Information dissemination and consumption in competitive networking urban environments

E. Kokolaki*

Department of Informatics and Telecommunications,
National & Kapodistrian University of Athens
Ilissia, 157 84 Athens, Greece
evako@di.uoa.gr

Abstract. The focus of this thesis lies on demonstrating, investigating and understanding decision making in human-driven information and communication systems within autonomous networking urban environments and competitive contexts. Indeed, the thesis examines modern networks that integrate mobile communication devices with online social applications and different types of pervasive sensor platforms and hence, foster unprecedented amounts of information. When shared, this information can enrich people's awareness about and enable more efficient management of a broad range of resources, ranging from natural goods such as water and electricity, to human artefacts such as urban space and transportation networks. Especially in environments where users' welfare is better satisfied by the same finite set of resources, it is important to understand how the presence of competition shapes decisions and behaviors regarding the information dissemination and building of collective awareness, on the one hand, and the way collective awareness is exploited under different assumptions about the rationality levels of decision-makers, on the other hand. We investigate these questions by exploiting insights and results from different disciplines ranging from Communication Networks and Decision Theory to Behavioral Economics and Cognitive Science. Our results provide theoretical support for the practical management of limited-capacity resources since they challenge the need for more elaborate information mechanisms. They also reveal useful insights to the dynamics and benefits emerging from human behavior in situations that expose "tragedy of commons" effects.

1 Introduction

The tremendous increase of urbanization necessitates the efficient and environmentally sustainable management of various urban processes and operations. Recent advances in wireless networking and sensing technologies can address this need by enabling efficient monitoring mechanisms for these processes and higher flexibility to control them, thus paving the way for the so-called *Smart Cities*. With the dawn of Smart Cities, the emerging networking environment has dramatically changed the role of end users and resulted in unprecedented rates of information generation and diffusion.

* Dissertation Advisor: Ioannis Stavrakakis, Professor

This information can be intelligently controlled by platforms that collectively enrich people's awareness about their environment, whether this is the natural environment or the physical space they move in while working, driving, or entertaining themselves. In parallel, this knowledge promotes new forms of participatory processes and approaches to managing the resources of their environment, which can range from natural goods such as water and electricity, to human artefacts such as urban space and transportation infrastructure. Besides possibly generating information by themselves via the sensing devices they might be equipped with, the networked entities are also typically involved in disseminating this information widely, contributing to building collective awareness. Furthermore, these same entities may actually exploit this awareness of their environment to meet own needs or achieve certain individual objectives. That is, these entities are involved in the *dissemination* and *consumption* of the information.

If the disseminated information concerns the availability of some limited resources or service, then competition naturally emerges among entities desiring to use such resources. In such environments, it is important to understand how the presence of competition shapes decisions taken by these entities regarding (a) the way these entities participate in disseminating information and creating collective awareness and (b) the way collective awareness is exploited if at all. The first of these very general and fundamental questions amounts to deciding whether a networked entity will deviate from the expected behavior (*misbehave*) by hiding or falsifying resource/service availability information, aiming at reducing the competition to its advantage. The second, amounts to deciding whether a networked entity will *compete or not compete* for some limited resources.

In this thesis, we study scenarios where some finite resource is of interest to a population of distributed users with variable perceptions about the resource supply and demand for it. The high-level question we address is *how efficiently the competition about the resources is resolved under different assumptions about the way the users make their decisions*. We devise analytical and simulation models that describe the decision-making process of users concerning the dissemination and consumption of information, when faced with multiple choices. We instantiate this context in a concrete case that we can study systematically, namely an urban environment in which parking space is the resource of interest to the users-drivers and whose availability is disseminated or becomes accessible to some extent. With this information, drivers can make more informed search for parking, while municipal authorities can address more efficiently the challenge to manage the available parking space and reduce the vehicle volumes that cruise in search of it, in order to alleviate not only traffic congestion but also the related environmental burden.

2 Outline of the thesis

In this section we outline the contents of the thesis in association with the related publications.

In the introductory part, we describe fundamental concepts and principles in networking solutions for the upcoming smart city environments and present socio-tech issues, trends and challenges that arise in various application paradigms that have been developed through these networks and serve as case-studies in our research.

