Game Theory for Cooperation in Multi-Access Edge Computing

José André Moura
Rui Neto Marinheiro
João Carlos Silva
ISCTE-IUL, Portugal

ABSTRACT

Cooperative strategies amongst network players can improve network performance and spectrum utilization in future networking environments. These new network requisites require for a distributed and flexible management framework. Game Theory is very suitable for this framework, since it models high-complex interactions among distributed decision makers. It also finds the more convenient management policies for the diverse players, e.g. content providers, cloud providers, edge providers, brokers, network providers or users. These management policies optimize the performance of the overall network infrastructure with a fair utilization of their resources. This chapter discusses relevant theoretical models that enable cooperation amongst the players in distinct ways through namely, pricing or reputation. In addition, we highlight open problems, such as the lack of proper models for dynamic and incomplete information scenarios. The chapter finalizes by discussing a business model for future networks.

1.1. INTRODUCTION

Game Theory (GT) techniques have recently emerged in many engineering applications, notably in communications and networking. With the emergence of cooperation as a new communication paradigm, alongside the need for self-organizing, decentralized, and autonomic networks, it has become imperative to seek suitable GT tools to analyze and study the behavior and interactions of nodes in Future Networks (FNs). The final goal is to find low-complexity distributed algorithms that can efficiently manage the high-complexity future network environment formed by heterogeneous technologies, enhancing collaboration among players and punish selfish or misbehaving nodes. In addition, the new management solutions should reduce the unwanted effects of stale information (e.g. oscillation around a specific network status) by choosing the proper values, namely, for both sampling rate of network status and delay associated to the dissemination of status information amongst the network nodes. This chapter fills a hole in existing communications literature, by providing a comprehensive review about GT models/concepts that are highly relevant for enabling collaboration in FNs environments.

In FNs, distributed and intelligent management algorithms can manage (control) the network infrastructure. These algorithms create incentive mechanisms that force the players to cooperate instead of pursuing their own interest. This novel player's behavior enables the efficient usage of available (sometimes-constrained) network resources, satisfying the heterogeneous requirements of data flows. Broadly speaking, the current literature highlights two different ways to encourage cooperation (collaboration) among the players: one with a short-term control effect and the other with a long-term control effect. The first approach uses virtual payments (credit-based games) to relieve costs for relaying traffic, and the second approach enforces the creation of communities (or groups, clusters) to establish long-term relationships among the nodes (reputation-based games). The reputation-base games sustain cooperation among the players because defection against a specific node causes personal retaliation or sanction by others. In the limit, nodes that do not cooperate will not be able to use the network themselves. Effective corrective actions against cheating nodes are also required with either permanent or temporary measures. Other interesting

perspective to investigate is the deployment of hybrid solutions combining credit-based and reputation-based methods to enhance collaboration amongst players.
There is a relatively new and a very interesting set of games designated by evolutionary coalitional games that can enable more intelligent, self-adjustable, and robust algorithms for the management of FNs. In addition, the social networks, like Facebook or Flickr, can rapidly disseminate the positive impact of collaborative actions among the users of FNs (Apicella, Marlowe, Fowler, & Christakis, 2012) (Bond et al., 2012). Furthermore, the deployment in large scale of vehicular and sensor networks supported by the convergent (Moura & Edwards, 2015) and heterogeneous (Moura & Edwards, 2016) wireless access can enable some collaborative behavior amongst players.
The current chapter reviews the literature to discuss the more promising GT proposals that can incentivize the collaboration among the diverse players, aiming to use more intelligently and efficiently the available resources of FNs. This chapter has the following structure. Section 1.2 introduces and discusses important GT aspects for FNs. Section 1.3 gives the background and highlights collaborative strategies in FNs. It also presents our vision about FNs. Then, section 1.4 describes how GT can enable and enhance collaboration in FNs. Section 1.5 offers a broad GT literature survey in wireless networking. Section 1.6 discusses some relevant research work about how GT addresses the more significant functional aspects we expect to be present in FN environments. In addition, Section 1.7 discusses the business perspective for FNs. Finally, Section 1.8 concludes with relevant GT open problems to support collaboration in FNs.

1.2. DISCUSSING GAME THEORY

The current section introduces and discusses relevant aspects of GT, which can be very useful to model the emergent network environments of FNs.

Roots and Scope

The earliest predecessors of GT are economic analysis of imperfectly competitive markets of the French economist Augustin Cournot in 1838 (Dutta, 1999). The next great advance is due to John Nash who, in 1950, introduced the Nash equilibrium (NE) which is the most widely used concept in modern GT. The NE consists on a game status where no rational actor playing that game has enough incentives to deviate from its current strategy. In fact, as any player would decide to use a different strategy from the one associated to the NE state then that player would be punished in the sense that his (her) reward is reduced. Nash´s initial work created a new branch in GT grouping all non-cooperative games. Further GT historical evolution is available in (Dutta, 1999).
GT is the study of multi-person decision problems (which differentiates it from the classical decision theory) in applications drawn from industrial organization, labor economics, macroeconomics, financial economics, and international economics (Gibbons, 1992). Alongside with previous applications in Economics and Finance, GT could be applied to other completely different real world cases (Dutta, 1999). Classical GT essentially requires that all the specified players of a specific game make rational choices among a pre-defined set of static strategies. Therefore, it is fundamental in GT that each player must consider the strategic analysis that the players' opponents are making in determining that his (her) own static strategic choice is appropriate to receive the best payoff (reward) as possible. Otherwise, if other players do not influence a player’s reward, then GT is not a proper tool. In this case, it is more convenient to use constrained optimization in the place of GT. Following, we discuss how GT can create a mathematical model (e.g. matrix form) that mimics real-life scenarios with conflict situations among the players, trying to solve those conflict situations.

Matrix Games

Matrix games are those in which the payoff to a player can be determined from a matrix of payoffs. The payoffs are assigned to each element of the matrix assuming that interactions among players are pairwise. One player chooses a row of the matrix and the other chooses a column of the matrix. The intersection between the row and the column points out a unique element of the matrix. As an example, if player A’s strategy is to choose the third row and player B's strategy is to choose the first column, the resultant payoff to player A is the value in the third row and first column of the matrix. A consequence of this is that the number of strategies available to the players is finite and discrete.

The matrix games can be asymmetric or symmetric. On one hand, a game is asymmetric if players have different set of strategies and/or if players are distinctively rewarded from choosing a given strategy against an opponent with a particular strategy. A classic example of an asymmetric game is the battle of sexes that is modelled by two distinct payoff matrixes. On the other hand, a game is symmetric if players have the same set of strategies and experience the same reward of using a given strategy against an opponent with a particular strategy. A classic example of a symmetric game is the prisoner's dilemma, which can be modelled with a single matrix. Following, we discuss with further detail the prisoner's dilemma because is the classical GT approach to solve the dilemma of an individual choice between cooperate or defect (not cooperate) with others, which is the focus of the current chapter.

The prisoner's dilemma can be formulated in terms of a single payoff matrix with two players, each one with two possible strategies, as shown in Table 1. Suppose that two individuals are being held in a prison in isolated cells. In this game, regardless of what the other prisoner decides, each prisoner gets a higher pay-off by betraying the other ("defecting"). The reasoning involves an argument by dilemma: B will either cooperate or defect. If B cooperates, A should defect, since going free is better than serving 1 year. If B defects, A should also defect, since serving 2 years is better than serving 3. Therefore, either way, A should defect. Parallel reasoning shows that B should also defect. As both players choose to defect, they will be serving 2 years. Yet both players choosing to cooperate obtain a higher payoff (serving only 1 year) than both players defecting! In this way, GT results in both players being worse off than if each chose to lessen the sentence of his accomplice at the cost of spending more time in jail himself. Later, in the current chapter, we use this game to show that the cooperation among network operators is very useful to all of them. In the following text, we discuss evolutionary game theory.

Table 1: Payoff matrix of prisoner's dilemma

		Prisoner B	
		Cooperate (Silent)	Defect (Betray)
Prisoner A	Cooperate (Silent)	1, 1	3, free
	Defect (Betray)	free, 3	2, 2

Evolutionary Game Theory

In opposition to the classical GT, Evolutionary GT (EGT), states that the players aren´t completely rational. The players have limited information about available choices and consequences and their strategies are not static. In fact, the players have a preferred strategy that continuously compare with other strategies, checking if they need to change their current strategy to get a better reward (fitness). The decision to change the preferred strategy can be also influenced by other neighboring players belonging to the same population (by observation and leaning). In this way, the strategy with the highest selection score inside a group of individuals forming a community will become the predominant strategy for that generation of individuals. Then, this strategy is transferred to the next generation of individuals (evolutionary aspect). Following, we discuss how EGT can model the upcoming scenarios of FNs. These future scenarios will be more complex and dynamic than current networking scenarios. Table 2 briefly compares traditional GT with EGT.

Table 2: Comparison between traditional GT and EGT.

Game Characteristic	Traditional GT	EGT
Pure strategies	Yes	No
Strategy adaption over time	No	Yes
Hyper rational behavior	Yes	No

Equilibria is always possible	No (in some scenarios due to restrictions on the strategy options)	Yes (i.e. at least it discovers an asymptotic equilibrium due to unrestricted strategy space)
Model dynamic and high complex game	No	Yes

EGT has been developed as a mathematical framework to study the interaction among rational biological agents in a population. In evolutionary games, the agent revolves the chosen strategy based on its payoff. In this way, both static and dynamic behavior of the game can be analyzed (Han, Niyato, Saad, Baar, & Hjrungnes, 2012). In this way, on one hand, evolutionary stable strategies (ESS) are used to study a static evolutionary game. On the other hand, replicator dynamics is used to study a dynamic evolutionary game.
EGT usually considers a set of players that interact within a game and then die, giving birth to a new player generation that fully inherits its ancestor's knowledge. The new player strategy is evaluated against the one of its ancestors and its current environmental context. Also, through mutation, a slightly distinct strategy may be selected by a set of players belonging to a specific generation, probably offering better payoffs. Next, each player competes with the other players within the evolutionary game using a strategy that increases its payoff. In this way, strategies with high payoffs will survive inside the system as more players will tend to choose them, while weak strategies will eventually disappear. Following, we present a tutorial in how EGT can be applied to wireless networks (Y. Zhang & Guizani, 2011).
Formally, we should consider within an evolutionary game an infinite population of individuals that react to changes of their environmental surroundings using a finite set of n pure strategies S = {s_1, s_2, …, s_n}. There is also a population profile, i.e. x = {x_1, x_2, …, x_n}, which denotes the popularity of each strategy $s_i \in S$ among the individuals. This means that x_i is the probability that a strategy s_i is played by the individuals. By this reason, x is also designated by the set of mixed strategies.
Consider an individual in a population with profile x. Its expected payoff when choosing to play strategy s_i is given by f (s_i, x). In a two-player game, if an individual chooses strategy s_i and its opponent responds with strategy s_j, the payoff of the former player is given by f (s_i, s_j). In a more generic way, the expected payoff of strategy s_i is evaluated by (1), whereas the average payoff is given by (2).
The replicator dynamics is a differential equation that describes the dynamics of an evolutionary game without mutation (Y. Zhang & Guizani, 2011) (Taylor & Jonker, 1978). According to this differential equation, the rate of growth of a specific strategy is proportional to the difference between the expected payoff of that strategy and the overall average payoff of the population, as stated in (3). Using this equation, if a strategy has a much better payoff than the average, the number of individuals from the population that tend to choose it increases. On the contrary, a strategy with a lower payoff than the average is preferred less and eventually is eliminated from the system set of strategies.
Considering now the mutation issue, suppose that a small group of mutants $m \in [0,1]$ with a profile $x' \neq x$ invades the previous population. The profile of the newly formed population is given by (4). Hence, the average payoff of non-mutants will be given by (5) and the average payoff of mutants will be given by (6). In this context, a strategy x is called evolutionary stable strategy (ESS) if for any $x' \neq x, m_{mut} \in [0,1]$ exists such that for all $m \in [0, m_{mut}]$, then equation (7) holds true. In this way, when an ESS is reached, the population is immune from being invaded by other groups with different population profiles. By other words, in this context the population is not affected by mutation issues.

