-strategy) Nash equilibrium and always exists. As discussed in the seminal work about potential games [24], generically the inverse (every equilibrium of a potential game corresponds to a potential minimum) is not necessarily true, but it is easy to prove that for  $G_{\text{cost}}$  it is true due to the endogenous nature of  $G_s$  and the pure externality of  $G_d$  (see theorem 1 in [21] where this same property is proven for the peering game).

This property has an important impact on implementation: thanks to the simple game structure, the complexity of finding Nash equilibria is not NP-hard, but polynomial: it is linear,  $O(n)$  where  $n$  is the number of strategy profiles, i.e., the square of the product of the number of each endpoint's interfaces. It is worth noting that, to explicate P in calculus, an arbitrary starting potential has to be chosen, i.e., we need to fix whatever strategy potential value to be able to set a value for other profiles moving out unilaterally from the arbitrary starting potential. For example, in Table III we set to 0 the potential of social optimum profile, i.e.,  $P(x_0, y_0) = 0 \forall (x_0, y_0) \in X \times Y$  such that  $f(x_0, y_0) + g(x_0, y_0) = \min\{f(x, y) + g(x, y)\}$ , hence for this example  $(x_0, y_0) = (S_2D_2, S_2D_1)$  is the single social optimum profile, then we apply (1) to find the other components—note that (i) in the example, other neighboring

profiles do also have null potential even if they are not social optimum profiles; (ii) generally, equilibria can obtain a negative potential, as in Table V.

The Nash equilibrium is thus guided by  $G_s$ . When there are multiple equilibria,  $G_d$  might help in selecting an efficient equilibrium in the Pareto-sense.<sup>5</sup>

The addition of a performance game to  $G_{\text{cost}}$  possessing the same cost function structure, as described in the next subsection, does not change the nature of the resulting composed cost functions, hence guaranteeing the same Nash equilibrium computation property.

### C. Accounting for One-Way End-to-End Delay Components

In transport level end-to-end communications, several factors can affect the connection performance such as the one-way delay, the round trip time, or for TCP communications the congestion window. In particular, it is well known that in TCP communications the throughput is inversely proportional to the round-trip time.

In our multihoming decision context, the end-to-end paths may be asymmetric (the path between the interfaces depends on the Border Gateway Protocol, which implements various routing policies), and a strategy profile indicates a single direction (an MP-TCP subflow) from a source endpoint interface towards a destination endpoint interface. For these reasons, for performance improvement, the simplest yet most appropriate factor one shall include in the game, as an additional cost component, is the one-way delay (obviously, the round-trip time is the sum of the one-way delays along the two subflows in opposite directions). Such information is nowadays retrievable using Internet monitoring platforms, and is commonly used by many Internet applications (e.g., in P2P).

1) *Performance Game Modeling*: For the sake of clarity, consider the example in Fig. 2(b); for each path between the endpoints, a subflow delay component is placed next to the outgoing interface.<sup>6</sup> Given the Internet scope of transport communications such that the end-to-end delay is affected by significant shift of aggregate traffic volumes, we assume that the Internet transit delay variation due to a single MP-TCP connection load-balancing is negligible. Table IV shows the corresponding strategic form of the sample delay game related to Fig. 2(b). We can notice that the game components are symmetric for the two players: one-way delay costs, even if directional,

<sup>5</sup> *Pareto-efficiency*: A strategy profile  $p$  is Pareto-superior to another profile  $p'$  if a player's cost can be decreased from  $p'$  to  $p$  without increasing the other players' costs. The Pareto-frontier contains the Pareto-efficient profiles, i.e., those not Pareto-inferior to any other. In the game, incoming costs affect the Pareto-efficiency (because of the  $G_d$  pure externality). In particular, given a set of many strategy profiles, the Pareto-superiority among the equilibria strictly depends on  $G_d$ . Moreover, it is possible that, after an iterated reduction of strategies,  $G_{\text{cost}}$  assumes the form of a Prisoner-dilemma game, in which the equilibria are Pareto-inferior to other profiles.

<sup>6</sup> Note that the fact that one precise delay value is set for each transit path in the examples does not imply path delay is considered as constant. As described in Section VI, upon relevant changes in delay components, the resulting multihoming game—characterized hereafter—changes and a new solution can be computed. To avoid unnecessary computations, approximations can be easily integrated in the model.

TABLE IV  
FIG. 2(b) GAME EXAMPLE WITH TWO-SIDE  
DELAY COST COMPONENTS ONLY

I \ II	$S_1D_1$	$S_1D_2$	$S_2D_1$	$S_2D_2$
$S_1D_1$	(14, 14) <sup>5</sup>	(13, 13) <sup>4</sup>	(16, 16) <sup>7</sup>	(15, 15) <sup>6</sup>
$S_1D_2$	(10, 10) <sup>1</sup>	<b>(9, 9)<sup>0</sup></b>	(12, 12) <sup>3</sup>	(11, 11) <sup>2</sup>
$S_2D_1$	(12, 12) <sup>3</sup>	(11, 11) <sup>2</sup>	(14, 14) <sup>5</sup>	(13, 13) <sup>4</sup>
$S_2D_2$	(11, 11) <sup>2</sup>	(10, 10) <sup>1</sup>	(13, 13) <sup>4</sup>	(12, 12) <sup>3</sup>

affect both endpoint players given that they affect the performance of the connection independently of their direction.

Mathematically, let  $G_{\text{perf}} = (X, Y; f_p, g_p)$  be the performance game, where  $f_p, g_p : X \times Y \rightarrow \mathcal{N}$  are the delay cost functions for endpoints I and II, respectively, such that  $f_p(x, y) = g_p(x, y) \forall (x, y) \in X \times Y$ . Moreover, as anticipated above,  $f_p(x, y) = \Phi_p(x) + \Psi_p(y)$ , where  $\Phi_p : X \rightarrow \mathcal{N}$ ,  $\Psi_p : Y \rightarrow \mathcal{N}$ , and dually for  $g_p(x, y)$ , such that  $\Phi_p$  and  $\Psi_p$  components represent outgoing path and incoming path delays, respectively (considered as independent as above mentioned).  $G_{\text{perf}}$  therefore has the same structure of  $G_{\text{cost}}$ , as the sum of an endogenous component and of a pure externality component. The potential difference upon unilateral moves between two strategies is therefore equal to the difference of the delay cost function of the player changing the strategy (i.e., conditions (1) are verified).

2) *Resulting Performance–Cost Multihoming Game*: In order to jointly take both interconnection and delay cost components into account for the multihoming coordination, we can integrate the two games into a single one. The objective is to use a multihoming game that takes into account monetary interconnection costs, and a performance cost component that directly affects MP-TCP performances. In order to explore the cost-performance trade-off in the strategic situation, the resulting multihoming game is defined as  $G = G_{\text{cost}} + \beta G_{\text{perf}}$ , where  $\beta$  is the trade-off coefficient (with  $\beta = 0$  just the interconnection cost is taken into account, while as  $\beta$  increases more importance is given to performance). Assuming the game computation is done unilaterally by each endpoint,  $\beta$  is possibly different for the two endpoints; in such a case, it does not affect the payoff of the other player. Moreover, it does not need to be communicated, since the basic information needed by each endpoint is just the other endpoint's costs for each strategy profile (see Section VI).

The properties discussed in the previous sections are maintained for the resulting  $G$  game: it is still a potential game as the sum of potential games, with an endogenous component (for the first player,  $\Phi_s(x) + \Phi_p(x)$ ) summed to a component of pure externality ( $\Phi_d(y) + \Psi_p(y)$ ), hence the minimum potential corresponds to a pure-strategy equilibrium, and vice-versa (this can be easily proven as done in [21]), and the equilibrium computation complexity is polynomial. Note that, as explained in Appendix A and later discussed, there are no additional equilibria exploring mixed strategies.

