Managing competition for (public) resources in human-centric networked environments

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***Abstract*—Advances in Information and Communication Technologies have dramatically changed the role of users and resulted in unprecedented amounts of information that enrich users' awareness about their environment and its resources. While this broad awareness for (low-priced) limited resources can bring benefits, it also intensifies competition phenomena in distributed and uncoordinated environments, shaping, in turn, the users' decisions whether to compete or not. This paper investigates the uncoordinated resource selection problem and discusses how competition awareness shapes decision-making under different levels of rationality. The case of strategic and fully rational users provides benchmarks and "reference" understanding, against which other more realistic or human-centric cases are compared.**

I. Introduction

The technological developments over the last decade have been changing dramatically the networking environment, resulting in a drift of interest, activities and potential from the core of the network to its periphery. Users nowadays undertake not only the role of the consumer of networked services/content but also that of the producer and/or provider, contributing heavily to the networked infrastructure. For example, this is the case with mobile ad hoc networks, opportunistic networks, and peer-to-peer networking. Consequently, the emerging networked environments are referred to as user-centric, emphasizing this prevailing role of the end-users. These user-nodes are typically self-owned and -managed. Their behavior and actions are not controllable but rather driven by self-centered interests and objectives that may well be in conflict with those of other nodes.

The behavioral factor is further accentuated by the strong emergence of what is referred to as a socio-tech dimension, *i.e.*, the bi-directional coupling and dependencies between the social dimension present in the human associated with a user-node and the networking technologies and capabilities in and around the user-node. This coupling has been realized through the ever increasing closeness of the service/content production, service/content consumption, and related network processes to a human. This socio-tech dimension is particularly evidenced in smart urban environments where the integration of sensing devices of various sizes, scope and capabilities with mobile communication devices, on the one hand, and the wide proliferation of online social applications, on the other, leverage the heterogeneity of users in terms of interests, preferences, and mobility, and enable the collection of huge amounts of information with very different spatial and temporal context. When shared, this information can enrich people's awareness about and foster more efficient management of a broad range of resources, ranging from natural goods to urban space and transportation networks.

While awareness can bring benefits, it also brings drawbacks that can be severe in certain cases. As awareness synchronizes the perception of different users about the state of their environment (such as the state of some resource of limited capacity), it also "synchronizes" behaviors and decisions, intensifying competition phenomena in distributed and uncoordinated environments, creating a number of challenges and side issues. Understanding and managing this competition will allow unlocking the tremendous potential that the technology-enabled, highly-connected, distributed and participatory human beings can bring about for the benefit of the society and the environment.

As resource awareness creates competition, the users end up experiencing the congestion penalties induced by the lack of coordination that is typically the case in such environments. As a result, the users become competition-aware and need to decide whether they will compete or not compete for some limited resource, factoring in the risk of paying an excess cost in case of a failure in finding the limited resource available. A major challenge is then to understand decision-making under competition awareness: *how competition shapes decisions taken in a collective awareness environment by decision-makers under different assumptions on their rationality*.

A first step to understanding the aforementioned uncoordinated resource selection problem is to consider strategic and rational users fed with precise information on the available resources and number of competitors. This case will provide certain benchmarks and "reference" understanding, against which other more realistic or human-centric cases can be compared. The latter are also discussed in this paper and include cases under the broad umbrella of "bounded rationality", where information is incomplete or the decision-makers have computational, cognitive or other limitations or biases (human-centric constraints), resorting to (fast and frugal) heuristics on decision-making. Besides exploring the existence of equilibria and their (in)efficiencies, it is important to understand the performance outcomes of decision-making under human-centric constraints, as well as assess the cost of the lack of coordination in accessing the distributed resources (price of anarchy) and directions to reduce it.

Congestion phenomena appear in various ICT sectors. Examples come from the emergent fairly autonomic network-

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ing environments, where each user runs a service resource selection task and seeks to maximize his benefit, driven by self-centered interests and biases. Our studies that support most of the discussions in this paper have considered the parking spot selection problem. Drivers are faced with a decision as to whether to compete for the low-cost but scarce on-street parking space or directly head for the typically over-dimensioned but more expensive parking lots. In the first case, they run the risk of failing to get a spot and having to *a posteriori* take the more expensive alternative, this time suffering the additional *cruising* cost in terms of time, fuel consumption (and stress) of the failed attempt. Drivers might make their decisions drawing on information of variable accuracy about the parking demand, capacity and the applied pricing schemes on the parking facilities, that parking assistance systems collect and broadcast. Other applications of the uncoordinated resource selection problem include the route selection problem [1], the wireless access point association problem [2], *etc.*.