$$f_i = \sum_{j=1}^{n} x_j \,.\, f(s_i, s_j) \qquad (1)$$

$$f_x = \sum_{i=1}^{n} x_i \,.\, f_i \qquad (2)$$

$$\dot{x} = x_i \,.\, (f_i - f_x) \tag{3}$$

$$x_{final} = m.x' + (1-m)\,.\,x \tag{4}$$

$$f_{x_{final}}^{non-mutant} = f\left(x, x_{final}\right) = \sum_{j=1}^{n} x_j . f(j, x_{final}) \tag{5}$$

$$f_{x_{final}}^{mutant} = f\left(x', x_{final}\right) = \sum_{j=1}^{n} x'_j . f(j, x_{final}) \tag{6}$$

$$f_{x_{final}}^{non-mutant} > f_{x_{final}}^{mutant}. \tag{7}$$

EGT may be successfully applied to model a variety of network problems. The authors of (Y. Zhang & Guizani, 2011) review the literature concerning the applications of EGT to distinct network types such as wireless sensor networks, delay tolerant networks, peer-to-peer networks and wireless networks in general, including heterogeneous 4G networks and cloud environments. In addition, (Han et al., 2012) discusses selected applications of EGT in wireless communications and networking, including congestion control, contention-based (i.e. Aloha) protocol adaptation, power control in CDMA, routing, cooperative sensing in cognitive radio, TCP throughput adaptation, and service-provider network selection. By service-provider network selection, (Han et al., 2012) suggests EGT to study different scenarios:

- user churning behavior that impacts the revenue of service providers;
- user choice among candidate service providers of the access network that maximizes the perceived QoS for a service type.

In (Nazir, Bennis, Ghaboosi, MacKenzie, & Latva-aho, 2010), an evolutionary game based on replicator dynamics is formulated to model the dynamic competition in network selection among users. Each user can choose a service class from a certain service provider (i.e. available access network). They present two algorithms, namely, population evolution and reinforcement-learning for network selection. Although the network-selection algorithm based on population evolution can reach the evolutionary equilibrium faster, it requires a centralized controller to gather, process, and broadcast information about the users within the corresponding service area. In contrast, with reinforcement learning, a user can gradually learn (by interacting with the service provider) and adapt the decision on network selection (through a trial-and-error learning method) to reach evolutionary equilibrium without any interaction with other users.

Some work (Nazir et al., 2010) (Bennis, Guruacharya, & Niyato, 2011) investigated and compared the convergence behavior of Q-learning with EGT to enable a satisfactory performance of cellular networks with femtocells. The authors of (Nazir et al., 2010) introduce two mechanisms for interference mitigation supported by EGT and machine learning. In the first mechanism, stand-alone femtocells choose their strategies, observe the behavior of other players, and make the best decision based on their instantaneous payoff, as well as the average payoff of all other femtocells. They also formulate the interactions among selfish femtocells using evolutionary games and demonstrate how the system converges to equilibrium. By contrast, using the second mechanism (i.e. reinforcement learning), the information exchange among femtocells is no longer possible and hence each femtocell adapts its strategy and gradually learns by interacting with its environment (i.e., neighboring interferers). The femtocells can self-organize by relying only on local information, while mitigating interference inside the macrocell. In this way, the macrocell user can meet its Quality of Service requirements. They have concluded that the biologically inspired evolutionary approach converges more rapidly to the desired equilibrium as compared to the reinforcement learning and random approach. Nevertheless, this faster convergence requires more context information at the femtocells. The authors of (Bennis et al., 2011) reached equivalent results as (Nazir et al., 2010).

Further references that address EGT applications to the networking area are available for wireless (M. A. Khan, Tembine, & Vasilakos, 2012a) (M. A. Khan, Tembine, & Vasilakos, 2012b) and wireline (Eitan Altman, El-Azouzi, Hayel, & Tembine, 2009) networks. The impact of evolutionary games in future wireless networks is analyzed in (Tembine, Altman, El-Azouzi, & Hayel, 2010). Evolutionary models have been also proposed for hierarchical mobile (Semasinghe, Hossain, & Zhu, 2015) (Lin, Ni, Tian, & Liu, 2015) and vehicular (Shivshankar & Jamalipour, 2015) networks. In the text below, we discuss the Stackelberg game, which it is like a NC repeated game.

Stackelberg Game

Figure 1 shows the model of a Stackelberg game (SG). This game is like a Non-Cooperative (NC) game but instead of the players playing a single shot as a typical NC game, the players execute the SG game via a step-by-step way. In addition, a SG has a player, designated by a leader that has the highest priority to take the first action. However, before doing that, the leader observes other players' strategies. Then, the leader announces its preferred strategy to the remaining players, also designated by followers. The followers perceive the leader's action and adjust their strategies to minimize their own cost. After, the followers reveal their strategies again to the leader. In summary, the SG model is a sequential one with hierarchical decision-making that analyses the interaction between a leader (or leaders) and a set of followers to achieve a specific set of model goals. The final aim of a SG model is to discover the Stackelberg Equilibrium (SE), i.e. (Strategy_leader, Strategy_follower). We conclude that SE is an evolution from a NC game, where the former model adds two novel aspects: action observation and stage repetition.

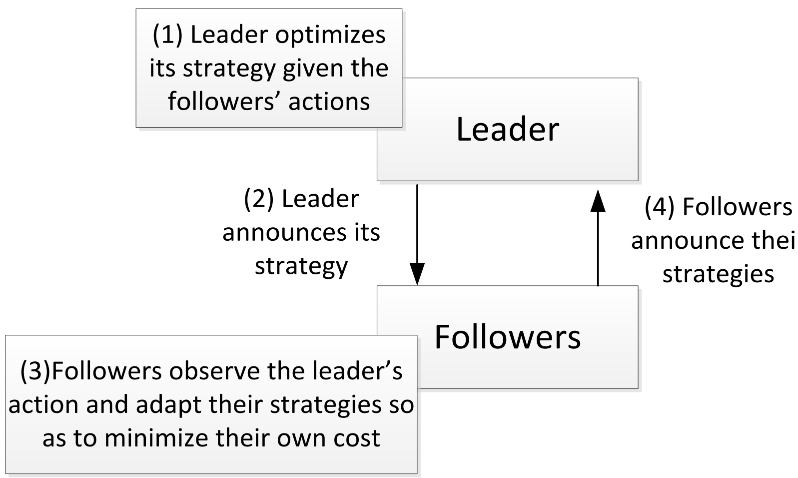

Figure 1: Steps of a Stackelberg Game Theory.

Some applications of SE games are: Software Defined Networking (SDN) scenarios, where the SDN controller is the Leader; Femtocell power control (Han et al., 2012) in hierarchized mobile networks; and device-to-device (D2D) communication (Zhu & Hossain, 2015). The main advantage of using a SG model is to optimize diverse virtualized resources (e.g. computation, storage, and networking) of very complex topologies at the network edge under users' Quality of Experience. The main challenges the network designer should be aware of are as follows: i) implement a robust mechanism to ensure the correct and synchronous shift among leaders and followers; ii) the Stackelberg Equilibrium (SE) could give a worst result than NE due to the hierarchical decision-making process among leaders and followers (Han et al., 2012); and iii) a SE game requires complete and perfect information about other strategies and payoffs. In this situation, communication jitter among a leader and followers of a SG could disrupt the right control sequence and create instabilities on the control loop, affecting the obtained results from that model. In the next section, we discuss a model game that deals with a real problem that each player could have. It is related with the player uncertainty (full or partial) about the other players decisions. In this way, the players hardly predict how the pool of network resources shared among all them will be used.

Bayesian Game

In a Bayesian game (BG) the players have incomplete information about their environment (Y. Zhang & Guizani, 2011). This can occur due to some practical physical impairments that counteract the global dissemination among the nodes of useful information about the status of the system being studied, e.g. channel gain (Duong, 2016). Following Harsanyi's work (Harsanyi, 2004), a BG has a special player with random behaviour, i.e. 'Nature'. These games are called Bayesian because they require a probabilistic analysis. Players have initial beliefs about others' payoff functions. A belief is a probability distribution over the possible types for a player. Then, the initial beliefs might change based on the actions the players of the game have taken. As a game with incomplete information is repeated, the folk theorem (Fudenberg & Maskin, 1986) can find its social-optimum solution. The game also enables a distributed model to study the system. In this way, this game type can support user privacy as users do not need to disclose private data to an external centralized server or controller. However, it could be complicated to find the Bayesian NE, due to the dynamic characteristic of this game, where the players adjust their decisions based on their learning from the acquired information during the time the game is played (Han et al., 2012). The players' learning could be adversely affected also by jitter, security attacks, interference, errors, available battery energy to transmit, system unpredictability, etc. The reader could find in (Böge & Eisele, 1979) a comparison between a BG and a non-BG. In (Chawla & Sivan, 2014) a Bayesian mechanism design is also explained.

We have found in the literature some BGs for wireless networking environments. These games cover the following areas: hierarchical small cells (Bu, Yu, & Yanikomeroglu, 2015) (Z. Khan, Lehtomaki, DaSilva, Hossain, & Latva-aho, 2016) (Duong, Madhukumar, & Niyato, 2016); D2D communications (Kebriaei, Maham, & Niyato, 2015) (Xiao, Chen, Yuen, Han, & DaSilva, 2015) (Yan, Huang, & Wang, 2013)(Yan, 2013); vehicular scenarios (Duong et al., 2016) (Kumar, Misra, Rodrigues, & Obaidat, 2015) (Kumar, Zeadally, Chilamkurti, & Vinel, 2015); and wireless sensors (Kumar, Chilamkurti, & Misra, 2015) (La, Quek, Lee, Jin, & Zhu, 2016) (Zheng, Liu, & Qi, 2012).