Table V shows the resulting strategic form of the example, with  $\beta = 1$  (remembering that (i) we arbitrary set the null potential to the social optimum profile as suggested in Section II-B, and (ii) the equilibria, corresponding to the potential minima, are highlighted in bold). Moreover, we can see that this game assumes the form of a Prisoner-dilemma game,

TABLE V  
FIG. 2 COMPLETE MULTIHOMING GAME EXAMPLE  
(WITH TWO-SIDE INTERCONNECTION AND DELAY COSTS)

I \ II	$S_1D_1$	$S_1D_2$	$S_2D_1$	$S_2D_2$
$S_1D_1$	(23, 45) <sup>10</sup>	(27, 44) <sup>9</sup>	(25, 39) <sup>4</sup>	(29, 38) <sup>3</sup>
$S_1D_2$	(19, 35) <sup>6</sup>	(23, 34) <sup>5</sup>	(21, 29) <sup>0</sup>	<b>(25, 28)<sup>-1</sup></b>
$S_2D_1$	(20, 43) <sup>7</sup>	(24, 42) <sup>6</sup>	(22, 37) <sup>1</sup>	(26, 36) <sup>0</sup>
$S_2D_2$	(19, 36) <sup>6</sup>	(23, 35) <sup>5</sup>	(21, 30) <sup>0</sup>	<b>(25, 29)<sup>-1</sup></b>

in which the equilibria are Pareto-inferior to other profiles (as previously defined). This does not show up in Table III, but it does in the example of Table V where the delay components have a significant importance: the non-equilibrium strategy profile  $(S_1D_2, S_2D_1)$  is Pareto-superior to the Nash equilibrium  $(S_2D_2, S_2D_2)$ .

So far, the multihoming game example has shown only a limited number of equilibria. The multihoming solution corresponding to the two equilibria of Table V is such that either one of the two equilibria is chosen, or both are concurrently used, because equivalent: the endpoint I uses the two MP-TCP subflows  $S_1 \rightarrow D_2$  and  $S_2 \rightarrow D_2$ , evenly distributing the load on them, and that the endpoint II uses the subflow  $S_2 \rightarrow D_2$ . However, with the objective to further enlarge the equilibrium set, and therefore the number of used subflows, while allowing for arbitrary load-balancing on the selected subflows, we can exploit the potential value as described in the next section.

#### D. On Equilibrium vs. Social Optimum Solutions

As evidenced by the previous examples, equilibrium points can be far from global optimum points (it is worth noting that lower potential value does not imply a lower global cost). Global optimum profiles are commonly referred to as social optimum (or social welfare) profiles, considered as utopia solutions. Under the assumptions of player selfishness, social optimum solutions can be unrealistic. For example, consider the two equilibria of the game in Table V: they have a global cost (53 and 54) higher than the global optimum's cost: the social optimum is  $(S_1D_2, S_2D_1)$  with a global cost equal to 50. For this example, the worst equilibrium therefore has a gap of 4 from the social optimum: the ratio between the worst NE and the social optimum,  $54/50 = 1.08$  in the example, is commonly referred to as the Price of Anarchy (PoA) [26], [27], and indeed represents the price one has to pay when adopting game equilibrium solutions versus social optimum solutions.

A reader with a background on single-decision maker optimization could be confused about the advantage to use game theory rather than classical optimization models, since a game equilibrium always has a  $\text{PoA} \geq 1$ . However, non-equilibrium social optimum points can be unrealistic solutions to practical strategic situations with selfish agents: there could always be at least one player for which the social optimum is unilaterally disadvantageous, as it is the case for the profile  $(S_1D_2, S_2D_1)$  in Table V. In strategic situations in which selfish agents have to interact to solve a problem, social optimum solutions are not always acceptable as solutions for all the agents, and in practical cases (as our) often there is no alternative existing way to reach the social optimum.

Therefore, in practice non-cooperative game equilibrium solutions should not be seen as alternative to optimal solutions. A PoA sensibility analysis would be useful and would express a practical concern only when the social optimum is a practically implementable solution. Indeed, global optimum solutions do not minimize each agent’s cost, but a global cost (sum of each agent’s costs), with the result that the globally optimal solution could not correspond to the unilaterally optimal solution. Moreover, it is worth mentioning that equilibrium solutions can also be worse than unilaterally optimum solutions: a rational analysis of the situation by the other agents could make that unilaterally optimal solution never reachable because conflicting with their utility/cost. Therefore, from a classic optimization modeling perspective, equilibrium solutions can (informally) be seen as “strategically optimal” solutions taken from a subset of the available strategies, composed of strategically justified strategies accounting for other agents’ preferences. It is worth noting that the PoA can measure the quality of the equilibrium even in settings where the global optimum is not practically implementable.

### III. MP-TCP SUBFLOW LOAD-BALANCING SOLUTION

The multihoming game structure provided in Section II-C therefore allows to take into consideration the strategic interaction between two endpoints using a utility function composed by interconnection cost and delay cost components. The existence of a multihoming game equilibrium is guaranteed. Moreover, many equilibria may exist, leading to subflow load-balancing. The multihoming equilibrium computation remains an unilateral task, without any explicit coordination signal between endpoints. Multiple equilibria can be considered equivalent, from a strategic perspective, as for instance do two equal-cost shortest paths in link-state routing protocols; dually, load-balancing over multiple pure-strategy equilibria shall be done equally proportioning the traffic over the corresponding paths.

In practice, the multihoming game allows an implicit strategic restriction on the number of subflows, due to both interconnection cost and performance considerations, following the pure-strategy equilibria. For example, accordingly to the two equilibria in Table V, endpoint I may evenly use two subflows at 50%, and endpoint II may use only one among the four available subflows. Indeed, the impact of load-balancing is limited to the appearance of more than one pure-strategy equilibrium, which may often not happen. Because of the independence of the different cost components, this can be, in practice, a very rare event, which is a pity as using multiple subflows yields to increased network resiliency and transfer time; it looks therefore appropriate to investigate how, while respecting the strategic setting of the multihoming game, the equivalence condition among multiple equilibria can be extended to go beyond the rare occurrence of multiple pure-strategy equilibria.

In non-cooperative games, one classical way to get additional equilibria, hence for our case to increase the path diversity of the multihoming solution, is to compute mixed-strategy equilibria that consist in determining probability distributions that lead to equilibrium expected payoff [23]. A pure strategy

equilibrium can also be seen as a mixed strategy equilibrium with a single strategy with probability one and all other strategies with zero probability. However, as detailed in Appendix A, for the multihoming game no additional equilibria are introduced with mixed-strategies. Therefore, adopting multihoming game pure-strategy equilibria, one may end up with a too low number of subflows, while the connection resiliency would be improved if many subflows may be used concurrently. Our goal is to find a performance–cost strategically acceptable way to enlarge the multihoming path diversity to better absorb application traffic fluctuations and react to subflow congestions.

Following canonical game-theory approaches, this goal cannot be reached while maintaining the provided game formulation. Classically, studies on non-cooperative game theory seek one single equilibrium as, from a mathematical perspective, equilibrium unicity is often considered as a desirable property because then there is no dilemma about which equilibrium to use. From a networking perspective, instead, selecting multiple equilibria is desirable for the above-mentioned resiliency and performance reasons.