The thesis continues with the study of the effectiveness and side-issues of information within competitive settings. In [4] and [13], we explore how the discovery of service can be facilitated or not by utilizing service location information that is opportunistically disseminated primarily by the consumers of the service themselves. We apply our study to the real-world case of parking service in busy city areas which has attracted the interest of the research community and the private sector in the context of the so-called "Smart City" initiative. As the vehicles drive around the area, they opportunistically collect and share with each other information on the location and status of each parking spot they encounter. The parking space scenario serves as an example of opportunistic networking environments where the user-nodes can collectively gain from the sincere exchange of (parking availability) information (*i.e.*, cooperation), yet each one of them can only gain if certain information is hidden from others (potential competitors); thus, an environment, where the processes of information dissemination (benefiting service discovery) and competition (reducing the service delivery prospects) are coupled and counter-acting. This opportunistically-assisted search is compared against the "blind" non-assisted search and a centralized approach, where the allocation of parking spots is managed by a central server holding global knowledge about the parking space availability. This comparative study concludes with the observation that the availability of information is not always better than the lack of it in competitive environments, as the sharing of information assists nodes by increasing their knowledge about parking space availability but, at the same time, synchronizes nodes' parking choices. This synchronization in turn increases the effective competition and, ultimately, the congestion penalties experienced (*e.g.*, long car cruising when searching for cheap on-street parking spots in busy urban environments).

Being aware of the competition, the nodes are motivated to defer from sharing information or deliberately falsify information to divert others away from a particular area of own interest. In [6] and [12], we implement those facets of misbehaviors in the opportunistically-assisted parking search. We show that as long as the portion of misbehaving nodes is not very high, the overall performance does not deteriorate significantly, nor does the misbehaving node enjoy any notable performance improvement. This observation suggests that the spatial-temporal-interest diversity in large-scale distributed settings and the dynamicity of the environment, which may render falsified data correct or lack of outdated data advantageous, might confer robustness against misbehaviors.

In the sequel, we investigate how the competition awareness affects the decision to compete or not for some limited-capacity resource set. In essence, we are concerned with the comparison of the decision-making under full against bounded rationality conditions. Fully rational users possess all the information they need to reach decisions and, most importantly, are capable of exploiting all information they have at hand. The impact of perfect rationality is investigated in [8] by considering an environment in which the parking space is the resource of interest to the users-drivers and whose availability is disseminated or becomes accessible to some extent. Drivers decide whether to go for the inexpensive but limited on-street public parking spots or the expensive yet over-dimensioned parking lots, incurring an additional cruising cost when they decide for on-street parking spots but fail to actually acquire one. The drivers are viewed as strategic agents who make rational decisions while attempting to minimize the cost of the acquired parking spots. We take a game-theoretic approach and analyze the uncoordinated parking space allocation process as *resource selection game* instances. We derive their equilibria and quantify their (in)efficiency with the related *Price of Anarchy* values. In [11] we propose auction-based systems for realizing centralized parking allocation schemes, whereby perfectly informed drivers bid for public parking space and a central authority coordinates the parking assignments and payments to alleviate congestion phenomena. This market-based parking spot allocation is compared against the conventional uncoordinated parking search practice with fixed parking service cost. In line with intuition, the auctioning system increases the revenue of the public parking operator exploiting the drivers' differentiated interest in parking. Less intuitively, the auction-based mechanism does not necessarily induce higher cost for the drivers: by avoiding the uncoordinated search and thus, eliminating the congestion effects, it turns out to be a preferable option for both the operator and the drivers under various combinations of parking demand and pricing policies.