<u>Mechanism Design</u>

There is a subfield of GT designated by Mechanism Design (MD) that allows a game designer to define initially the desired outcome and then specify the game rules to achieve that outcome (Han et al., 2012, 221-252). This is the opposite of game analysis, in which the game rules are predefined and then the outcome is investigated, as shown in Figure 2. That is why MD is also designated as reverse GT.

A very important result in MD is the Revelation Principle that states for any Bayesian Nash Equilibrium is associated a Bayesian game with the same equilibrium outcome but in which players truthfully report their choices (it could be a preference list), which simplifies the game analysis, eliminating the need to consider either strategic behavior or lying. So, no matter what the mechanism, a designer can confine attention to equilibrium in which players only report truthfully. To accomplish this, the model needs to consider incentives for players to truthfully cooperate among them, optimizing the game outcome.

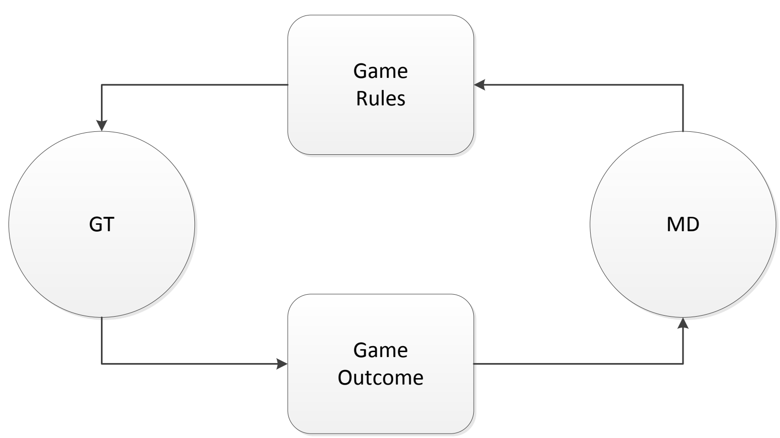

Figure 2: Game Theory (GT) vs. Mechanism Design (MD).

1.3. BACKGROUND AND TRENDS IN FUTURE NETWORKS

According to the Cisco Global Forecast (CISCO, 2016) more than three-fourths of the world's mobile data traffic will be video by 2021. From the same source, sixty percent of total mobile data traffic was offloaded onto the fixed network through Wi-Fi or femtocell in 2016. This traffic offloading occurs due to the lack of capacity in the mobile network infrastructure, originally dimensioned to support only voice and messages. The traffic offloading is one possible solution to mitigate congestion, avoiding the loss on the perceived quality by users' applications.

However, the first approach to the problem has been to perform an inter-technology handover between available technologies, with all the traffic routed through the most convenient access technology. A survey about mobility is available in (Fernandes & Karmouch, 2012). In our opinion, a better usage of available resources on the network-edge with a more fine-grained traffic management based on flows (e.g., Web traffic, VoIP) should alleviate the negative impact of network congestion, which has been reported very often essentially in the mobile broadband access. Multi-interface handheld terminals will soon have the battery autonomy and the capability to perform network access using simultaneous multi-radio access technologies (RAT). In addition, it is of particular interest the support of simultaneous data/multimedia flows through different access systems (LTE-A, WLAN, Wimax). Recent works (Yap et al., 2012) (Silva, Marinheiro, Moura, & Almeida, 2013) (Moura & Edwards, 2015) (Moura & Edwards, 2016) (Alves, Silva, Neto Marinheiro, & Moura, 2018) propose that mobile multimode terminals should use all the available connectivity options simultaneously. The mobile terminal should choose dynamically the most suitable network to each flow, obtaining faster connections by stitching flows over multiple networks, decrease the usage cost by choosing the most cost-effective network that meets application requisites, and reduce the energy consumption by selecting the technologies with the lowest energy-usage per byte. The management of the flows per network interface may not only be implemented independently by the terminal, but also be assisted transparently by the network (Alves et al., 2018).

This concept for FNs contributes to the perspective of integrating complementary access technologies with overlapping coverage to provide the expected ubiquitous coverage and to achieve the Always Best Connected (ABC) concept (Louta, Zournatzis, Kraounakis, Sarigiannidis, & Demetropoulos, 2011). This concept allows a flow to use at any time the most suitable access network/Network Attachment Point (NAP). This management of flows should be done in a distributed way with low complexity and reliable algorithms/protocols in networks formed by heterogeneous access technologies, where the most part of involved nodes should cooperate. Network brokers such as in (Moura & Edwards, 2016) follow on this idea. Brokerage systems, possibly implementing GT algorithms, can manage the network architecture, in which distributed nodes discover relevant context information to enhance the usage of local available connectivity resources (Mateus & Marinheiro, 2010). In this way, mobile operators can develop policies for IP flow mobility, and control which traffic is routed over different access technologies (Alves et al., 2018).

Another aspect to consider is that the Internet was initially designed to support communications between remote hosts. Since its early days, the Internet has evolved drastically, with a huge evolution in broadband access penetration and dissemination of mobile terminals with unforeseen capacities. This evolution has altered the Internet into a medium to connect people in multiple ways with content made available in completely new and complex modes through the entire network infrastructure. In fact, current users are more interested in searching for information over Google, watch videos on YouTube, and share files via Dropbox than to worry about connectivity to a particular host.

This content demand has catalyzed an exponential growth of Internet traffic volume and content distribution is increasingly becoming more centric in the Internet, and this is challenging and changing how the Internet is being organized.

Content delivery network (CDN) operators, content providers as well as ISPs are important players to consider in the typical content-centric cases of FNs. However, these players interact with a mix of technologies that are difficult to manage in a comprehensive and global ways.

Research efforts have been made to move the Internet away from its current reliance on purely point-to-point primitives and, to this end, have proposed detailed designs that make the Internet more data-oriented or content-centric (Jacobson et al., 2009)(L. Zhang et al., 2014). As such Information-centric networking has emerged as a new approach in the research community (Cheriton & Gritter, 2000) (Ahlgren, Dannewitz, Imbrenda, Kutscher, & Ohlman, 2012) to integrate content delivery as a native network feature and make networks natively content-aware.

Due to this, FNs most probably will sustain the next generation of the Internet infrastructure, interconnecting people and content through mobile cloud networks (as said before, the Internet is evolving from a node discovery to enable the discovery of specialized objects). These cloud networks will operate on an always best-connected scenario, where a person is allowed to choose the best available access technology (from small cells to standard base stations), access network and terminal device at any point in time. Generally, the idea is to enhance FNs to automatically interpret, process, and move content (information) independently of users' location. Additionally, the traditional approach, where resources are provided by remote clouds, is also not capable of giving adequate response to the fast-growing number of connected devises and their resource requirements. For all these reasons, new cloud architectures have been evolving, by migrating resources, such as services and data, closer to end users and devices (Figure 3).

With remote clouds, devices communicate directly with traditional distant resource-rich servers. These clouds can provide unlimited resources, but this approach does not easily scale, and long latency, bandwidth bottleneck, communication overhead, and location blindness is experienced. In face of this, it is necessary to bringing computing resources closer to end-users, to overcome the limitations of remote cloud computing (C. Li, Xue, Wang, Zhang, & Li, 2018). This is on the genesis of the edge computing paradigm, that allows more responsive cloud services, accomplished by extending the services from the core in cloud data centers to the edge of the network, by placing intermediate nodes between the cloud and the end user, which are responsible for better serving ubiquitous smart devices, fulfilling user resource requests.

Edge computing may follow different architecture implementations such as cloudlets, fog computing, or Multi-Access Edge Computing (MEC).

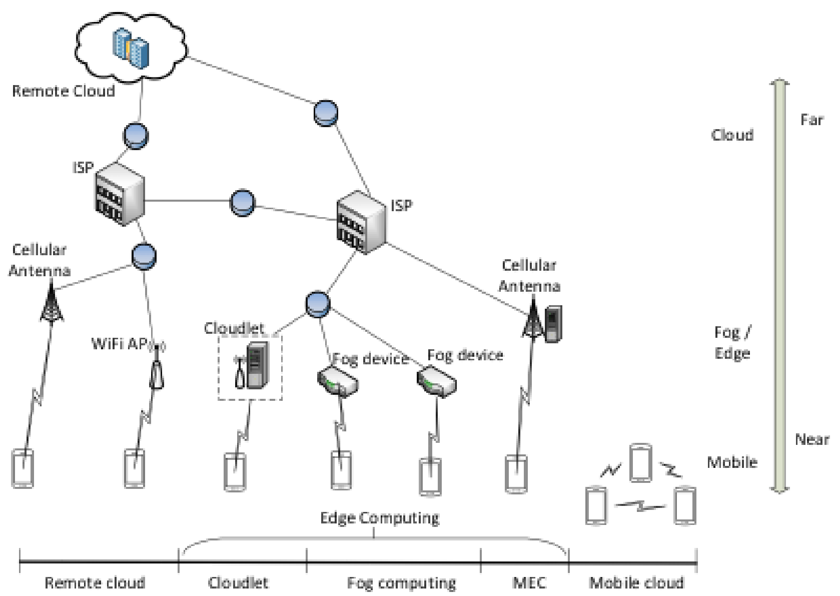

Figure 3: Cloud architectures providing services to end devices

Cloudlets (Jararweh, Tawalbeh, Ababneh, Khreishah, & Dosari, 2014) are trusted devices or a cluster of devices with high capabilities. They are most often installed along with Access Points (AP) to allow mobile devices to access it, and in some cases both of the cloudlet and AP are integrated in one entity. Fog Computing is a term introduced by Cisco Systems (CISCO, 2015). Their rationale for coining this term is that a fog is nothing more than a cloud that is closer to the ground. Fog computing's main feature is that the fog system is deployed close to end users in a widely distributed manner (Yi, Li, & Li, 2015) (C. Li et al., 2018), in the form of fog nodes (Tordera et al., 2016), possibly at different levels and numbers (Balevi &

Gitlin, 2018). The MEC paradigm (Taleb et al., 2017) was introduced by an industry lead initiative (ETSI 2014), to provide IT and cloud-computing capabilities within the Radio Access Network (RAN) in close proximity to mobile subscribers. Mobile network operators will allow the use of the access network, where low latency and high-bandwidth as well as direct access to real-time radio network information (such as subscriber location, cell load, etc.) is available. This can be used to allow content, services and applications to be accelerated, increasing server responsiveness from the edge. Additionally, MEC servers are context aware, as they manage information on end devices, such as their location and network information. Nevertheless, their capacity is limited, therefore deciding which and how resources can be managed at the edge can still be a trick endeavour (Gabry, Bioglio, & Land, 2016).