In the following of this section, we propose to enlarge the path diversity of the multihoming solution leveraging on the potential value and the possibility of strategic information exchange (see [28], or chapter 6 in [23]). The idea is to allow the endpoints to implicitly follow a coordination rule provided by a public signal, indicating to which strategy (subflow) to restrict. The signal is commonly supposed to be generated by a mediator (it could be an application program), and does not imply obeying to any binding agreement, that is, the players listen to the signal and, based on its common knowledge and on rationality assumptions, they implicitly change their beliefs on the strategy selection.

#### A. Potential Sensibility Consideration in Correlated Equilibrium Selection

The equilibrium selection problem under a public signal, allowing not binding coordination, has lead to the definition of the “correlated equilibrium.” A large number of studies on correlated equilibrium situations in communications networks exist, such as [29] and [22]. A generic definition of correlated equilibrium is given in chapter 3 of [25], where it is defined as a probability distribution on a restricted set of strategies (restriction due to the public signal) that offers an expected payoff higher or equal than the one without public signal. An assumption is that the public signal must be in the self-interests of the users. Under the rationality assumption, given the public signal, an implicit coordination takes place without the need of an explicit signaling to coordinate the unilateral choice.

Therefore, which can be the nature of the public signal in our multihoming context? The public signal should allow endpoints to determine additional profiles to take into account for load-balancing, yet higher importance should be given to pure-strategy Nash equilibrium profiles given their strategically more important weight. The next question hence is: how can we determine the strategic weight of a multihoming profile?

The multihoming game defined in Section II-C is a potential game. In potential games, the potential value qualifies the

profile's propensity to reach equilibrium, supposing that there is a possibility that the game components change in time. This is a realistic possibility in the multihoming scenario, particularly because of subflow delays continuously change, therefore changing the game equilibria. Considered that, in cost potential games, the minimum potential profiles are (pure strategy) equilibria, and the vice versa is also true for the multihoming game as above mentioned (hence all equilibria have equal potential value as explained in Section II-C2), game cost component changes can induce potential value changes and to a new equilibrium set. In this sense, the lower the potential value of a strategy profile is, the finer the profile can be considered, that is, the higher the probability it will become in next game settings an equilibrium. In fact, potential value can help in extending the equilibrium set including also those profiles that are not pure-strategy equilibria, but that have a possibility of becoming equilibria if minor changes occur. With the aim of increasing the diversity of the load-balancing decision, we can thus elevate those profiles that are not Nash equilibria, but that have a very low potential, to a sort of 'equilibrium status' and include them in the load-balancing decision. This corresponds to selecting as equilibrium all the strategy profiles that have a potential value equal or below a threshold.

Therefore, the answer to the second question above is to rely on the potential value to determine the strategic weight of a strategy profile, and the answer to the first question is to consider only the profiles below an arbitrary potential threshold opportunely taking into account game components' variation. The shared common public signal can be qualified as "let's play all profiles below the given potential threshold." Provided a threshold computation rule, a probability distribution on the restricted set of strategies can be computed accounting for the potential value of the strategy profiles.

### B. Potential Threshold Computation

Therefore, we can exploit the potential as a means to increase the path diversity of the multihoming game solution. Increasing the potential threshold, the equilibrium set is larger and the set of used interfaces is larger, while guaranteeing that they are rationally selected with respect to both interconnection cost and performance goals.

Since the trade-off coefficient  $\beta$  can already be used to enhance performance by weighting the importance of the one-way delay in the multihoming decision, logically the way the potential threshold is computed shall depend on  $\beta$ . A reasonable simple way to compute the potential threshold ( $\tau$ ) as a function of  $\beta$  is to set it linearly with  $\beta$  between the minimum ( $P_{\min}$ ) and the maximum ( $P_{\max}$ ) potential:

$$\tau(\beta) = (P_{\max} - P_{\min}) \cdot \beta / \beta_{\max} + P_{\min} \quad (2)$$

For example, taking the multihoming game setting in Table V,  $P_{\max} = 10$  and  $P_{\min} = -1$ , and with  $\beta = 1$  and  $\beta_{\max} = 10$ , we have  $\tau = 0.1$ . Therefore the correlated<sup>7</sup>

equilibrium set also includes the profiles with potential value equal to  $0 < \tau$ , i.e.,  $(S_1D_2, S_2D_1)$ ,  $(S_2D_2, S_2D_1)$ , and  $(S_2D_1, S_2D_2)$ . Certainly, this is one among different possible ways to link the performance–cost trade-off to the potential threshold (we evaluate in the simulation part). Alternative approaches may set the threshold accordingly to unilaterally estimated variations in subflow delays and/or endpoint interconnection costs. In the case unilateral information is used, as well as in the case the two endpoints use unilateral trade-off coefficients, the value of the potential threshold could be negotiated via the signaling channel (see Section VI), or set by both endpoints as the maximum among the two unilateral values.

### C. Subflow Load-Balancing Distribution

Let  $S \in X \times Y$  be the set of strategy profiles with a potential below the potential threshold  $\tau$  (hence kept as solution equilibria), i.e.:  $\forall (x, y) \in S, P(x, y) < \tau$ . A still open problem is therefore to compute the load-distribution among the interfaces corresponding to the selected equilibria in  $S$ . It cannot be an even load-balancing, because a subflow load should instead be an arbitrary distribution computed as a function of the potential values of the equilibria for the subflow. Let  $b_x$  and  $b_y$  be the load-balancing ratio for strategy  $x \in X$  and  $y \in Y$ , for endpoints I and II, respectively. The load-balancing ratios can be computed as the proportional weight, with respect to the distance from the potential threshold, of the unilateral strategy over all the available strategy profiles:

$$b_{x'} = \frac{\sum_{(x,y) \in S}^{x=x'} [1 + \tau - P(x, y)]}{\sum_{(x,y) \in S} [1 + \tau - P(x, y)]} \quad \forall x' \in X$$

$$b_{y'} = \frac{\sum_{(x,y) \in S}^{y=y'} [1 + \tau - P(x, y)]}{\sum_{(x,y) \in S} [1 + \tau - P(x, y)]} \quad \forall y' \in Y. \quad (3)$$

For instance, continuing the multihoming game example in Table V with  $\tau = 0.1$ , hence accounting for the profiles  $(S_1D_2, S_2D_1)$ ,  $(S_2D_2, S_2D_1)$ , and  $(S_2D_1, S_2D_2)$  with potential equal to 0, and the profiles  $(S_1D_2, S_2D_2)$  and  $(S_2D_2, S_2D_2)$  with potential  $-1$ , we get  $b_{x=(S_1D_2)} = 43\%$ ,  $b_{x=(S_2D_1)} = 14\%$ ,  $b_{x=(S_2D_2)} = 43\%$ , and  $b_{y=(S_2D_1)} = 29\%$ ,  $b_{y=(S_2D_2)} = 71\%$ . It is worth noting that in (3) the component  $\tau - P(x, y) \geq 0$ ,  $\forall (x, y) \in S$ , hence to avoid singularities we arbitrarily added 1 to each component; other variations of (3) can certainly be acceptable.

In conclusion, our proposition is to perform load-balancing across many strategies weighting each strategy as a function of the potential value, whose distance from the minimum represents the probability to become a pure-strategy equilibrium under independent, relative and successive variations of the game components. The probability distribution computation can be referred to as a particular correlated equilibrium solution, where the restriction of the strategy set is also due to a secondary performance objective not directly modeled in the multihoming game utility functions: the increased resiliency due to the implementation of load-balancing. One may argue that a mathematically nicer way would be to model the path diversity as a component of the game utility function; however,

<sup>7</sup>As of the generic definition of correlated equilibrium in [25] and previous considerations.