In [5], we relax the assumption of perfect information and study two game variants under incomplete demand information, where the agents either share common probabilistic information about the overall resource demand or are totally uncertain about it. In this case, the game solutions are derived in terms of Bayesian Nash equilibria. Essentially, Game Theory and the Nash equilibrium concept capture the agents' best responses in terms of expected utility maximization. Nevertheless, several experimental data have shown over time the limitations of the Expected Utility Theory framework to consistently explain the way human decisions are made. At the same time, they have revealed cognitive biases in the way people assess the alternatives they are presented with. Thus, we exploit insights from Behavioral Economics and Cognitive Psychology (Prospect Theory, Quantal Response and Rosenthal equilibria, heuristic reasoning) to model agents of bounded rationality who cannot exploit all the available information due to time restrictions and computational limitations [9]. We derive the operational states in which the competing influences are balanced (*i.e.*, equilibria) and compare them against the Nash equilibria that emerge under full rationality and the optimum resource assignment that could be determined by a centralized entity. Although these decision-making models are shown to predict and accommodate people's answers in various experimental data sets, they cannot describe the processes (cognitive, neural, or hormonal) underlying people's decisions. Yet, the efficient and environmentally sustainable management of various urban processes calls for novel solutions that account for behavioral decision-making in a transparent way that reflects the internal reasoning mechanisms. Indeed, transportation engineers need to be able to understand how drivers decide their route to effectively address the plethora of challenges for alleviating the congestion phenomena in city areas. In [7], we model drivers' decision-making with respect to the parking space search, which has been regarded as one of the major causes of traffic congestion. We view the parking search as an instance of *sequential search problems* and present a game-theoretic investigation of the efficiency of heuristic parking search strategies to locate available parking spot at minimum walking and driving overhead. The analytical study concludes by drawing similarities between the parking game and well-known archetypal games that Game Theory examines.

In the last part of the thesis, we seek to experimentally study some fundamental properties of vehicular social applications that have been deployed to assist in the parking search process. In [10], the awareness and incentive mechanisms that are commonly incorporated in different instances of social parking applications are modelled and simulation scenarios are considered to explore particular aspects of these applications. It is shown that application users experience improved performance due to the increased efficiency they generate in the parking search process, without (substantially) degrading the performance of non-users. This is extremely important since applications managing common (public) goods should not provide benefits to their users by penalizing or almost excluding non-users. The incentive mechanisms are effective in the sense that they do provide preferential treatment to those fully cooperating but they induce rich-club phenomena and difficulties to newcomers. Interestingly, those problems, that may be a concern for all applications managing common (public) goods, seem to be alleviated by free-riding phenomena and dynamic behaviors.

3 The resource selection environment

In this section we define the critical parameters for the resource selection environment, namely, a fairly autonomic networking environment, where each user runs a service resource selection task and seeks to maximize his benefit, driven by self-oriented interests and biases. In this setting, N agents are called to decide between two alternative sets of resources. The first set consists of R low-cost resources while the second one is unlimited but with more expensive items. When the amount of the low-cost resources is large and the interested user population is small, users can readily opt for using it. When, however, the low-cost resources cannot satisfy the demand, 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 and low-cost resources pay $c_{l,s}$ cost units, whereas those heading directly for the unlimited, but more expensive 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 suffering the results of congestion, 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 phenomena that appear in various ICT sectors when distributed and uncoordinated high volume demand appears for some limited service. Examples include congestion phenomena that emerge on a road that is advertised as the best alternative to a blocked main road due to an accident, the limited on-street public parking space in urban environments or an advertised low-cost wireless access point.

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 limited resources. However, the efficiency of these systems ultimately depends not just on the quality of the information about resources they can provide 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.

4 Fully rational decision-making

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, analyze all possible combinations of actions he and the other users can take, 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.

4.1 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 [1]. In [5] we have analyzed this task in the context of parking search application. In particular, in center areas of big cities, drivers are often faced with a decision as to whether to compete for the low-cost but scarce on-street public 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. In general, 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. Under the assumption of fully rationality, an assistance service announces information of perfect accuracy about the demand (number of users interested in the parking resources), 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, we consider automatic software agent implementations rather than human decision-makers yet, the actual human/driver undertakes the action with the assumption that he fully complies with the machines' suggestions.

We derive the drivers' behaviors at the equilibrium states of this strategic game and compare the costs paid at the equilibria against those induced by the ideal centralized system that optimally assigns the low-cost resources to minimize the social cost. We quantify the (in)efficiency of the uncoordinated resource selection using the Price of Anarchy (PoA) metric, computed as the ratio of the worst-case equilibrium cost over optimal cost. The analytical 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. In particular, for parking demand exceeding the supply ($N > R$), the number of competing drivers in the equilibrium state $N_{l,eq} = \min(N, N_0)$, with $N_0 = \frac{R(\gamma-1)}{\delta}$, exceeds the optimal number R that would compete for and succeed in getting an on-street parking spot in the ideal scenario. These congestion phenomena can be alleviated by properly manipulating the price differentials between the two types of resources. Notably, our 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 [14]. The results of this study will serve as a benchmark for assessing the impact of different rationality levels and cognitive biases on the efficiency of the resource selection process.