The clouds are migrating even closer to end users, with new computing architectures where mobile devices use their extra resources in a coordinated manner, to support cloud services. This contrasts with the previous edge implementations, where the mobile device's exclusive role in the cloud was that of a consumer. There is a myriad of proposals, either with centralised control, such as Hyrax (Marinelli, 2009) and FemtoClouds (Habak, Ammar, Harras, & Zegura, 2015), or a decentralised control, where nodes keep track of their own resources, such is the case with EECRS (Hu, Zhu, Xia, Chen, & Luo, 2012) (Lu et al., 2013), Phoenix (Panta, Jana, Cheng, Chen, & Vaishampayan, 2013), Mobile Host (Srirama & Paniagua, 2013) and (Monteiro, Silva, Lourenço, & Paulino, 2015).

This migration of clouds, to the proximity of users, in particular in the extreme case of clouds supported by autonomous mobile devices, brings new challenges regarding resource management. Once again this portrays a perfect scenario to apply game theoretic approaches, where conflicting interests have to be mediated.

Another trend gaining momentum for FNs is the Internet of Things (IoT). However, the IoT paradigm is not new (Corcoran, 2016), but building end-to-end IoT systems from scratch has always been a challenging and a risky enterprise, many times with ambiguous and uncertain business cases. To overcome this, a new trend in IoT, engaged by a surge of companies, is the building of complete solutions that encapsulate aspects of an end-to-end IoT system using building blocks that can be used in a repeatable and replicable way. These aggregated building blocks materialize many IoT platforms that allow companies to reduced development and deployment time and costs, and allow the creation of new business models, such as paying per use or fixed licensing. (Gluhak et al., 2016) provides an exhaustive review on different IoT platforms. In fact, IoT platforms have become so popular, which are present over 360 platforms on the market, with many more providers and consumers of this kind of platforms. The diversity of players at stake sometime have conflicting goals, and this challenge is an ideal use case for game theory approaches, such is the case with resource management (Semasinghe, Maghsudi, & Hossain, 2017).

But the IoT paradigm is progressing even further influencing new developments in various domains, such as the Internet of Mobile Things (IoMT), Autonomous Internet of Things (A-IoT), Autonomous System of Things (ASoT), Internet of Autonomous Things (IoAT), Internet of Things Clouds (IoT-C) and the Internet of Robotic Things (IoRT) (Vermesan et al., 2017), where new challenges are at stake. In fact, the initial tendency of centralized platforms, usually deployed at a remote cloud, following the classic centralized computing paradigm, faces several of such challenges such as high latency, low capacity and network failure. Because of these, the trend is now evolving to more distributed IoT platforms that can also, but not only, deployed at edge. This follows the same principles of fog computing to bring the cloud closer to IoT devices. The fog can provide IoT data processing and storage locally, instead of sending them to remote clouds, providing services with faster response and greater quality, enabling the IoT to provide efficient and secure services for many IoT users. (Atlam, Walters, & Wills, 2018) and (Mahmud, Kotagiri, & Buyya, 2018) reviewed pertinent state-of-the-art fog computing architectures and emerging IoT applications that will be improved by using the fog model, highlighting the benefits and implementation challenges. In these approaches, distributed resource management is usually more difficult to attain, and IoT devices are more than ever expected to act smart and resolve diverging goals. Once again, this is also a good used case for game theory approaches.

There are many applications for the IoT that include smart cities, like smart vehicles, surveillance systems, traffic monitoring, and smart parking, or homes and communities, like smart homes, wearable devices/mobile phones, healthcare, and hospitals, or the industry like business and production lines factories, or even agriculture, like automation and precision agriculture, and so on. This diversity of uses cases has also lead, regarding communication technologies, to the proliferation of a myriad of multi-radio access technologies for IoT, sometimes optimized to specific applications, to connect devices at the edge. (Vermesan et al., 2017). This has generated heterogeneous mobile networks that need complex configuration, management and maintenance, where it is important to have devices that play a more active role, at the edge of the network, making decisions and performing tasks without human intervention.

One of the major challenges for the the FN is how to achieve security in a growing networked world of distributed devices and services. To overcome this, blockchain and smart contracts have been a key technology to consider. The idea that supports blockchains, also referred to as distributed ledgers, is that distributed users maintain a public and identical dynamic digital register of all transactions that have taken place. The history of the recorded transactions alone determines the ownership, so it is imperative that transactions within this database are audited and agreed upon by consensus (Mingxiao, Xiaofeng, Zhe, Xiangwei, & Qijun, 2017). This decentralized method of keeping track of changes ensures the ledger cannot be practically controlled by any one entity. It also eliminates the possibility of single-points of failure and allows for the verification of transactions without the need for third-party intervention. The seminal paper for the Bitcoin protocol (Nakamoto, 2008) has triggered all this. With a blockchain in place, applications that could previously run only through a trusted intermediary, can now operate in a decentralized manner, without the need for a central authority, and achieve the same or better functionality with the same amount of certainty. This has prompted a new wave on security supported by blockchains and smart contracts, in several fields relevant for the FN such as the IoTs (Christidis & Devetsikiotis, 2016) and Wireless Mesh Networks (Selimi, Kabbinale, Ali, Navarro, & Sathiaseelan, 2018).

Blockchain technology can very well change and even disrupt future network (Mougayar, 2016) (Marsal-Llacuna, 2018) in several ways: it's reliable peer-to-peer communication model can lend to more effective IoT ecosystems; applications can be developed and hosted within decentralized storage environments, data bases can be connected using smart contracts; the overhead of managing and tracking large networks of devices without the need for a centralized controller could be reduced; network management could be further simplified using self-executing smart contracts, programmed to perform actions when certain requirements are met; transferring assets could be streamlined, in cloud-based architectures where edge devices are playing a greater role in networking; distributed and cooperative cloud storage environment over a peer-to-peer network could be possible.

Of course, the upcoming design of FNs (MEC/FC/IoT/Security) scheme to operate in a satisfactory way, a great number of very demanding requirements must be fulfilled, not only technical ones (e.g. autonomic self-x requisites with cognitive radios like self-learning) but also in terms of business relationships among operators and service providers, as well as, the handling of the service subscription.

The course of finding a solution that can satisfy all the involved entities in the high complex network environment of FNs, like content providers, cloud providers, home providers, brokers, network providers or users, can be found by means of GT (Moura & Hutchison, 2018). In this way, as the players define their strategies then the GT can find ways to build-up win-win situations for all of them. Cooperation between technologies and/or providers, alongside Machine to Machine (M2M) communications or Internet of Things deployment will require complex and dynamic management algorithms to maximize network efficiency, pricing, Quality of Service (QoS), Quality of Experience (QoE) and ultimately, profit.

Considering all previous facets, we foresee that FNs will have to form a network infrastructure with a collective intelligence, as shown in Figure 4. This intelligence is very pertinent in FNs to address emergent traffic requisites, the management complexity of the heterogeneous wireless access technologies, and the challenges faced by a more content and data centric network.

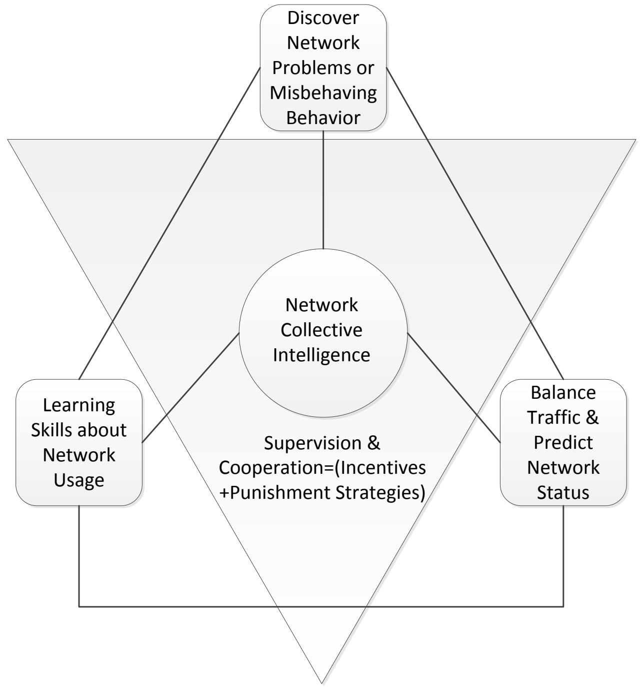

Figure 4: Collective Intelligence in FNs to manage emergent traffic and functional requisites.

To enhance the network intelligence, the future network infrastructure needs to be supervised in order to enable learning processes on management algorithms when these control some network problems (e.g. congestion situation, node misbehaving behavior). In this way, the network intelligence will be enhanced, enabling the network infrastructure to manage the high complex future heterogeneous access infrastructure in a much more efficient way. As an example, the load could be balanced among the diverse wireless access technologies, reacting to a detected congestion situation to mitigate its negative effects. Alternatively, the load could be also balanced in a flash crowd scenario where a network problem is predicted and some policies are applied to the network to avoid the occurrence of that problem, e.g. offloading flows from the technology that soon could become disrupted to other available technologies with low levels of traffic load. In addition, congestion situations could be controlled by limiting the transmission rate of some users and freeing network resources to others. The one-billion-dollar question that remains to be answered is to find out the more efficient levels of aggressiveness of the algorithm that dynamically increases/decreases the rate transmission in a high complex networking scenario with diverse wireless access technologies and flow requirements.

To enable the network collective intelligence, we argue that it is important to obtain cooperation among the nodes. In this way, the network nodes need to be incentivized to cooperate, and the nodes that do not cooperate should be detected in a truthful way and be gradually penalized (e.g. their access rate is diminished). Eventually, uncooperative nodes that afterwards would change to a cooperative behavior, they could have their reputation values being restored to values that allow them to use again the network resources without any restriction on their access rate.

In practical terms, the FNs should require distributed management algorithms to support the network self-configuring feature. GT seems a very important area to model, analyze and decide how these distributed algorithms need to be deployed. In the following Section, we discuss some literature contributions that use theoretical games to enhance the cooperation among the diverse network players.

1.4. GAME THEORY CONTRIBUTIONS FOR ENHANCING NETWORK COOPERATION

FNs will be demanding for the deployment of novel management solutions aiming more efficiently and fairly usage of the available network resources. To accomplish the overall network goals, the nodes should collaborate or cooperate essentially in a multi-hop network topology, the typical scenario of future heterogeneous and high-complexity networks. For example, a terminal node should process both related and non-related traffic, whereas non-related classifies traffic not originated (not destined) from (to) that node. This new collaborative functionality will become possible at the physical layer in future multi-hop wireless networks because the network edge infrastructure will be vastly deployed by radio technologies, which allow the easy share of data messages among local terminals due to their broadcast transmission characteristic.