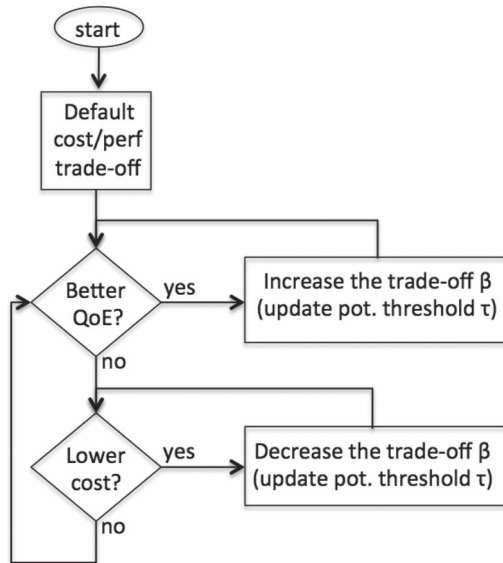


Fig. 3. User QoE tuning policy flowchart.

in such a case the game would no longer be a potential game, hence the equilibrium computation complexity would no longer be polynomial.<sup>8</sup>

#### D. User QoE Feedback Policy

In practice, a specific policy can be conceived around the tuning of the trade-off coefficient  $\beta$  and therefore the path diversity induced by potential threshold  $\tau$ . As already mentioned in Section II, the trade-off coefficient  $\beta$  is unilateral (potentially different for the two endpoints) and affects the computation of the strategy profile cost component of the endpoint tuning it.

As depicted in Fig. 3, the idea is that the end-user, aware of the interconnection cost and perceiving the performance, can decide if increasing the Quality of Experience (QoE) at the expense of a higher interconnection cost, and if decreasing the cost at the expense of the performance. Both operations

<sup>8</sup>Let us elaborate about how the game could have been modeled otherwise incorporating the load-balancing solutions. The strategy set of such an alternative game formulation, would have a number of strategies equal to the  $G$ 's number of strategies, say for player I,  $|X|$ , times the number of possible concurrent subflows, say  $|S|$ . The cost functions should incorporate the components already exposed ( $\phi$  and  $\psi$ ) and additional components that would have to express the change in performance and costs as a function of not unilateral cost functions only, but also functions merging improvements for player I and player II, i.e., as a function of both  $X'$  and  $Y'$ , where  $X'$  and  $Y'$  are the strategy sets of this alternative game formulation; these components can be expected to be monotonically increasing or decreasing, on the strategy steps increasing or decreasing the number of subflows, to map the positive or negative impact on performances or costs due to the increase of the amount of traffic and/or of subflows. We would obtain therefore a strategy set of dimensions  $|X'| = |X| \times |S|$  (and dually for  $Y'$ ), with the important problem of having to limit the number of possible subflows to a maximum. This would be in fact the first approximation in the model. Moreover, because of the additional components depending on  $(X', Y')$ , likely monotonic when increasing or decreasing the number of subflows, the game could not be a cardinal potential game, hence the equilibrium section problem would be NP hard. Additional approximations here would be needed to find a heuristic with a polynomial complexity, ideally linear (as the equilibrium computation complexity is for our multihoming game). All in all, we would risk to fall in a completely different model, with two approximations, and with the certainty that an acceptable heuristic's equilibrium computation complexity could not be linear.

are performed by tuning the trade-off coefficient, hence the potential threshold, which increases and decreases the MP-TCP path diversity, respectively. An equilibrium can be rapidly reached and stop the QoE–cost tradeoff setting loop.

For instance, a QoE-feedback policy could be implemented by an application installed in mobile terminals. The user would simply tune the performance–cost coefficient  $\beta$ , enabling the usage of more subflows while loading more the least-expensive interfaces (with an effect on both endpoints). The following simulation results can allow understanding which values of  $\beta$  would be likely chosen by the user during the exploration of the trade-off frontier.

## IV. SIMULATION RESULTS

In this section, we present simulation results to assess the cost-performance tradeoff of our approach, highlighting the differences with the basic MP-TCP implementation. We extended the NS-2 MP-TCP implementation [30] (including coupled congestion control).

We emulated a case with three interfaces at each endpoint, with 10 Mb/s links (note that this is only marginally important as the transport performance is affected by the delay). The interface connection cost and path delay are randomly chosen as shown in Fig. 4. We generated permanent FTP traffic in both directions for 60s, with a trade-off coefficient  $\beta$  ranging in the interval  $[0.01, 4]$  (above 4 there is no relevant change with the given example cost components). In the given example, for  $\beta = 4$  all strategy profiles are used (however, this does not correspond to greedy MP-TCP since a strategic load-balancing is still enforced), and for  $\beta = 0.01$  only one Nash equilibrium appears (which in fact correspond to single-path TCP over the least cost interface). It is important to mention that, for the sake of simplicity, in the simulations we use the same  $\beta$  value for both players, while in practice the values for the two players are uncorrelated and can be different.

In the following, we analyze the variation in throughput, interconnection cost and load-balancing distribution as a function of the trade-off coefficient  $\beta$ .

Fig. 5(a) shows the throughput plot, with one curve for each endpoint, the global throughput and the throughput with greedy MP-TCP (in logarithmic scale). As expected, the throughput generally increases with  $\beta$ , and so does the path diversity, since more importance is given to the one-way delay and more subflows are selected (see Fig. 6 with the load-balancing distribution). However, this is not a continuous throughput increase, sudden variations in single-player throughput are in fact due to subflow changes, while smooth variations are induced by equilibrium set modification without subflow changes. At the highest values of  $\beta$ , all subflows are used at both sides (see Fig. 6). However, the throughput of greedy MP-TCP is not reached because we keep computing the load-balancing distribution assigning higher weight to the equilibria with lower potential. The gap with greedy MP-TCP, about 35% less, is the price to pay to maintain a strategic load-distribution and ensure a rationally acceptable coordination between endpoints. On the other hand, even with low values of  $\beta$  (e.g.,  $\beta < 1$ ) we obtain a throughput up to four times the single-path TCP throughput



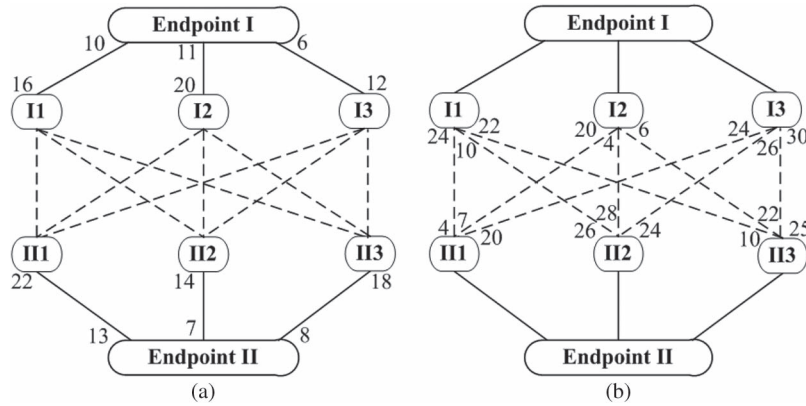


Fig. 4. Multihoming example with 18 subflows. (a) Interconnection costs. (b) Path delay cost.