The deployment of advanced (wireless) networking technologies has enabled new services and smart solutions to congestion problems that stem from the blind uncoordinated search for some limited resources. The efficiency of these systems ultimately depends not only on the quality of the information about the available resources that can be provided to the agents, but also on the way the provided information is used by the agents. Therefore, information may be precise and complete or imperfect and limited; whereas the agents may exhibit different levels of rationality in the way they process the provided information and determine their actions. Finally, while the competition induced by the broad resource availability awareness cannot be avoided, its negative impact on the efficiency in managing distributed (public) resources could be reduced by introducing mechanisms to enable some level of coordination among the distributed competitors.

II. Uncoordinated resource selection under competition awareness

In general, the competitive resource selection environments share a number of common features and expose some critical parameters that tune the intensity of competition. In order to analytically investigate the suffered congestion penalties due to the uncoordinated access to the limited resources, it is important to identify and model those key features. In this respect, we may consider N agents that are called to decide between two alternative sets of resources. The first set consists of R low-cost resources while the second one contains an unlimited number of more expensive resources. When the amount of the low-cost resources is large and the interested user population is small, users can readily opt for using them. Otherwise, an inherent competition emerges that should be factored by users in their decision to opt for accessing these resources or not. Those who manage to use the limited resources pay $c_{l,s}$ cost units, whereas those heading directly for the unlimited option pay $c_u = \beta \cdot c_{l,s}, \beta > 1$, cost units. However, agents that first decide to compete for the low-cost resources but fail to acquire one, pay $c_{l,f} = \gamma \cdot c_{l,s}, \gamma > \beta$, cost units. The excess penalty cost $\delta \cdot c_{l,s}$, with $\delta = \gamma - \beta > 0$, captures the impact of congestion.

In the sequel, we describe five decision-making approaches/models that accommodate various levels of rationality with respect to the knowledge and computational constraints of decision-makers. These models enable the quantitative description of fully and bounded rational decisions and hence, the assessment of their impact on the congestion levels.

A. Fully rational decision-making

General concept: In the ideal reference model of fully rational decision-making, the decision-maker is a software engine that in the absence of central coordination, acts as rational strategic agent that explicitly considers the presence of identical counter-actors to make rational, yet selfish decisions aiming at minimizing the cost of the acquired resource. In this case, the main assumption is that users can possess all relevant information, analyse all possible combinations of users' actions, assess the cost/gains of each possible outcome, and strategically make the choice that minimizes their own cost. It is notable that provision of sufficient local content for fully rational decision-making is likely not to be cost effective in terms of storage/networking resources and control mechanisms.

Formulation: The intuitive tendency to head for the low-cost resources, combined with their scarcity in the considered environments, give rise to congestion effects and highlight the game-theoretic dynamics behind the resource selection task. In several studies about ICT systems and applications where a number of selfish agents compete over a limited-capacity and low-cost resource, the way the competition is resolved has been addressed in game-theoretic terms and through the analysis of the equilibrium states of the system where the counteracting influences are balanced and no player has incentive to change his strategy, unilaterally. For instance, in a transportation paradigm in [1], the drivers choose between a number of routes from a common-to-all origin to a common-to-all destination. The cost incurred by each user is a non-decreasing function of the number of other users also follow the same trajectory. Likewise, in an instance of the access-point association problem, a number of mobiles compete over a finite number of access points where high access delays occur when many users associate with the same wireless access point [2].

Assessment of congestion penalties: In the same vein, the collective fully rational decision-making in resource selection can be formulated drawing on classical game-theoretic principles and concepts [3]. In [4], this scenario is analysed in the context of parking search application (Ref. Section I). An assistance service announces information of perfect accuracy about the demand (number of users interested in parking), supply (number of limited, low-cost, on-street parking resources) and pricing policy on the parking resources. The drivers act as rational and strategic selfish agents that try to minimize the cost the actual humans/drivers pay for the acquired parking space. In fact, automatic software agent implementations rather than human decision-makers are considered, yet the actual human/driver undertakes the action with the assumption that he fully complies with the machines' suggestions.