A very significant number of researchers have proposed GT models to encourage players (terminals and networks) to cooperate and enhance the overall network performance instead for acting selfishly to optimize their own performance. In this way, some additional incentives are required in FNs to enable collaboration among the nodes, defeating eventual misbehaving nodes like selfish or malicious ones. A selfish node may refuse to forward a non-related message to save its battery. In this way, this node needs a correct incentive to forward traffic, e.g. the network could increase the throughput of flows originated (destined) from (to) that node as a reward to previous collaboration in forwarding non-related traffic. Alternatively, a malicious node may try to disrupt the network functionality; in this case, the network could isolate that node from the network for a certain period as a punishment to that wrong procedure.

Broadly discussing, the right incentives to the nodes collaborate among them can be divided in two large groups: monetary-based and reputation-based. On one hand, the monetary-based solutions typically aim to achieve short/medium-term relationships among nodes. On the other hand, the reputation-based solutions typically aim to establish long-term relationships among nodes. This section will be highlighting some relevant work from these two groups, which is summarized in Figure 5.

The first group of contributions makes use of virtual payments for channel use and to incentive the collaboration among nodes in a multi-hop wireless network topology, as shown in Figure 6. Here, there are typically three types of nodes: the senders, the forwarders (intermediates) and the destination nodes. Some proposed credit-based systems suggest that distinct node types should be charged to cover the costs for packet forwarding. In fact, some proposals suggest that only the senders should be charged with a tariff initially specified (Zhong, Chen, & Yang, 2003) (L. Buttyan & Hubaux, 2000) (Buttyán & Hubaux, 2003) (Ileri, Siun-Chuon Mau, & Mandayam, 2005) (Shastry & Adve, 2006) (Chen, Yang, Wagener, & Nahrstedt, 2005) (T. Alpcan, Basar, Srikant, & Atman, 2001) (Saraydar, Mandayam, & Goodman, 2002) (Vassaki, Panagopoulos, Constantinou, & Vázquez-Castro, 2010). Alternatively, the destination nodes are charged (L. Buttyan & Hubaux, 2000) (Hua Liu & Krishnamachari, 2006) or destination and senders are both charged (Levente Buttyan & Hubaux, 2001) (Yanchao Zhang, Wenjing Lou, & Yuguang Fang, 2004). In addition, an incentive mechanism called bandwidth exchange was proposed in (D. Zhang, Ileri, & Mandayam, 2008), where a node can delegate a portion of its bandwidth to another node in exchange for relay cooperation. Finally, a different approach of credit-based schemes appear in (Chen & Nahrstedt, 2004) (Demir & Comaniciu, 2007), where auction-based incentive models are proposed. The basic idea of these schemes is that each intermediate node operates as a market; the users of the network put bids for their packets, the packets are accordingly scheduled to transmission and then charged after their transmission. The goals to achieve with auction models could be node truthful bidding and social network welfare maximization (Chen & Nahrstedt, 2004) or balancing residual battery energy and the current currency (credit) levels of the nodes in the network (Demir & Comaniciu, 2007).

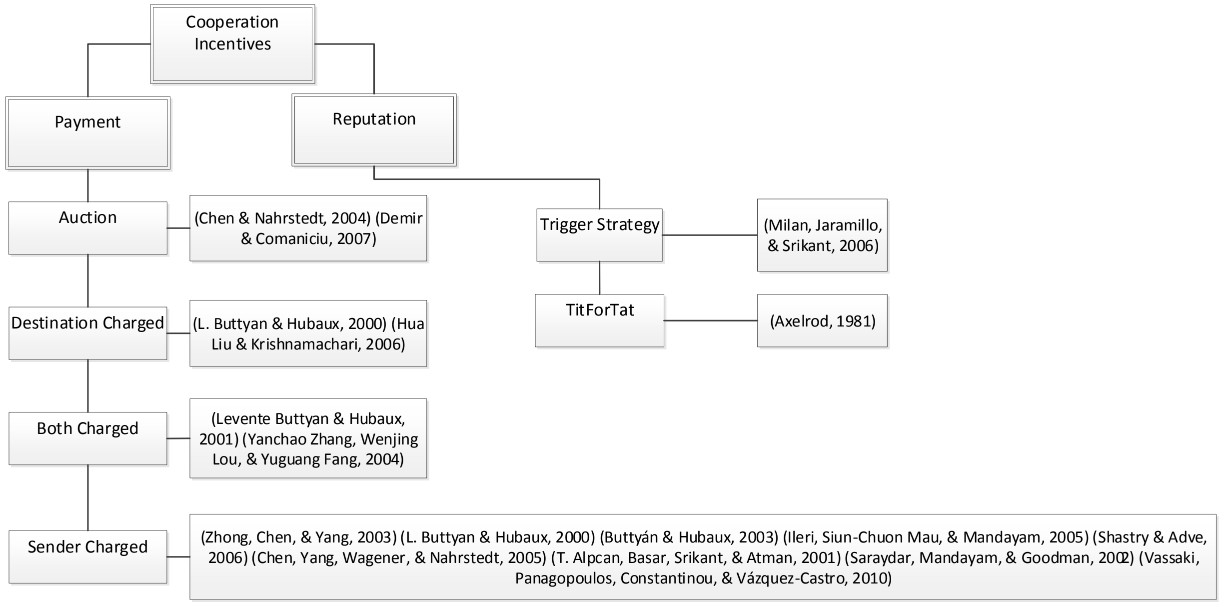

Figure 5: Summary of Game Theory Work Supporting Cooperation Incentives.

The main advantage of credit-based approaches is that they succeed in large-scale networks to enforce a distributed cooperation mechanism among selfish nodes. Moreover, credits are useful when an action and its reward are not simultaneous. This is valid for multi-hop wireless networks: the action is packet forwarding and the reward occurs after sending their own packets. These approaches could be useful to discover the more convenient routing policies, solving very challenging dilemmas in multi-hop networks. For example, these approaches could help to choose the cheapest route between a source and a destination node either by minimizing the total number of hops (minimizing end-to-end flow delay) or by choosing the less-congested hops (increasing flow data rate). The drawbacks of credit-based proposals are extra overhead and complexity to charge users fairly and avoid cheating, turning these proposals hard to deploy.

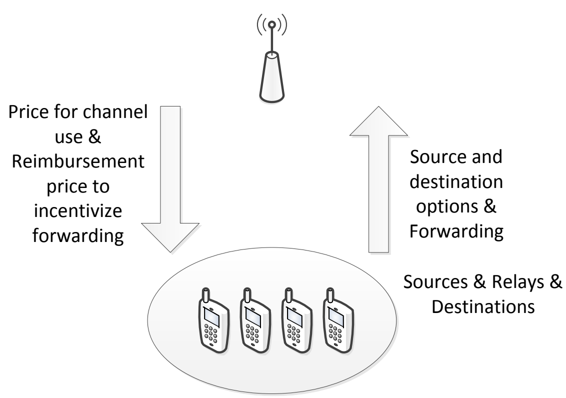

Figure 6: Credit-based incentive mechanism.

In FNs, customers can be billed using a congestion-sensitive tariff, where prices are set in real time according to current load and taking full advantage of demand elasticity to maximize efficiency and fairness (Saraydar et al., 2002). The demand elasticity utilizes historical information about expected peak load periods. According to (Felegyhazi & Hubaux, 2006), an investigation area where pricing has practical relevance is service provisioning among operators (e.g., renting transmission capacity).
The second group of contributions makes use of reputation-based proposals (Trestian, Ormond, & Muntean, 2011) (Munjal & Singh, 2018) to incentivize the collaboration among nodes in a multi-hop wireless network topology. The reputation metric represents the amount of trust the network community has about a node. Figure 7 illustrates the typical phases of a reputation system to incentivize a correct node behavior.

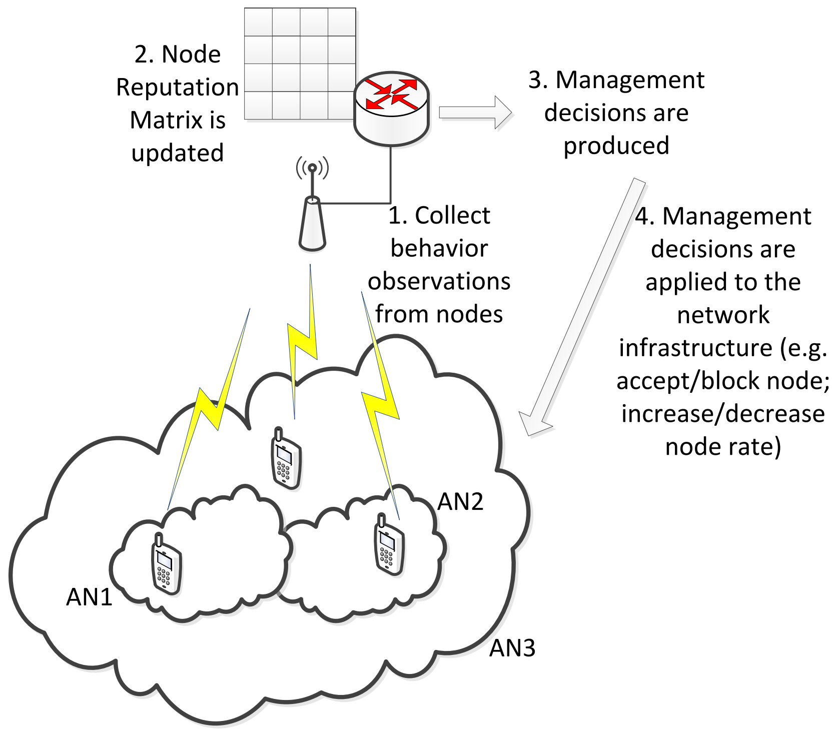

Figure 7: Reputation-based incentive mechanism.

During the initial phase, the reputation information of each node is collected to a central node connected to the wired network. After receiving the new reputation information, the central node updates a reputation matrix, which stores the reputation information from all the nodes (second phase). Then, in the next phase, management decisions are selected, which, during the fourth and last phase, are applied to the network infrastructure. In this way, as an example, members that have good reputation, because they helpfully contribute to the community welfare, can use the network resources; while nodes with a bad reputation, because they usually refuse to cooperate, are excluded from that community.

A very popular game-theoretic approach for reputation analysis is the repeated game because in this context it does not make sense that a game for reputation is based uniquely in its current (instantaneous) value; in fact, the reputation should be also evaluated through a historical term, normally with a higher weight than the one associated with the instantaneous value of reputation. In this way, it is possible to avoid false misbehavior detections due to temporary link communications failures. In addition, the uncertainty about the information that is available to other players and their decisions is normally modeled with Bayesian Game or Game with Incomplete Information (Harsanyi, 2004). Finally, to correctly model the robustness to changes on the behavior of the participants, auction games are preferred (Nurmi & Nurmi, 2006).