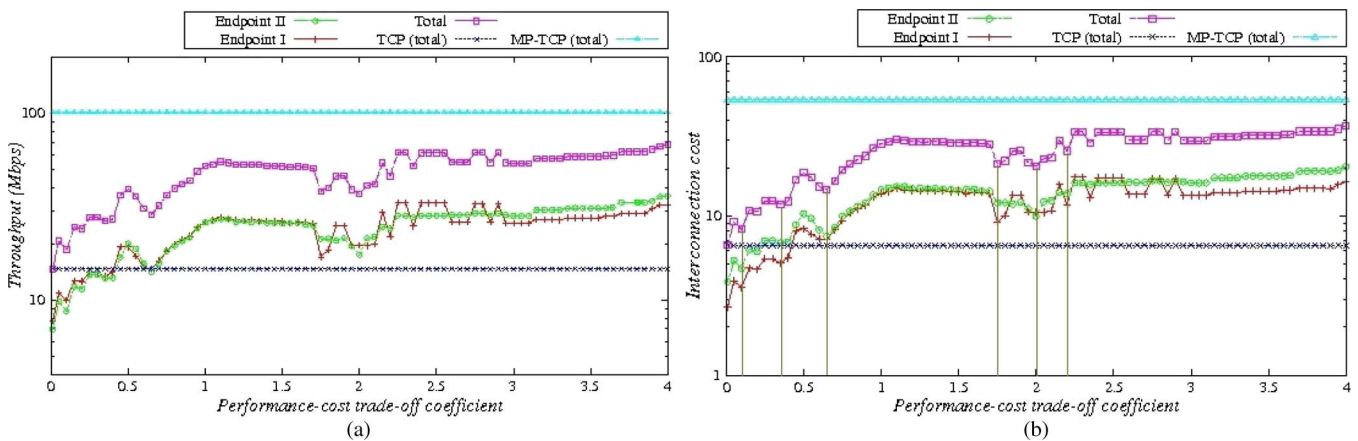


Fig. 5. Results as a function of the trade-off coefficient. (a) Throughput. (b) Interconnection cost.

( $\beta = 0.01$ ). Indeed, our distribution follows the requirements of those users willing to access at the least possible cost multiple paths in a coordinated way. The coordination granted by the game-theoretic modeling of our approach manifests in Fig. 5 with quite close throughput and interconnection cost for the two players.

Fig. 5(b)<sup>9</sup> shows the interconnection cost results (in logarithmic scale): its increase as a function of  $\beta$  is quite similar to the throughput increase behavior, since a performance improvement always comes with an interconnection cost increase. With low values of  $\beta$ , that is, with more importance given to the interconnection cost than to the performance, one can save about 50% in interconnection cost with respect to high values of  $\beta$ . Moreover, our strategic MP-TCP scheme grants more than 50% saving with respect to greedy MP-TCP, for low trade-off values (e.g.,  $\beta < 1$ ).

It is worth recalling that  $\beta$  scales the performance game and not the interconnection cost game, and that an increased value of  $\beta$  can bring to an increased potential threshold, hence possibly a higher number of selected subflows. Coupling the analysis of plots in Fig. 5, one can deduce that with a user QoE

feedback policy (see Section III-D), the trade-off tuning would end with a value of  $\beta$  that corresponds to local minima of the interconnection cost. The tuning of  $\beta$  would consist in moving from a local minima to a next one. For example, in Fig. 5(b), it is easy to identify six values of  $\beta$  corresponding to local minima, indicated by vertical lines. In particular, the most likely chosen values will be the one with the longest distance to the next minima, in our case  $\beta = 0.65$ . Such trade-off equilibrium points can be the result of an autonomous learning, or of an initiation learning phase between MP-TCP speakers.

As evidenced by Fig. 6, which reports the load-balancing distribution for the two endpoints, the  $\beta = 0.65$  point corresponds to a solution with 4–5 subflows and 2–3 interfaces concurrently used for endpoint I, and 5–6 subflows and 3 interfaces for endpoint II. We can observe how giving higher importance to performance (increasing  $\beta$ ) the path diversity (number of subflows and interfaces) increases until reaching the maximum number of subflows (18), as done with greedy MP-TCP (plotted in the last column for comparison). Indeed, basic MP-TCP greedily uses all the available subflows and interfaces (filling the corresponding buffer in a round-robin fashion). Nevertheless, even for high values of  $\beta$ , our distribution differs from the greedy MP-TCP one because we differently weight the load using the potential value of the corresponding strategy profiles.

This aspect is clarified by Fig. 7 that reports the **global** value of exchanged traffic volume per subflow during the 60s

<sup>9</sup>Note that, in Fig. 5, the shapes of the two plots are similar. The main reason is that we set the example's costs so that the two components are comparable, and then the equilibrium computation pushes both costs down (though not always to the minimum). Other settings on different scales could create a much flatter shape for one of the components.

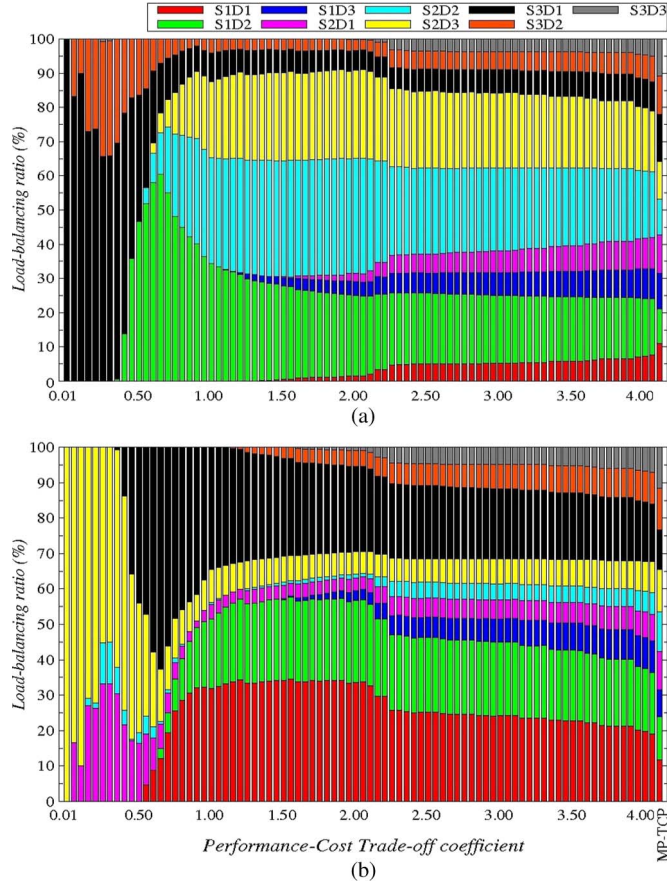


Fig. 6. Load-balancing distribution. (a) Endpoint I. (b) Endpoint II.

simulation duration. Increasing the trade-off coefficient  $\beta$ , the traffic is gradually moved towards the subflows that benefit from lower delays. It is interesting to notice that, especially for lower  $\beta$ , our strategic MP-TCP scheme can also offer better usage of some subflows than greedy MP-TCP, which is a particularly desirable property since some interfaces may be far less expensive than others (e.g., Wi-Fi vs. 4G), and our scheme allows filling first those interfaces, coordinatively.

## V. TRADE-OFFS RELAXING STRATEGIC CONSTRAINTS

As evidenced in previous figures, the tuning of the trade-off coefficient does not lead to equality between the multihoming game and the greedy MP-TCP approach for the highest values of the trade-off coefficient (fully favoring performance to interconnection cost). Indeed, a negative gap persists for the multihoming game, which is due to the fact that we keep weighting differently the strategies as a function of the corresponding profiles' potential values: the lower the potential is, the higher the load a strategy (subflow) will attract, proportionally, as given by (3).