The drivers' behaviors at the equilibrium states of this strategic game are derived and the costs paid at the equilibria are compared against those induced by the ideal centralized system that optimally assigns the low-cost resources to minimize the social cost. The (in)efficiency of the uncoordinated resource selection is quantified using the Price of Anarchy (PoA) metric, computed as the ratio of the worst-case equilibrium cost over optimal cost. The analytic investigation shows that *PoA deviates from one, implying that, at equilibrium, drivers tend to over-compete for the on-street parking space, giving rise to redundant cruising cost*. These congestion phenomena can be alleviated by properly manipulating the price differentials between the two types of resources. Notably, these results are in line with earlier findings about *congestion pricing* (*i.e.*, imposition of a usage fee on a limited-capacity resource set during times of high demand), in a work with different scope and modelling approach [5]. The results of this study serve as a benchmark for assessing the impact of different rationality levels and cognitive biases on the efficiency of the resource selection process.

B. Decision-making under knowledge constraints

General concept: Perfectly accurate information about the resource demand is hard to obtain within a dynamic and complex environment. The resource operator may provide the competing agents with different levels of information about the demand for resources; for example, historical statistical data about the utilization of the low-cost resources. Thus, in this case, the information is impaired in accuracy since it contains only some estimates on the parameters of the environment.

Formulation: This type of rationality where agents have only knowledge constraints, while they satisfy all other criteria of full rationality, (*i.e.*, no computational or time constraints decrease the quality of their decisions), can be accommodated in Bayesian and pre-Bayesian models that devise prescriptions of the classical Game Theory. In the Bayesian model of the game, the agents determine their actions on the basis of private information, their types. In the resource selection problem, the type can operate as a binary variable indicating whether an agent is in search of resources (active player). Every agent knows his own type, yet he ignores the real state at a particular moment in time, as expressed by the types of the other players. The agents draw on common prior probabilistic information about the activity of agents (*i.e.*, the probability for an agent to be active, namely, interested in resources) to derive estimates about the expected cost of his actions. Thus, now, the agents try to minimize the expected cost, instead of the pure cost that comes with a strategy, and play/act accordingly. In the resulting Bayesian Nash equilibrium states, the agents perform their best-response actions and no agent can further lower his expected cost by unilaterally changing his strategy.

In the worst-case scenario the agents may possess some knowledge about the upper limit of the potential competitors, yet their actual number is not known, not even probabilistically. In this case, the resulting agents' interactions can be modelled as an instance of pre-Bayesian games and the game dynamics are discussed in terms of safety-level equilibria; namely, operational states whereby every player minimizes over his strategy set the worst-case (maximum) expected cost he may suffer over all possible types and actions of his competitors.

Assessment of congestion penalties: The game formulation for the full rationality case (Ref. Section II-A) can be extended in order to analyse Bayesian and pre-Bayesian models that accommodate two expressions of uncertainty where drivers either share common probabilistic information about the overall parking demand or are totally uncertain about it. Similarly to the full rationality case, the conclusions can be drawn on equilibrium states. Ultimately, the results in [4] show that under imperfect information *the congestion penalties remain at the levels obtained under full rationality*. Namely, the social cost curves for the equilibrium states in the strategic and Bayesian games have the same shape, since the expected number of competing agents as derived by the symmetric mixed-action equilibrium competing probability in the strategic game, is realized through the symmetric mixed-action equilibrium competing probability in the Bayesian game (under an appropriate choice of the symmetric activation probability).

Interestingly enough, this setting fosters less-is-more effects whereby more information does not necessarily improve the efficiency of service delivery but, even worse, may hamstring users' efforts to minimize the cost incurred by them. This holds in the context of the pre-Bayesian game. In fact, the safety-level equilibrium of the pre-Bayesian game corresponds to the mixed-action equilibrium of the strategic game. In the strategic game, the social cost conditionally increases with the equilibrium competing probability, on the one hand, and the equilibrium competing probability decreases with the number of users, on the other hand. Therefore, *at the safety-level equilibrium*, the users end up competing with a lower probability than that corresponding to the game they actually play (*i.e.*, as determined by the real number of players) and hence, *they may end up paying less than they would if they knew deterministically the competition they face*.

C. Decision-making under computational constraints

General concept: Experimental data suggest that human decisions reflect certain limitations and exhibit biases in comparing the expected utilities of different alternatives. To accommodate the empirical findings, researchers from economics, engineering, sociology, operations research and cognitive psychology, have tried either to expand/adapt the Expected Utility Theory (EUT) or completely depart from it (and its expressions as embodied in the Nash equilibrium concept) and devise alternatives theories as to how decision options are assessed and decisions are eventually taken. The study of the decisions people make is, indeed, the focus of the interdisciplinary behavioral decision theory which has contributed to a re-evaluation of what human decision-making requires.

a) Cumulative Prospect Theory: General concept: Tversky and Kahneman in [6] proposed the Cumulative Prospect Theory (CPT) framework to explain, among others, why people buy lottery tickets and insurance policies at the same time, and the fourfold pattern of risk attitude, namely, people's tendency to be risk-averse for alternatives that bring gains and risk-prone for alternatives that cost losses, when these alternatives occur with high probability; and the opposite risk attitudes for alternatives of low probabilities.