There are at least two different strategies on how the reputation could incentivize cooperation among nodes (or players). One of the ways is to develop a strategy such that the cooperation of a node is measured and if the fraction of packets it has dropped is above a threshold, it is considered selfish and is disconnected for a given amount of time. This strategy is known as a Trigger Strategy (Milan, Jaramillo, & Srikant, 2006). An alternative way is designated by Tit For Tat (TFT) (Axelrod, 1981). A player using this strategy will cooperate initially and then act regarding the opponent´s previous action: if the opponent previously was cooperative then the former player will be cooperative as well; otherwise, the former player will not cooperate. To illustrate the advantages of the TFT strategy being used by game players, a Finite Repeated Prisoner's Dilemma Game was simulated via Matlab (5000 iterations). The game is between two players. Each player tries to score the most number of points against each opponent player during each game. In this case, the player Operator1 can choose in each game's iteration between 'cooperate' or 'defect', like player Operator2. In each game's iteration, points are then awarded to both players based on the combination of their choices, following what is shown in Table 3.

Table 3: Points awarded to each player based on individual player's choices.

		Operator2	
		Cooperate	Defect
Operator1	Cooperate	3, 3	0, 5
	Defect	5, 0	1, 1

The maximum number of points a player can win during a game's iteration is five. This maximum score only occurs if that player defects and the opponent cooperates. Nevertheless, the former player scores one point instead five points if both players defect. As one can easily conclude, the main difficulty imposed to each player of the current game is to choose the option that maximizes his reward because he ignores the opponent's choice, as both players, during a game's iteration, perform their choices simultaneously. The previous difficulty in a player choosing the right option to maximize the reward points won by that player is perfectly evident from the simulation results presented in Figure 8. In fact, the random strategy used by each player to make a choice gives the worst performance. In opposition, TFT strategy shows a better performance.

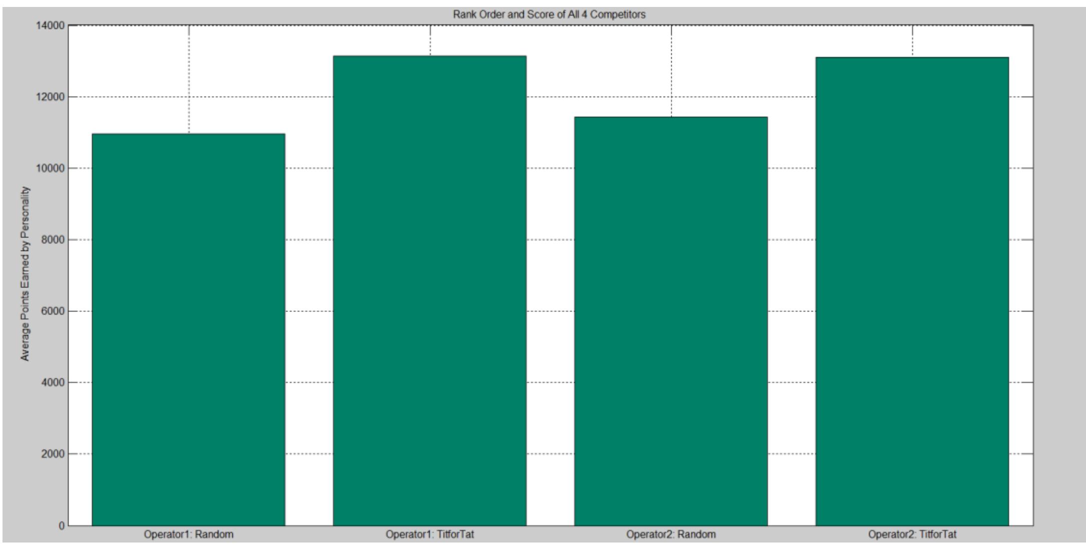

Figure 8: Outcomes of a finite repeated prisoner's dilemma game using two distinct strategies.

Despite the good performance of TFT, it could reveal some drawbacks in a wireless scenario. As an example, TFT does not distinguish uncooperative behavior from a transmission failure due to a collision. In this way, TFT could penalize a collaborative player that had the bad luck of suffering a collision during a data transmission tentative. Consequently, a few TFT variants have been proposed (Milan et al., 2006) (Jaramillo & Srikant, 2007) (Q. Li, Zhu, & Cao, 2010) (Vedhavathy & Manikandan, 2018) (Ntemos, Plata-Chaves, Kolokotronis, Kalouptsidis, & Moonen, 2018) to correct that problem.

For a multi-hop wireless network, there is an interesting tradeoff between the amount of available information to evaluate a node´s behavior (reputation) and the protocol overhead/complexity used to disseminate the necessary information through the network. Some proposals are more concerned with all the nodes having access to the full information about node behavior (Buchegger & Le Boudec, 2002) (Jochen & Le, 2005) (Qi He, Dapeng Wu, & Khosla, 2004) to enhance the accuracy on how the reputation is evaluated. These proposals could have problems related with fake information disseminated among the nodes that create wrong reputation values. To avoid these problems, the protocol used to disseminate the reputation values through the network must be enriched with additional authentication and trust functional features. Alternatively, to keep the protocol overhead low, each node should only disseminate the reputation values he directly measured to its neighbors (it only uses first-hand reputation changes) (Bansal & Baker, 2003).

Recent work proposed dynamic reputation-based incentives for cooperative relays present in a network topology formed by heterogeneous networks (Hwang, Shin, & Yoon, 2008) (Skraparlis, Sakarellos, Panagopoulos, & Kanellopoulos, 2009) (Z. Zhang, Long, Vasilakos, & Hanzo, 2016) (Kwon, Lim, Choi, & Hong, 2010). The incentive for cooperation among nodes can be given either by additional throughput (Hwang et al., 2008) or by additional time-slots for transmission (Skraparlis et al., 2009) (Z. Zhang et al., 2016) (Kwon et al., 2010).

Regarding strategies for penalizing misbehaving users, the research community has proposed several ways to perform it: isolate misbehaving users from the network (Buchegger & Le Boudec, 2002), reduce misbehaving users' bandwidth (Hwang et al., 2008) or reduce the transmission slots of misbehaving users (Skraparlis et al., 2009).

The main advantage of reputation-based proposals is that they rely on observations from multiple sources, turning it relatively resistant to the diffusion of false information from a small number of lying nodes. Some potential problems are the usage of additional bandwidth and battery energy to intensively monitor the behavior of each network node. In addition, some nodes could collude to cheat the reputation of other nodes by the dissemination of false information through the network about the latter nodes to the former nodes increase their benefits.

Game theory approaches have also been applied to blockchain security. The decentralized cooperative method of keeping track of blockchains, by miners, without the need for third-party intervention, is a relevant use case for many game models. (Nakamoto, 2008) already uses incentives in a simple, albeit insufficient, model. But unfortunately, distilling the essential game-theoretic properties of blockchain maintenance is far from trivial, and there have been many works that examines possible types of attacks against the blockchains and suggest adaptations of the protocol to ensure its security. A brief mention of some of these works follows.

In (Kroll, Davey, & Felten, 2013) the equilibria of the Bitcoin game are considered, and prove that any monotonic strategy is a Nash equilibrium (one of many). In (Eyal and Sirer, 2014), present a specific attack strategy called the "Selfish Mine" and examine when it is beneficial for a pool of miners. This is further exploited by (Sapirshtein, Sompolinsky, & Zohar, 2017), with a wider set of possible strategies, that includes the "Selfish-Mine" strategy, and explore this space computationally. In (Eyal, 2015) the author considers attacks performed between different pools where users are sent to infiltrate a competitive pool, giving raise to a pool game, the miner's dilemma, an instance of the iterative prisoner's dilemma. Further on, (Lewenberg, Bachrach, Sompolinsky, Zohar, & Rosenschein, 2015) has made a (cooperative) game theoretic analysis regarding pool mining. (Babaioff, Dobzinski, Oren, & Zohar, 2012) deals with Sybil attacks and propose a reward scheme which will make it in the best interest of a miner to propagate transactions. (Kiayias, Koutsoupias, Kyropoulou, & Tselekounis, 2016) have considered two simplified forms of a stochastic game, in which the miners have complete information: the Immediate-Release Game and the Strategic-Release Game.

The development of more suitable and fair schemes to incentivize cooperation in FNs is a challenging research direction. According to the authors of (Han et al., 2012) (Bouhaddi, Radjef, & Adi, 2018)(Ungureanu, 2018), hybrid schemes that combine both reputation and credit aspects are of particular interest to be further investigated. Lastly, by defining mechanisms of incentives for cooperation and disincentives against cheating or selfish behavior, and applying repeatedly both of these mechanisms, the cooperation among the players apparently becomes stronger in a distributed way without the need to sign a contract among the players (Trestian et al., 2011) (Munjal & Singh, 2018).

1.5. GAME THEORY FOR WIRELESS NETWORKING

In this section, we revise the literature in terms of how GT can be successfully applied to networking and wireless communications areas, including IoT.

(MacKenzie & DaSilva, 2006) describes ways in which GT can be applied to real applications in wireless communications and networking, such as: pricing, flow control, power control, medium access and interference avoidance. They also pointed out some appealing future applications of GT: cognitive networks and learning, mobility support and cooperation in wireless networks. (Y. Zhang & Guizani, 2011) explores applications of different economic approaches, including bargaining, auctions, cooperation incentives and dynamic coalition games for cooperation. (Han et al., 2012) discusses game-theoretic models in a wide range of wireless and communication applications such as cellular and broadband wireless access networks, wireless local area networks, multi-hop networks, cooperative networks, cognitive-radio networks, and Internet networks. In addition, some relevant Internet problems such as, congestion control, pricing, revenue sharing among Internet service providers, and incentive mechanisms to enable cooperation into peer-to-peer applications, are also discussed.

(Jianwei Huang & Zhu Han, 2010) presents several GT models/concepts that are highly relevant for spectrum sharing, including iterative water-filling, potential game, supermodular game, bargaining, auction, and correlated equilibrium. (Huang, 2013) outlines a taxonomy to systematically understand and tackle the issue of economic viability of cooperation in dynamic spectrum management. The framework divides the problem space according to four orthogonal dimensions, including complete/incomplete network information, loose/tight decision couplings, user/operator interactions, and static/dynamic decision processes. The vast majority of the key methodologies for each dimension involve GT. (Walid Saad, Han, & Hjørungnes, 2011) reviews coalitional GT for cooperative cellular wireless networks. (Marina, Saad, Han, & Hjørungnes, 2011) revises GT work about malicious behavior.