As the tradeoff coefficient increases, one may desire to relax the strategic constraint in the load balancing, too. This can be reached by increasingly lowering the value of strategies' potential value for increasing  $\beta$ . A possible way to scale the potential value is as follows:

$$P'(x, y) = \lfloor P(x, y) * e^{-k\beta} \rfloor \quad \forall (x, y) \in X \times Y \quad (4)$$

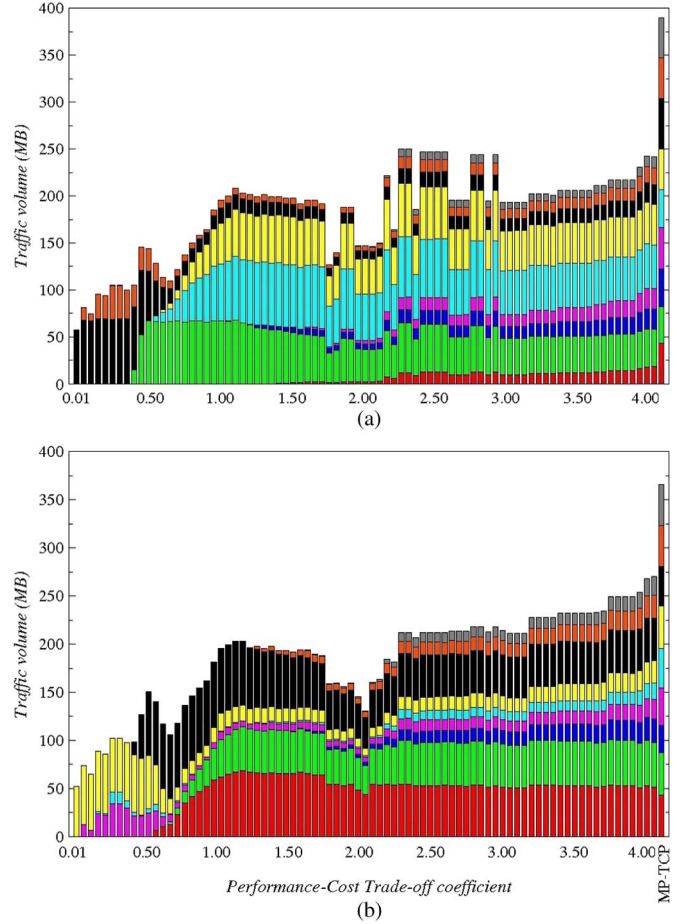


Fig. 7. Exchanged volumes. (a) Endpoint I. (b) Endpoint II.

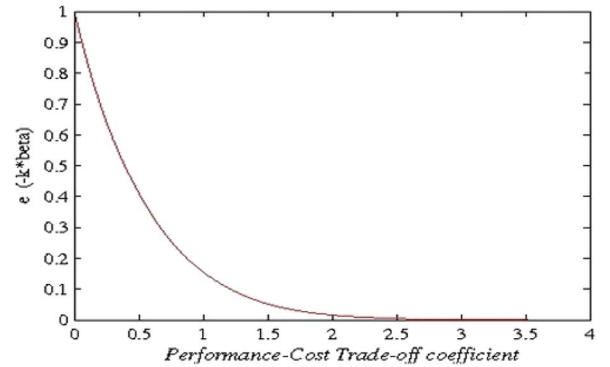


Fig. 8. Relaxation of strategic constraints: Potential scaling factor.

where the scaling function is exponentially decreasing with  $\beta$  as plotted in Fig. 8, and  $k$  is a constant such that the scaled potential is inferior to one for the maximum value of  $\beta$  for all possible strategy profiles, i.e., such that:

$$e^{-k\beta_{\max}} < \frac{1}{P_{\max}}. \quad (5)$$

Eventually,  $P'(x, y)$  will be null for the highest values of  $\beta$  since we round it down to the closest integer.

Replacing  $P(x, y)$  by  $P'(x, y)$  in (3), eventually for the maximum value of  $\beta$  the load-balancing among all the subflows will be even as with greedy MP-TCP. This is visible in Fig. 9. As compared to Fig. 5, we notice that the effect of scaling the

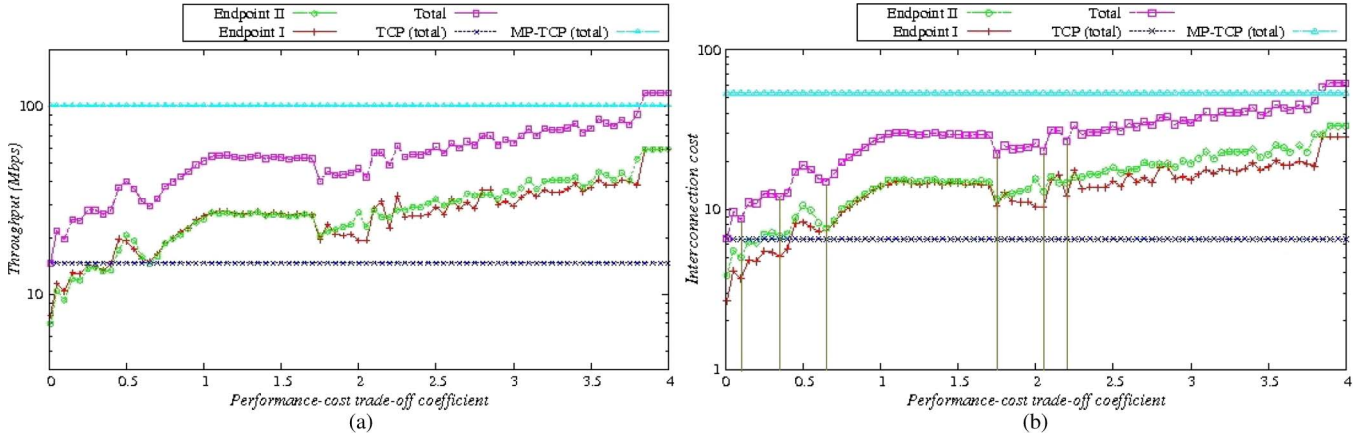


Fig. 9. Results as a function of the trade-off coefficient with relaxed strategic constraints. (a) Throughput. (b) Interconnection cost.

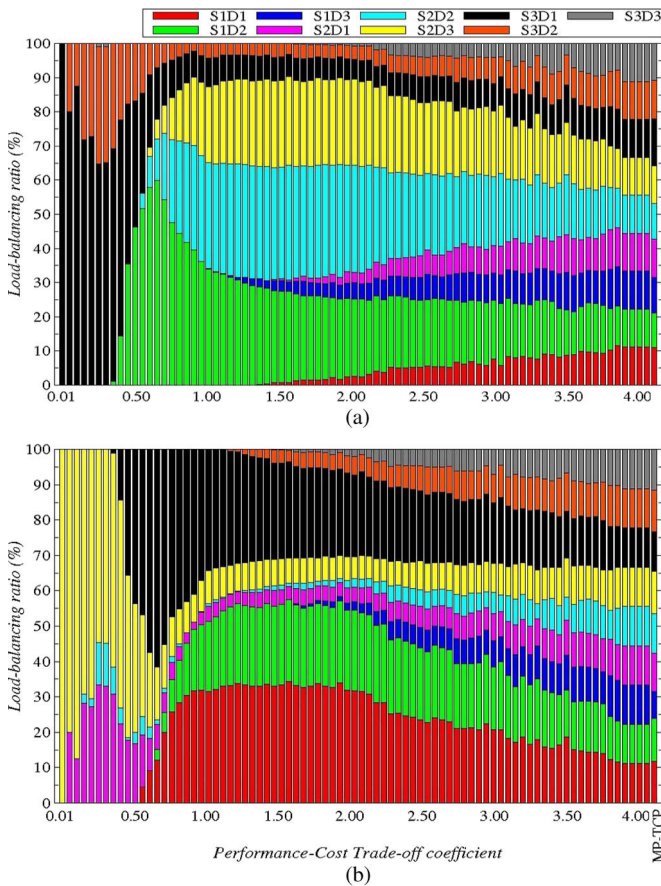


Fig. 10. Load-balancing distribution with relaxed strategic constraints. (a) Endpoint I. (b) Endpoint II.