Formulation: According to CPT the alternatives are now termed prospects and lead to a number of outcomes that are obtained with a probability. The prospects are valued by an expression of weighted sum of values that resembles the expression of EUT, only now both the individual outcomes and the corresponding probabilities are modified. However, users are still maximizers, *i.e.*, they try to maximize the expected utilities of their prospects. In [6], the authors propose concrete functions to transform objective probabilities and outcomes with shapes that are consistent with experimental evidence on risk preferences. Indeed, empirical measurements reveal particular patterns of behavior, termed as loss aversion and diminishing sensitivity. The loss aversion refers to the fact that people tend to be more sensitive to decreases than to increases in their wealth (*i.e.*, a loss of 80 is felt more than a gain of 80, with reference point equal to zero); whereas the diminishing sensitivity (appeared in both the value and the weighting function) argues that people are more sensitive to extreme outcomes and less in intermediate ones (*i.e.*, people discriminate less between 80 and 100 than between 0 and 20, with reference point equal to zero).

In the resource selection problem, the decisions are made on two alternatives/prospects differing in capacity and pricing. In addition, both prospects consist only of negative outcomes/costs. Using the expressions that measure the desirability of the two prospects, it is possible to extend the equilibrium concept and define states where the competing influences are balanced, this time with respect to the corresponding CPT values. Namely, under an equilibrium state, no agent has the incentive to deviate from this unilaterally because by changing his decision, he will only find himself with more prospect cost. Thus, the symmetric mixed-action equilibrium strategy can be derived when equalizing the CPT values of the two prospects.

Assessment of congestion penalties: In [7], the efficiency of CPT is assessed through a comparative study between the per-user costs under the Nash equilibrium, the CPT equilibrium and the optimal resource assignment that could be determined by a centralized entity. When the agents have the opportunity to experience a marginally or significantly lower charging cost by using the low-cost resource set, at low or moderate risk, respectively, their biased risk-seeking behavior turns to be fully rational, and thus, minimizes the expected cost over others' preferences. On the contrary, in the face of a highly risky option reflected in significant extra penalty cost for those who fail in the competition, the risk attitude under the two types of rationality starts to differ; that is, the CPT leads to a more risk-prone behavior when compared to the Nash equilibrium strategy. The comparison between the Nash and CPT equilibria against the optimal resource allocation shows that both the fully rational and the biased practice are more risk-seeking than they should be, increasing the actual per-user cost (or equivalently, the social cost) over the optimal levels. As a result, *being prone to biased risk-seeking behaviors cannot score better than acting fully rationally*.

b) Rosenthal and Quantal Response Equilibria: General concept: Casual empiricism as well as experimental work suggested systematic failure of standard Nash equilibrium predictions to track laboratory data, even in some of the simplest two-person games. For instance, according to the theoretic analysis of the matching pennies game, a change in a player's own payoff that comes with a particular strategy/choice, must not affect that player's choice probability. However, experimental evidence indicates "own-payoff effects", arguing that people's interest for a particular strategy/choice increases as the corresponding payoff gets higher values [8].

Formulation: Triggered by this kind of observations, probabilistic choice models have been used to incorporate stochastic elements in the analysis of individual decisions and hence, represent unobserved and omitted elements, estimation/computational errors, individual's mood, perceptual variations or cognitive biases. Rosenthal in [9] and, later, McKelvey and Palfrey in [10], propose alternative solution concepts to the Nash equilibrium in an effort to model games with noisy players. Rosenthal argued that "the difference in probabilities with which two actions are played is proportional to the difference of the corresponding expected gains (costs)". In a similar view of people's rationality, McKelvey and Palfrey explained people's inability to play always the strategy that maximizes (minimizes) the expected utility (cost) by introducing some randomness into the decision-making process. The underlying idea in the proposed Quantal Response equilibrium is that "individuals are more likely to select better choices than worse choices, but do not necessarily succeed in selecting the very best choice". In both equilibrium concepts the rationality of agents is quantified by a degree of freedom which measures the capacity to assess the difference in the utilities between two outcomes. Thus, the models' solution converges to the Nash equilibrium as this rationality parameter goes to infinity. It should be noted that, contrary to EUT and Prospect Theory that consider independent evaluations (*i.e.*, every option has a value that is measured by a single number) in these equilibrium models, different options are evaluated relatively to other options. This practice has been observed in people's decision-making when judging the value or size of objects. Ratings were more inconsistent, both with and between individuals, when objects were evaluated independently rather than in comparison to other objects [11].