From the literature a significant number of surveys have been found about GT application in wireless communications and networking, as summarized in Figure 9. These surveys cover the following areas: wireless networks (Charilas & Panagopoulos, 2010) (Akkarajitsakul, Hossain, Niyato, & Kim, 2011) (Ghazvini, Movahedinia, Jamshidi, & Moghim, 2013) (Niyato & Hossain, 2007) (Trestian et al., 2011) (Larsson, Jorswieck, Lindblom, & Mochaourab, 2009) (M. A. Khan et al., 2012a); wireless Ad Hoc networks (Srivastava et al., 2005); wireless sensor networks (WSNs) (Machado & Tekinay, 2008) (Shen, Yue, Cao, & Yu, 2011) (Shi, Wang, Kwok, & Chen, 2012); MIMO systems (Scutari, Palomar, & Barbarossa, 2008); cognitive radio networks (Beibei Wang, Wu, & Liu, 2010) (B Wang, Wu, Liu, & Clancy, 2011); 4G networks (M. A. Khan et al., 2012b); smart grids (Fadlullah, Nozaki, Takeuchi, & Kato, 2011) (W Saad, Han, Poor, & Basar, 2012); telecommunications (E Altman, Boulogne, El-Azouzi, Jiménez, & Wynter, 2006); and Internet of Things (IoT) (Semasinghe et al., 2017).

Figure 9: Summary of Game Theory Surveys.

Covering the area of wireless networks where GT is applied, we can explicit the following surveys: a significant number of GT proposals are discussed in a network-layered perspective (Charilas & Panagopoulos, 2010); multiple access games are analyzed in (Akkarajitsakul et al., 2011); games of random access with Carrier Sense Multiple Access (CSMA) are covered in (Ghazvini et al., 2013); games about resource management and admission control are addressed by (Niyato & Hossain, 2007); games for network selection and resource allocation are available in (Trestian et al., 2011); games of spectrum allocation, power control, interference are covered in (Larsson et al., 2009); and finally, evolutionary coalitional games for wireless networking and communications are available in (M. A. Khan et al., 2012a).

Since the application of GT to enhance cooperation in FNs, formed by heterogeneous wireless access networks, is the main focus of the present chapter, we particularize now some surveys related to Wireless Sensor Networks (WSNs), cognitive radio networks and 4G networks. (Machado & Tekinay, 2008) reviewed the literature about the usage of game-theoretic approaches to address problems related to security and energy efficiency in WSNs. (Shen et al., 2011) main concern was to revise GT approaches towards the enhancement of WSN security. Finally, (Shi et al., 2012) offered a more comprehensive survey than previous referred ones about GT applied to WSNs.

The games for cognitive radio networks are classified by (Beibei Wang et al., 2010) into four categories: non-cooperative spectrum sharing, spectrum trading and mechanism design, cooperative spectrum sharing, and stochastic spectrum sharing games. For each category, they explained the fundamental concepts and properties, and provided a detailed discussion about the methodologies on how to apply these games in spectrum sharing protocol design. They also discussed some research challenges and future research directions related to game theoretic modeling in cognitive radio networks.

Cognitive attackers may exist in a cognitive radio network, who can adapt their attacking strategy to the time-varying spectrum opportunities and secondary users' strategy. To alleviate the damage caused by cognitive attackers, a dynamic security mechanism is investigated in (B Wang et al., 2011) by a stochastic game modeling. The state of the anti-jamming game includes the spectrum availability, channel quality, and the status of jammed channels observed at the current time slot. The action of the secondary users reflects how many channels they should reserve for transmitting control and data messages and how to switch between the different channels. Since the secondary users and attackers have opposite goals, the antijamming game can be classified as a zero-sum game.

Regarding IoT, many challenges need to be addressed in order to efficiently manage available resources. Centralised resource management is however infeasible when a large number of entities is involved, not only because of the computational complexity involved but also due to information acquisition requirements. For this reason, in IoT there has been a trend in performing distributed resource management, in particular using game theoretic approaches such as proposed by (Al-Kashoash, Hafeez, & Kemp, 2017) (Borah, Dhurandher, Woungang, & Kumar, 2017) (Kim, 2016) (Sedjelmaci, Senouci, & Al-Bahri, 2016).

However, conventional game models are not always suitable for large-scale IoT systems, due to the massive information acquisition overhead, the slow convergence to equilibrium, the inefficiency of equilibrium, the extreme computational complexity, and the complexity required to characterize the equilibrium set (Semasinghe et al., 2017). Therefore, non-conventional game theoretic models are required to match the intrinsic characteristics of future large-scale IoT systems. These are characterized by having random deployments, scalability issues, limited fronthaul/backhaul, inhomogeneity, non-guaranteed energy supply, uncertain and incomplete information. Game models will inevitably have to overcome these challenges for an efficient distributed resource management. (Semasinghe et al., 2017) discusses several promising game models for IoT such as evolutionary games, mean field games, minority games, mean field bandit games, and mean field auctions. They describe the basics of each of these game models and access the potential IoT-related resource management problems that can be solved by using these models (Table 4)

The authors of (M. A. Khan et al., 2012b) study game dynamics and learning schemes for heterogeneous 4G networks. They propose a novel learning scheme called cost-to-learn that incorporates the cost to switch, the switching delay, and the cost of changing to a new action. Considering a dynamic and uncertain environment, where the users and operators have only a numerical value of their own payoffs as information, and strategy reinforcement learning (CODIPAS-RL) is used, they show the users are able to learn their own optimal payoff and their optimal strategy simultaneously. Using evolutionary game dynamics, they prove the convergence and stability properties in specific classes of dynamic robust games. They also provide various numerical and simulation results in the context of network selection in wireless local area networks (WLAN) and Long Term Evolution (LTE). In addition, (Silva et al., 2013) clearly shows the main advantages of cooperation among wireless access technologies. The following sections justify why the collaboration aspect should be very important in FNs and how GT can help to study the best ways to deploy this new functionality in a distributed way.

Table 4: Potential IoT applications for different game models

Game theoretic model	**Potential use case for IoT**
Evolutionary games	Power control, spectrum/subcarrier allocation, transmission mode/network selection
Mean field games	Energy/queue/channel-aware resource allocation, resource management under mobility
Minority games	Scheduling, transmission mode/network selection, interference management
Mean field bandit games	User association, scheduling, channel allocation
Mean field dynamic auctions	User association, scheduling, channel allocation

1.6. GUIDELINES TO APPLY GAME THEORY ON FUTURE NETWORKS

The current section discusses some relevant research work in how GT can be used to address the more significant operational or functional expected aspects of Future Network (FN) environments. The most-part of the discussed scenarios belongs to the network edge of Internet. More specifically, these scenarios are concerned in how the heterogeneous wireless access infrastructure can be efficiently used by multimode terminals, as well as, to guarantee a reliable access to the Internet through wireless backhaul links. In this way, several possible functional/operational enhancements are envisioned to use efficiently the heterogeneous wireless access infrastructure in the following topics: network planning, multi-technology wireless networks, network management, Internet of Things (multi-hop reliable networks) and reliable wireless backhaul. These should be hot research areas in FNs and are summarized in Table 5 together with references for relevant work that should be initially studied in order to find innovative ways to plan, control, manage and operate FNs.

Table 5: Relevant FN topics/areas where GT can be successfully applied

Topic/Area	**Scenario/Game Type**	**Reference**
Network planning	Stackelberg game to control power transmission in a network formed by macrocells and femtocells	(Guruacharya, Niyato, Hossain, & Kim, 2010)
Multi-technology wireless networks	Bayesian game to study vertical-handovers in which the users have distinct bandwidth requirements	(Zhu, Niyato, & Wang, 2010)
Network management	Evolutionary game to study rate selection for VoIP service; non-zero sum game for studying user admission control to avoid congestion	(Watanabe, Menasche, de Souza e Silva, & Leao, 2008) (Yu-Liang Kuo, Eric Hsiao-Kuang Wu, & Gen-Huey Chen, 2004)
Internet of things (multi-hop reliable networks)	Hop price-based routing game; auction theory to support truthfulness and security;	(Hua Liu & Krishnamachari, 2006) (Anderegg & Eidenbenz, 2003) (Eidenbenz, Resta, & Santi, 2008)

Reliable wireless backhaul	Evolutionary game to study traffic routing through multi-hop wireless backhaul links	(Anastasopoulos, Arapoglou, Kannan, & Cottis, 2008)
Multi-access edge computing	How game theoretical games should model wireless data communication networks to understand how to deploy in an efficient way upcoming edge technologies/services, such as the Internet of Things, user wearables, and virtual/augmented reality applications.	(Moura & Hutchison, 2018)

Network Planning

Imperfect network coverage, especially in indoor locations is an important problem in existing cellular networks. To overcome this problem, the concept of Femtocell Access Points (FAPs) has recently been proposed as a means to overlay, on existing mobile networks, low-power and low-cost Base Stations (BSs). FAPs are connected by an IP backhaul through a local broadband connection such as DSL, cable or fiber.
Notably, various benefits of using FAP technology have been already identified:

- Enhances indoor coverage
- Provides high data rates
- Improves Quality-of-Service (QoS) to subscribers
- Ensures longer battery life for handheld terminals
- Offloads traffic from the mobile operator's backhaul to the wired residential broadband connection, reducing the backhaul cost of the mobile operator.

When FAPs are deployed on top of an existing cellular system, and since FAPs operate on the same frequency bands as macrocell BSs, a new problem arises. This problem is related with the interference among channels that can impair the overall network performance. In such a network scenario, it is of interest to study the problem of transmit-power control in the downlink, minimizing the interference problem and ensuring an acceptable network performance.
In this section, we adopt the approach of (Guruacharya et al., 2010), also thoroughly discussed in (Han et al., 2012), for studying the transmit-power control in the downlink from a game-theory perspective. First, we model the scenario as a Stackelberg game. Then, we discuss the properties of the considered game and its solution. In the following text, we present a low-complexity algorithm to reach the desired outcome (Han et al., 2012).