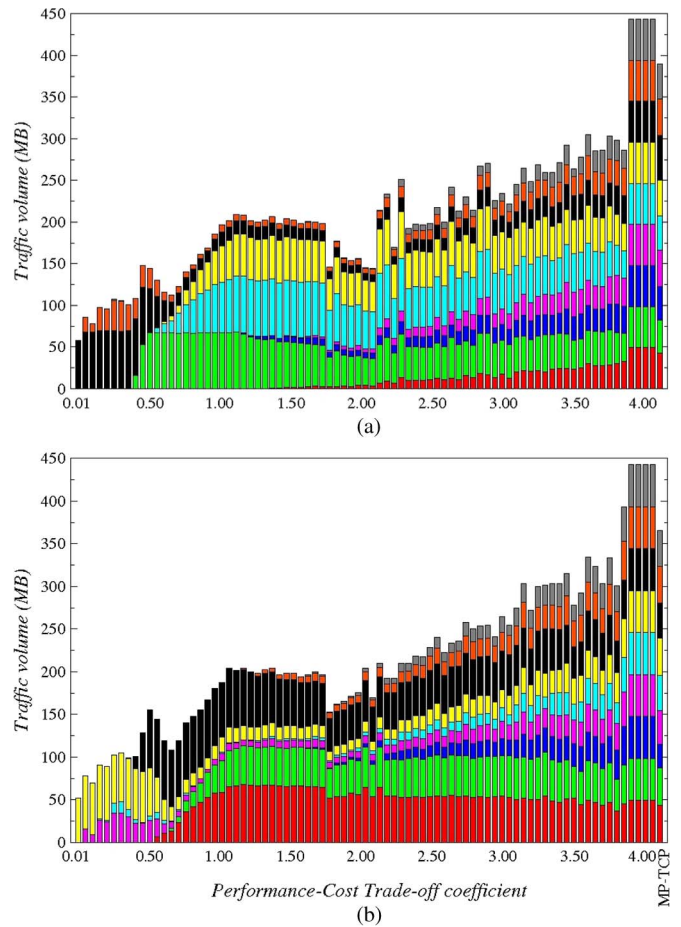


Fig. 11. Exchanged volumes with relaxed strategic constraints. (a) Endpoint I. (b) Endpoint II.

potential value (on the throughput and the interconnection cost) is evident only for higher values of the trade-off coefficient. Differences in load-balancing are however more clearly perceivable also for lower values of  $\beta$ , comparing Figs. 6 and 5 to Figs. 10 and 11. For higher values, the throughput, the interconnection cost and the overall volume reach results close to those of MP-TCP. Interesting is the fact that higher utilization of the subflow capacity, and hence higher interconnection cost and overall traffic volumes, are reached using  $P'(x, y)$ : this is likely due to rounding approximations in the NS-2 implementation of MP-TCP, while theoretically it should be equal.

## VI. POLICY IMPLEMENTATION ASPECTS

In practice, the presented approach can be implemented to allow performance-cost coordination among communicating multihomed mobile users' Internet applications, or for transport connections between a mobile user and a MP-TCP enabled Internet server. The non-cooperative nature of the multihoming game comes without binding agreements and support an implicit coordination among selfish and rational agents, such as mobile Internet applications and servers. The implementation

of our policy can be fully transparent with respect to the Internet network layer. However, minor points deserve attention.

- *Exchange of game cost component*: each endpoint needs to be informed about the other endpoint strategy profiles' costs. Instead of exchanging all interconnection cost, delay components, and trade-off coefficients, it looks more simple to send to the other endpoint just the final cost without detailing the different cost components. The related signaling could be in-band, encoded in some specific options that could be specified for MP-TCP. However, it would be much simpler to let this be handled by the application layer to avoid middle-box filtering and blocking issues (e.g., by firewalls, TCP optimizers, etc.).
- *Cost equalization*: when summing up interconnection cost and delay components, they should have a comparable scale. The corresponding scaling can be object of coordination and possibly incorporated in the trade-off coefficient.
- *Delay component information*: in real scenarios, the Internet path delay is certainly subject to variations, as Internet path delay variation level agreements cannot be guaranteed to the general public. This induces uncertainty to the multihoming subflow load distribution, hence delay rounding or approximation errors should be introduced, also simply unilaterally, to guarantee semi-steady load-balancing. The consideration of roundings or approximation errors, in potential routing games with multiple equilibrium selection, would have the effect of (further) elevating a potential threshold, as described in [21]. Coupled with an existing potential threshold, this could further enlarge the solution path diversity.
- *Load-balancing enforcement*: an important implementation difficulty is how to distribute the traffic into the specific selected subflows in order to achieve exact computed shares, when all interfaces are busy during the transmission. For example, how to send 70% over Ethernet and 30% over 3G with both interfaces busy all the time with these shares. The way this can be implemented in MPTCP (and this is how we did in our NS implementation) is to share the same TCP buffer among the different subflows, with possibly another second-level buffer for each subflow. The load-balancing can be enforced in the shared buffer's outgoing scheduler. Loss in the second-level buffer can be anticipated either decreasing the primary buffer size (preferable) or allowing loss.
- *Implementation in Internet servers*: when one endpoint is an Internet server, it would typically not be multihomed, and the game would be degraded to a simple game with just one strategy available to the server player. However, Internet datacenter architectures are migrating towards multipath-enabling solutions for intra-datacenter communications, such as TRILL (Transparent Interconnection of a Lot of Links) campus or IEEE 802.1aq networks. Moreover, to jointly manage Internet carrier multihoming and path diversity and inter-datacenter virtual-machine migration management, carrier multihoming management solutions, both proprietary and standard ones such as Locator/

- Identifier Separation Protocol (LISP), are being considered. In this context, the path diversity introduced by TRILL, IEEE 802.1aq and/or by LISP can be easily propagated down to datacenter servers by means of multiple virtual interfaces, VLANs or other techniques. In this context, different game components (delay, provider cost) can be included for the Internet server side.
- *Dealing with cheating behaviors*: it is certainly possible for an endpoint to configure the coordination policy to send not real interconnection costs and delay information, but artificial ones. Announcing false game components could allow attracting more convenient equilibria for the cheating endpoint. However, since the two endpoints are not obliged to coordinate, i.e., they have no binding agreement, the result of such a malicious behavior could be an interruption of the connection, which would be bad for the cheating endpoint. Moreover, in the case one endpoint is an Internet server, normally there is no interest in cheating with its clients. In fact, non-cooperative interactions with cheating normally make sense only when the two players have to play. In our case, there remains the menace to stop playing if such a malicious behavior is detected.
- *Complexity*: our algorithm has a negligible impact in terms of time and space complexity. Indeed, the computation of the Nash equilibria of potential games uses the minimization of the potential function, which is a mono-dimensional matrix. The time complexity is not NP-hard as in standard games; it is polynomial  $O(n)$  thanks to the game properties illustrated in previous sections, where  $n$  is bound by the number of subflows, hence the number of interfaces of each endpoint. We can consider a situation with endpoints with three interfaces each as the worst case situation in real scenarios, which corresponds in a total number of 18 MP-TCP subflows and a matrix with just 81 entries. The related data structures would take just a few kilobytes of memory.

## VII. CONCLUSION

With the extremely rapid pace at which mobile Internet usages increase, novel solutions have been proposed to increase the performance of multihomed devices with many Internet access interfaces. The most recent and interoperable one seems multipath TCP (MP-TCP), which in its current form fully uses the available interfaces while performing multiple end-to-end subflow control. Nevertheless, the basic specification of MP-TCP does not cover practical issues related to the different costs of access technologies. The objective of this paper is to precisely study this topic, assessing the importance of the performance–cost trade-off and proposing a strategic MP-TCP load-balancing scheme mixing performance and interconnection cost factors.