5 Bayesian and pre-Bayesian models

In the resource selection context, perfectly accurate information about the resource demand is hard to obtain within a dynamic and complex environment. For instance, when the agents do not possess perfect information about the resource availability, one could imagine that resource information will be disseminated in the network following some dynamics resembling epidemics. In the presence of an infrastructure-based information and sensing mechanism, 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.

5.1 Formulation

This type of bounded rationality where agents have only knowledge constraints, while they satisfy all other criteria of full rationality, *i.e.*, no computational or time constraints deteriorate 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, *i.e.*, 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, p_{act}, namely, interested in resources) to derive estimates about the expected cost of their 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 (strictly incomplete information/full uncertainty), the agents may avail some knowledge about the upper limit of the potential competitors for the resources, 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.

In [5], we extend the game formulation for the full rationality case and analyze 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. Interestingly enough, we show less-is-more phenomena under uncertainty, 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. In fact, the safety-level mixed-action equilibrium of

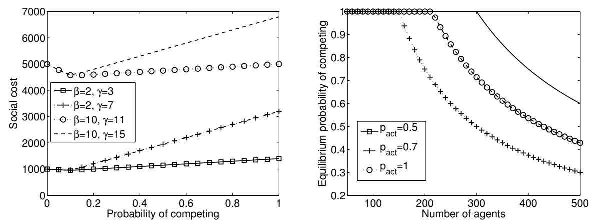

Fig. 1. Social cost for $N = 500$ agents competing for $R = 50$ resources with $c_{l.s} = 1$ (left). Probability of competing in the equilibrium for $R = 50$, $c_{l.s} = 1$, $\beta = 5$, $\delta = 2$ (right).

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 agents, on the other hand (Ref. Fig. 1). Therefore, at the safety-level equilibrium, the agents end up competing with a lower probability than that corresponding to the game they actually play and hence, they may end up paying less than they would if they knew deterministically the competition they face.

6 Behavioral desision theory

Experimental data suggest that human decisions reflect certain limitations and exhibit biases in comparing the expected utilities that come with 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 framework or completely depart from it (and its expressions as embodied in the Nash equilibrium concept) and devise alternative theories as to how decision alternatives 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.

6.1 Formulation

Cumulative Prospect Theory Tversky and Kahneman in [19] 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. 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 components of the EUT (*i.e.*, individual outcomes and corresponding probabilities) are modified. However, users are still maximizers, *i.e.*, they try to maximize the expected utilities of their prospects. In [19], the authors propose concrete functions to transform objective probabilities and outcomes with shapes that are consistent with experimental evidence on risk preferences.

In [9], we apply the CPT model to the resource selection problem, where the decisions are made on two alternatives - prospects consisting only of negative outcomes/costs, and present 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 high risk, respectively, their biased risk-seeking behavior turns to be full 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. This is in line with the theory for losses: an agent may decrease the prospect cost by switching his decision from the certain more expensive resource set to the risky low-cost one. 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.

Rosenthal and Quantal Response Equilibria Both 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 (*e.g.*, generalized matching pennies games). 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 [16] and, later, McKelvey and Palfrey in [15], 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' solutions converge to the Nash equilibria as this rationality parameter goes to infinity.

Let $c(l,p) = \sum_{n=0}^{N-1} g_l(n+1)B(n; N-1, p_l)$, where $g_l(k) = min(1, R/k)c_{l,s} + (1 - min(1, R/k))c_{l,f}$ and $B(n; N; p)$ is the Binomial probability distribution, and $c(u,p) = c_u$ denote the expected costs for choosing "low-cost/limited-capacity resource set" and "expensive/unlimited resource set", respectively, when all other agents play the mixed-action $p = (p_l, p_u)$. The Rosenthal equilibrium strategy $p^{RE} = (p_l^{RE}, p_u^{RE})$, $p_u^{RE} = 1 - p_l^{RE}$ and Quantal Response equilibrium strategy $p^{QRE} = (p_l^{QRE}, p_u^{QRE})$, $p_u^{QRE} = 1 - p_l^{QRE}$ are given as fixed-point solutions of equations $p_l^{RE} - p_u^{RE} = -t(c(l, p^{RE}) - c(u, p^{RE}))$ and $p_l^{QRE} = \frac{e^{-tc(l,p^{QRE})}}{e^{-tc(l,p^{QRE})} + e^{-tc(u,p^{QRE})}}$, respectively.