Assessment of congestion penalties: In [7], the equilibrium strategy and the resulting per-user cost under full rationality are compared against that under the two alternative equilibrium concepts in the context of the resource selection task. The implementation of these expressions of bounded rationality increases randomness into agents' choice probabilities drawing them towards 0.5. The more different the expected costs of the two options are, the less these equilibria differ from the Nash one, since the identification of the best action becomes easier. Thus, we notice almost no or limited difference when the risk to compete for a very small benefit is high due to the significant penalty cost or the high demand. The same reason underlies the differences between the Rosenthal and the Quantal Response equilibrium. Essentially, the three equilibrium types form a three-level hierarchy with respect to their capacity to identify the less costly option, with the Quantal Response equilibrium at the bottom level and the Nash one at the top level. Overall, contrary to the risk attitude as expressed in CPT, *the inaccuracies in computing the best action as modelled in these equilibrium concepts decrease the competing probability under low to medium demand and hence, the per-user cost in these cases is drawn to near-optimal levels*.

c) Heuristic decision-making: General concept: In a more radical approach, models that rely on heuristic rules reflect better Simon's early arguments in [12] that humans are satisficers rather than maximizers.

Formulation - Heuristic decision rule: The satisficing notion in the competitive resource selection task can be applied with a simple heuristic decision rule, *i.e.*, the confidence heuristic rule, arguing that instead of computing/comparing the expected costs of choices, individuals estimate the probability to get one of the "popular" resources (based on beliefs about the activity of others) and play according to this [7]. In essence, as common sense suggests, one appears overconfident under low demand for the scarce low-cost resources and underconfident otherwise.

Formulation - Cognitive heuristics: Cognitive science suggests that people draw inferences (*i.e.*, predict probabilities of an uncertain event, assess the relevance or value of incoming information *etc.*), exploiting heuristic principles. The cognitive heuristics could be defined as fast, frugal, adaptive strategies that allow humans (organisms, in general) to reduce complex decision tasks of predicting, assessing, computing to simpler reasoning processes. Some popular instances of heuristics rely on notions such as that of recognition, priority, availability, familiarity, accessibility, representativeness *etc.*.

The various analytic models of bounded rationality that are presented in previous paragraphs, depart from the norms of classical rationality as expressed in EUT. However, people do not seem to perform the calculations that these models require, at least not under all conditions and especially in situations where there is pressure to be "rational". In other words, a criticism against these models is that they no longer aim at describing the processes (cognitive, neural, or hormonal) underlying a decision but just at predicting people's final choices for a large chunk of choice problems. Furthermore, they give no insight as to how should the corresponding models be parametrized each time.

Models that rely on cognitive heuristics originate from the cognitive psychology domain and specify the underlying cognitive processes while they make quantitative predictions. In connection to this, the parking search problem could be addressed within the framework of sequential search/optimal stopping problems (*e.g.*, mate choice, secretary problem), whereby people devise simple heuristic strategies (rules of thumb) to overcome the complexity of finding the optimal decision. Results from experiments with driving emulators reveal that drivers devise threshold-type heuristics [13]. An instance of these heuristics is the *fixed-distance heuristic*, which ignores all places until the driver reaches a specific distance from the destination and then takes the first vacant one [14]. This heuristic incorporates two fundamental practices in behavioral decision theory: one-at-a-time processing of pieces of information and the use of thresholds. Interestingly, simple rules of thumb can frequently perform as well as more sophisticated search approaches by exploiting the structure of the information in the environment (Ref. *ecological rationality* in [15]). In [16] we analytically investigate the effectiveness of fixed-distance heuristic through a game-theoretic analysis.