We modeled the interaction among distant multihomed devices as a non-cooperative game to allow a rational coordination towards multihoming equilibria. In particular, a trade-off coefficient allows users to weight the load-balancing on the available interfaces and MP-TCP subflows according to their propensity to pay more for the interconnection, hence to get a better quality

of experience. Simulation results show that our approach can grant roughly 50% cost saving with respect to greedy MP-TCP, with a roughly double throughput with respect to single-path TCP. Moreover, it is possible to identify isolated values of the trade-off coefficient following local minima of the interconnection cost behavior; we described a rational yet light coordination scheme among MP-TCP endpoints to set up arbitrary load-balancing distribution on the available subflows. More generally, our analysis allows understanding the rather unexplored aspect of performance–cost tradeoff in access multihoming.

#### APPENDIX A ON MIXED STRATEGY EQUILIBRIA

In a non-cooperative routing game, a strategically acceptable way to seek an *arbitrary load-balancing distribution* (e.g., 24%, 47% and 29% for three locators) might theoretically be reached implementing “mixed strategy” equilibria that could appear in addition to pure-strategy equilibria (the standard ones discussed so far).

It is worth doing a small digression on this aspect. In game theory, with mixed strategies the player no longer chooses a single strategy, but a probability distribution on its (unilateral) available strategies. Somehow the player can rely on a random process that implements his decision following the probability distribution. In non-cooperative games, players adopt independent random processes, and the probability distribution of a strategy profile (e.g., an equilibrium) is given by discrete multiplication of the probabilities each player assigned to its corresponding strategy. Note that an equilibrium in pure strategies can be seen as a particular (degenerated) equilibrium in mixed strategies where each player strategy, hence the strategy profile, has a probability equal to 1. For example, in the game of Table V, the equilibrium strategy  $S_2D_2$  can be played by endpoint I with probability  $p = 1$  and the other three strategies with probability  $1 - p = 0$ , and dually for endpoint II and the equilibrium strategy  $S_2D_2$  played with probability  $q = 1$ , so that the equilibrium profile  $(S_2D_1, S_2D_2)$  is played with probability  $p \cdot q = 1$ . The second equilibrium  $(S_1D_2, S_2D_2)$  can be used as an alternative solution, or (as suggested before) as a complementary one by evenly balancing the load on the two.

It has been proven that the mixed extension of a finite cardinal potential game, such as  $G$ , is also a cardinal potential game [24]. Therefore, we are interested in knowing if there can be additional mixed-strategy equilibria for  $G$ .

*Proposition A.1:* All the equilibria of the game  $G$  are pure-strategy equilibria, i.e., no additional equilibria are added with mixed strategies.

In game theory parlance, this is quite straightforward once noted that the Nash equilibrium(a) of  $G$  can be found by iterated elimination of strongly (strictly) dominated strategies. Considering that, given two endpoint I’s strategies  $x^*$  and  $x'$ , if one of them is not an equilibrium then  $f(x^*, y) - f(x', y) \neq 0 \forall y \in Y$ ; if both were equilibria, they would have equal potential and  $f(x^*, y) - f(x', y) = 0$ . Then,  $x^*$  strongly (strictly) dominates  $x'$  if:

$$f(x^*, y) - f(x', y) > 0 \quad \forall y \in Y \quad (6)$$

and dually for endpoint II. Given two unilateral strategies in the multihoming potential game, either both are equilibria and (6)

is not true, or one of them strongly dominates the other, which can be eliminated.

For example, in Table V the equilibrium can be obtained by first excluding, for endpoint I, all  $D_1$  strategies since whatever endpoint II chooses the endpoint I cost is always minor, and by then conversely excluding  $S_1$  and  $S_2D_1$  strategies for endpoint II. The reduced game is the game degenerated to the single Nash equilibrium, if it is unique, and thus no mixed strategy is conceivable. If multiple equilibria exist for the general setting, the reduced game is composed of as much strategies and strategy profiles as needed to encompass the equilibria, and no additional mixed-strategy equilibria arise. Mixed strategies are therefore not implementable as a load-balancing distribution in our multihoming game modeling.

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**Guy Pujolle** received the Ph.D. and “These d’Etat” degrees in computer science from the University of Paris IX and Paris XI, Paris, France, in 1975 and 1978, respectively.

He is currently a Professor with the University Pierre and Marie Curie (UPMC) and a member of the Institut Universitaire de France. He spent the period 1994–2000 as a Professor and Head of the Computer Science Department, Versailles University. He was also a Professor and Head of the MASI Laboratory (Pierre et Marie Curie University) in 1981–1993, a Professor at the Ecole Nationale Supérieure des Télécommunications in 1979–1981, and a Member of Scientific Staff of INRIA in 1974–1979. He is currently an Editor of the *International Journal of Network Management* and the *ACM/Springer Journal on Wireless Networks (WINET)* and the Editor-in-Chief of *Annals of Telecommunications*. He was in charge of a large number of European and French projects.



**Stefano Secci** has been an Associate Professor with the University Pierre and Marie Curie (UPMC—Paris VI, Sorbonne Universités), Paris, France, since 2010. He received the “Laurea” degree in telecommunications engineering from Politecnico di Milano, Milan, Italy, in 2005 and the dual Ph.D. degree in computer networks from Politecnico di Milano and Télécom ParisTech, Paris, in 2009.

He was a Research Fellow with the Norwegian University of Science and Technology (NTNU), George Mason University, Ecole Polytechnique de Montreal, and Politecnico di Milano and a Network Engineer with Fastweb Italia. His works mostly cover network optimization, protocol design, Internet routing, and traffic engineering. His current research interests are about Internet resiliency and Cloud networking.

Dr. Secci has been a member of many Technical Program Committees of many leading conferences (NOMS, CLOUDNET, ICC, GLOBECOM, WCNC, VTC, and Networking), a TPC Co-Chair of IEEE CLOUDNET 2012, the Chair of the Cloud Networks Track at IEEE GLOBECOM 2014 and IEEE CCNC 2015, and a referee for the Italian Ministry of Research and University. He has been an Associate Editor of the IEEE COMMUNICATIONS SURVEYS AND TUTORIALS since 2012 and of the *Journal of Network and Systems Management* (Springer) since 2013 and a Guest Editor of the 2013 *Computer Networks* (Elsevier) Special Issue “Communications and Networking in the Cloud” and the 2015 IEEE Communications Magazine Feature Topic on Mobile Cloud Computing. He has been a Vice Chair of the Internet Technical Committee, a joint between the IEEE Communication Society and the Internet Society, since 2013.



**Thi Mai Trang Nguyen** received the Engineer degree in telecommunications from Ho Chi Minh City University of Technology, Ho Chi Minh, Vietnam, in 1999, the M.S. degree in computer science from the University of Versailles, Versailles, France, in 2000, and Ph.D. degree in computer science from the University Pierre and Marie Curie (UPMC), Paris, France, in 2003.

She is currently an Associate Professor with UPMC. She has been involved in many national and European projects related to the development of the next generation of the Internet. She also has publications in international journals and has one French patent on mobile networking. Her main research interest is the design of new architecture, protocols, and algorithms related to the quality of service, security, and mobility management.

**Sinh Chung Nguyen** received the Engineer degree in telecommunications from Hanoi University of Technology, Hanoi, Vietnam, in 2006 and the degree in computer networking from the University Pierre and Marie Curie (UPMC), Paris, France, in 2007. He is currently working toward the Ph.D. degree in computer networking in the LIP6, UPMC.