In [9], we compare the fully rational strategies against the two alternative types of equilibrium strategies and the resulting per-user costs in the context of the resource selection task. The implementation of these expressions of bounded rationality increases randomness into agents' choices and hence, draws choice probabilities towards 0.5. Second, the more different the - expected - costs of the two options are, the less the Rosenthal and Quantal Response equilibrium 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 extra penalty cost or due to the high demand for the resources. The same reason underlies the differences between the Rosenthal and the Quantal Response equilibrium. Essentially, the three types of equilibrium form a three-level hierarchy with respect to their capacity to identify the less costly resource option, with the Quantal Response equilibrium at the bottom level and the Nash one at the top level. Finally, contrary to the risk attitude as expressed in CPT, the inaccurate but frugal computation of the best action as modelled in these equilibrium concepts decreases the competing probability under low to medium demand and hence, the per-user cost is drawn to near-optimal levels.

Heuristic decision-making In a more radical approach, models that rely on heuristic rules reflect better Simon's early arguments in [17] that humans are satisficers rather than maximizers.

Heuristic decision rule: In an effort to get the satisficing notion in our competitive resource selection setting, we came up with a simple kind of 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. In essence, as common sense suggests, one appears overconfident under low demand for the scarce low-cost resources and underconfident otherwise. Interestingly, applying this trivial decision rule in the resource selection problem leads to near-optimal results. Unlike CPT or the alternative equilibrium solutions, it does not take into account the charging costs. Yet, this reasoning mode 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.

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. In the salient of heuristic-based decision theory, notions such as recognition, priority, availability, fluency, familiarity, accessibility, representativeness and adjustment - and - anchoring stand out.

The various analytical models of bounded rationality that are presented in previous paragraphs, depart from the norms of classical rationality as expressed in the Expected Utility Theory framework. 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" (*e.g.*, route and parking spot selection). 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, in [7] we analytically investigate drivers' decision-making concerning parking spot selection in city environments drawing on results from experiments with driving emulators [3]. In particular, we address the parking search problem 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. Interestingly, albeit the human cognitive limitations, time constraints and lack of full information in those reasoning contexts, 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 [2]). In this investigation, we envisage that drivers use a decision rule based on their distance from the destination, namely 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 [18]. This instance of heuristics incorporates two fundamental practices in behavioral decision theory: one-at-a-time processing of pieces of information and the use of thresholds. Through a game-theoretic investigation, 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.

7 Conclusions

In this thesis, we study networking environments where some finite resource is of interest to a population of distributed users with variable perceptions about the resource supply and demand for it. In such competitive environments, the easier acquisition of environmental information has its negative side, since it synchronizes the perception of different users about the state of resources and, at a second and most important level, their decisions. Consequently, the competition awareness should be factored in the decision (a) to distribute the availability information as expected or misbehave and (b) to go for some limited resources (compete) or not (not compete). The first question has been investigated by considering an urban environment in which the parking space is the resource of interest to the users-drivers and whose availability is disseminated through an opportunistic assistance service. The investigation of the vulnerability of this service to misbehaving nodes that either defer from sharing information or deliberately falsify information, reveals a remarkable resilience as long as the portion of misbehaving nodes is not high and a persistent fate-sharing effect between what misbehaving and cooperative nodes achieve. The second question has been investigated by considering various levels of users' rationality as expressed in the amount of available knowledge and users' computational capacity. We draw on bayesian models to capture the impact of imperfect information and exploit analytical insights from Behavioral Decision Theory to model users with processing limitations. Interestingly, counterintuitive less-is-more effects emerge where more information does not necessarily improve the efficiency of service delivery but, even worse, may hamstring users' efforts to maximize their benefit.

Likewise, very simple heuristic reasoning approaches that are devised to override the complexity of computing the optimal strategy, are shown to yield near-optimal results with respect to the social cost incurred by the user population.

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