Assessment of congestion penalties: Interestingly, applying *the trivial confidence heuristic decision rule* to the resource selection task *leads to near-optimal results*. Unlike CPT or the alternative equilibrium solutions, it does not take into account the charging costs. Yet, it expresses a pessimistic attitude that takes for granted the failure in a possible competition with competitors that outnumber the resources. As a result, it implicitly seeks to avoid the tragedy of common effects and, eventually, yields a socially beneficial solution. Likewise, through a game-theoretic investigation and analysis of the equilibrium behaviors, we show that when the drivers are risk-averse (namely, they prefer walking than driving), *the simple fixed-distance heuristic strategy leads to optimal parking spot allocation and hence, minimum social cost.*

III. A NOTE ON INTRODUCING COORDINATION IN THE RESOURCE SELECTION PROBLEM

The negative impact of the broad resource availability awareness on the efficiency in managing distributed (public) resources could be reduced by introducing some level of coordination among the distributed competitors. One direction would be to resolve the resource competition at the price setting level through a resource auctioning mechanism, hoping that any higher prices paid are compensated for by the elimination of the congestion cost induced by the uncoordinated access to the resource [17]. Another distinct direction would be based on user subscription to an information service that coordinates in a decentralized way the usage of the resources among the user-subscribers. Besides fairness and free-riding phenomena among the subscribers, a major issue is to ensure that the presence of the service does bring benefits to the subscribers without deteriorating the position of the non-subscribers [18].

REFERENCES

[1] R. Holzman and N. Law-yone (Lev-tov), "Network structure and strong equilibrium in route selection games," *Mathematical Social Sciences*, vol. 46, pp. 193–205, 2003.

[2] C. Hasan, E. Altman, J.-M. Gorce, and M. Haddad, "Non-cooperative association of mobiles to access points revisited," in *Proc. 10th Inter. Symposium on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt)*, Paderborn, Germany, 2012.

[3] I. Ashlagi, D. Monderer, and M. Tennenholtz, "Resource selection games with unknown number of players," in *Proc. AAMAS*, Japan, 2006.

[4] E. Kokolaki, M. Karaliopoulos, and I. Stavrakakis, "Leveraging information in parking assistance systems," *IEEE Transactions on Vehicular Technology*, vol. 62, no. 9, 2013.

[5] R. C. Larson and K. Sasanuma, "Congestion pricing: A parking queue model," *Journal of Industrial and Systems Engineering*, vol. 4, 2010.

[6] A. Tversky and D. Kahneman, "Advances in prospect theory: cumulative representation of uncertainty," *J. Risk and Uncertainty*, 1992.

[7] E. Kokolaki, M. Karaliopoulos, and I. Stavrakakis, "On the human-driven decision-making process in competitive environments," in *Proc. Internet Science Conference*, Brussels, 2013.

[8] J. K. Goeree *et al.*, "Risk averse behavior in generalized matching pennies games," *Games and Economic Behavior*, 2003.

[9] R. Rosenthal, "A bounded-rationality approach to the study of noncooperative games," *Int. J. Game Theory*, pp. 273–292, 1989.

[10] R. McKelvey and T. Palfrey, "Quantal response equilibria for normal form games," *Games and Economic Behavior*, pp. 6–38, 1995.

[11] K. V. Katsikopoulos and G. Gigerenzer, "One-reason decision-making: Modeling violations of expected utility theory," *Journal of Risk and Uncertainty*, vol. 37, 2008.

[12] H. A. Simon, "Rational choice and the structure of the environment," *Psychological Review*, vol. 63, no. 2, pp. 129–138, 1956.

[13] K. V. Katsikopoulos, *Advanced guide signs and behavioral decision theory*. D. L. Fisher, M. Rizzo, J. K. Caird, and J. D. Lee. Boca Raton, FL: CRC Press, 2011.

[14] P. M. Todd *et al.*, *Ecological rationality: intelligence in the world*. New York: Oxford Univ. Press, 2012.

[15] D. G. Goldstein and G. Gigerenzer, "Models of ecological rationality: The recognition heuristic," *Psychological Review*, vol. 109, no. 1, 2002.

[16] E. Kokolaki and I. Stavrakakis, "Equilibrium analysis in the parking search game with heuristic strategies," in *2nd IEEE VTC Workshop on Vehicular Traffic Management for Smart Cities*, May 2014.

[17] E. Kokolaki, M. Karaliopoulos, and I. Stavrakakis, "Trading public parking space," in *First IEEE WoWMoM workshop on Smart Vehicles*, Sydney, Australia, 2014.

[18] ——, "Parking assisting applications: effectiveness and side-issues in managing public goods," in *3rd IEEE SASO workshop on Challenges for Achieving Self-Awareness in Autonomic Systems*, USA, 2013.