Stackelberg game to control transmission power

In order to tackle the power-control problem using GT, a framework of a Stackelberg game has been used (Han et al., 2012). In the studied femtocell deployment model, it is considered that the macrocell BSs are the leaders and the FAPs are the followers in a Stackelberg game, as summarized in Table 6. In this multi-leader multi-follower Stackelberg game, there exists a competitive game among the leaders and a competitive game among the followers. The Stackelberg game keeps a distinct hierarchy among leaders and followers such that the leaders can anticipate, and take this into consideration, the behavior of the followers (the reciprocal is not true), before making their own decisions to maximize their data rate.
It was considered a Stackelberg game with complete and perfect information. As already mentioned, the leaders are the set of macrocell BS transceivers M, the followers are the set of FAPs N. Therefore, the total set of players in this game is $M\ U\ N$. The strategy space of the leaders is given by $P^{up} = \prod_{i \in M} P_i$, and any

point in P^{up} is called a leader strategy. Let P_i denote the set of all feasible power vectors of transmitter i. The leaders compete with each other in a non-cooperative way to maximize their individual data rate, while always anticipating the strategic responses of the followers. This game among the leaders is referred as the upper subgame, and its equilibrium is referred as the upper subgame equilibrium. After the leaders apply their strategies, the followers make their moves in response to the leaders' strategies.
The strategy space of the followers is $P^{low} = \prod_{i \in N} P_i$, and any point in P^{low} is called a follower strategy. The followers also compete with each other in a non-cooperative way to maximize their own data rate, and this competition among the followers is referred as the lower subgame. It is expected this game could offer an equilibrium state designated by the lower subgame equilibrium.

Table 6: Summary of Relevant Characteristics of Femtocell Deployment Game (Guruacharya et al., 2010)

Scenario	Game Type	Player	Player's Strategy	Payoff
Femtocell deployment	Stackelberg with complete and perfect information to control power	Base-stations (leaders)/femtocell access points (followers)	Choose the maximum transmission power constrained by power constraints	Maximize Shannon data rate that each player can achieve

For any user $i \in \{M \cup N\}$, it is defined the best-response function as shown in (8).

$$p_i = argmax_{p_i}(p_i, p_{-i}) = b_i(p_{-i}, \overline{p_i}, \overline{m}_i) \qquad (8)$$

Where the notation $-i$ refers to all of the users in the set $\{M\ U\ N\}$ except user i; $\overline{p_i}$ is the total power constraint; $\overline{m_i}$ is the individual power constraint, where $\overline{m_i}$ is chosen so as to maximize user i's capacity function subject to the power constraints.

Lower subgame equilibrium

It is defined the lower subgame equilibrium as any fixed point $p^{low^*} = (p_1^*, \cdots, p_N^*) \in P^{low}$ such that expression in (9) is satisfied.

$$p_i^* = b_i(p_{-i}^*, p^{up}, \overline{p_i}, \overline{m_i}) \qquad (9)$$

Where $p^{up} \in P^{up}$ is a fixed but arbitrary leader strategy for all the $i \in N$. Note that this definition is the same as a Nash Equilibrium (NE) of the lower subgame.

Following (Han et al., 2012), since every user participating in the lower subgame will maximize in a myopic way their individual data rate, the best response $b_i(.)$ of each user in the subgame can be given by the following water-filling game function (Lai & El Gamal, 2008), as shown in (10).

$$p_i = F(p_{-i}, \overline{p_i}, \overline{m_i}) = w_i(A_i)v_i + r_i(A_i, S_i) \qquad (10)$$

Where $W_i(A_i)$ is an L_i x L_i symmetric matrix which contents is explained in more detail in (Han et al., 2012); $r_i(A_i, S_i)$ is an L_i-dimensional column vector detailed in (Han et al., 2012).

The main goal of a water-filling game is to identify a set of resource allocation strategies distributed among rational and selfish users (i.e. not interested in the overall system performance), who are interested in maximizing the utilities they obtain from the network (Lai & El Gamal, 2008).

By letting $b^{low} \equiv (b_i(.))^N_{i=1}$, it is possible to express the lower subgame equilibrium as any fixed point of the system-power space $p^* \in P$ such that $p^* = b^{low}(p^*)$

Note that the function $b^{low}(.)$ does not impact the upper subgame strategy.

Upper subgame equilibrium

It is defined the upper subgame equilibrium as any fixed point $p^{up^*} = (p_1^*, \cdots, p_M^*) \in P^{up}$ such that the expression in (11) is satisfied.

$$p_i^* = b_i(p_{-i}^*, p^{low^*}, \overline{p_\iota}, \overline{m_\iota}) \qquad (11)$$

Where $p^{low^*} \in P^{low}$ is an equilibrium follower strategy conditioned on the upper subgame strategy, for all $i \in M$.

Equivalently, let $b^{up} \equiv (b_i(.))^M_{i=1}$; then the upper subgame equilibrium as the fixed point $p^{up^*} \in P^{up}$ such that (12) is a valid expression.

$$p^{up^*} = b^{up}(p^{up^*}, b^{low}(p^{low^*}, p^{up^*})) \qquad (12)$$

For convenience, the notation can be further simplified by writing the upper subgame equilibrium in terms of a system-power vector, i.e. as any fixed point $p^* \in P$ such that (13) is true.

$$p^* = b^{up}(b^{low}(p^*)) \qquad (13)$$

Note that although the function $b^{up}(.)$ acts only on the upper subgame strategy, the lower subgame equilibrium strategy (the reaction of the followers) associated with each upper subgame strategy needs to be computed as well, since the leaders compute their strategies given their knowledge of what the followers might play.

Multi-leader multi-follower Stackelberg equilibrium

A suitable solution for the formulated hierarchical game between the base stations and the FAPs is the Stackelberg equilibrium. In such a multi-leader multi-follower game, the Stackelberg equilibrium is defined as any fixed-point $(p^{up^*}, p^{low^*}) = p^* \in P$ that satisfies both conditions as shown in (14).

$$\begin{cases} p^* = b^{low}(p^*) \\ p^* = b^{up}(b^{low}(p^*)) \end{cases} \qquad (14)$$

Algorithm for reaching the Stackelberg equilibrium

Finding, iteratively, the fixed point of the lower subgame using the water-filling algorithm usually yields an unstable system for a random channel gain matrix (Han et al., 2012). Therefore, it can be used a technique designated by Mann iterative methods, which allows a weaker stability criterion but it ensures that a stable system status point can be reached. To achieve this further discussion is available in (Han et al., 2012).

Multi-technology Wireless Networks

The FN environment will be a heterogeneous network infrastructure composed by distinct wireless access technologies and several users/terminals aiming to monitor and select the best technology/Access Point (AP)/ Base Station (BS) to connect to, depending on their Quality-of-Service (QoS) requirements. One possible QoS requirement is the best throughput as possible each user can have through each AP/BS taking in consideration the overload imposed by the other attached users. Each user (the player of this network selection/vertical handover game) after its monitoring phase about all the available AP/BS connection possibilities should choose the one that ensures the maximum throughput value among all the options. Most of the existing work on vertical handover assumes that users have complete information on one another (Han et al., 2012). In FNs, the users will lack the ability to predict the behaviors of others based on past actions. In this case, it is more convenient to utilize a game with incomplete information, i.e. a Bayesian game, like the one adopted by (Zhu et al., 2010). Since the payoff (i.e. utility) for a mobile user is composed by private information (see Table 7), each user has to make a network selection given only the distribution of the preferences of other users (Han et al., 2012). In this game, it is very interesting to investigate the impact of different system parameters on the game performance itself using a practical setting, like the one composed by three different access technologies (Wifi, Wimax and cellular). The studied system parameters have been the convergence property of the aggregate best-response dynamics for the considered network selection game, the game adaptation for different handover costs (delay or packet loss), the impact of connection price on the equilibrium distribution and the impact of learning (i.e. user strategy adjustment) rate on game dynamics. The obtained results are discussed in (Han et al., 2012).

Table 7: Summary of Relevant Characteristics of Network Selection with Incomplete Information Game (Zhu et al., 2010)

Scenario	Game Type	Player	Player's Strategy	Payoff
Network selection with incomplete information	Bayesian game	Users in a service area with K available access networks	Represents the probability of choosing an access network K and the minimum user bandwidth requirement (only the user knows about this, which turns this game an incomplete one)	User utility combines user achieved throughput above a minimum threshold (user private information) vs. price paid for the connection

Network Management

The support of voice service in FNs will be a challenging task due the heterogeneity of both the network infrastructure and user requirements. A very interesting starting point to this problem is available in (Watanabe et al., 2008). It is proposed an analytical model based on Evolutionary Game Theory (EGT) (see Table 8) to analyze the consequences of a situation in which all users are allowed to freely choose the transmission rate. They perform that by selecting the codec and Forward Error Correction (FEC) mode to maximize the voice quality (payoff), which can be experienced by them. They show that in a scenario where the users know only their own perceived voice quality, the system converges to a total transmission rate close to that of the effective cell's capacity. They concluded that each individual user's MOS, which is estimated by a Random Neural Network (RNN), can also be satisfied. Further, cell's congestion is avoided by local user adaptation (dynamically changing its codec/FEC to maximize its perceived quality) without any intervention from a centralized controller.

Table 8: Summary of Relevant Characteristics of an Evolutionary Game to Study Rate Selection for VoIP Service (Watanabe et al., 2008)

Scenario	Game Type	Player	Player's Strategy	Payoff
Study rate selection to guarantee the QoS offered to VoIP users	Evolutionary game	VoIP users in a service area	Each user selects the transmission rate through the codec and FEC mode	Voice quality experienced by the user and measured via a Mean Opinion Score (MOS) technique

Internet of things (Multi-hop Reliable Networks)

FN environments will have a large-scale deployment of wireless networks, which consist of small, low-cost nodes with simple processing and networking capabilities. This emergent environment is commonly designated inside the research community as the Internet of Things. In order to reach the desired destination such as the data sink node, transmissions depending on multiple hops are necessary (Han et al., 2012). Because of this, the routing optimization is a pertinent problem that involves many aspects but the one more relevant for the current work is the nodes not willing to fully cooperate in the routing process through multiple wireless hops, forwarding traffic from other nodes, because relaying external traffic consumes their limited battery power. Hence, it is crucial to design a distributed –control mechanism encouraging cooperation among the nodes in the routing process (see Table 9). The literature describes two typical approaches to enforce cooperation. First, in a price-based approach, each hop has a price and the game outcome is controlled between the source-destination pair and the intermediate hops. Second, an auction-based approach is suggested to ensure that users reveal their information truthfully to others for network cooperation, because this strategy will bring them the best benefits.

Table 9: Summary of Characteristics of Games to incentivize cooperation among multi-hop nodes

Scenario	Game Type	Player	Player's Strategy	Payoff
Incentivize cooperation among nodes (Hua Liu & Krishnamachari, 2006)	Hop price-based reliable routing game	All the nodes except the destination one	A node to participate in this game should at least choose one next hop node in the path from the source to the destination; otherwise it is out of this game	The source's utility is the expected income (destination payment minus the payments to all of the intermediate nodes, times the probability that the packet will be delivered over the route) minus the link set-up cost for the first hop of the route; The utility for each intermediate routing node equals the expected payment that it obtains from the source node, times the ongoing route reliability minus the transmission cost per packet to its next-hop neighbor. If any node does not participate in the routing, it gains (and loses) nothing.
Incentivize cooperation among nodes (Eidenbenz et al., 2008)	Vickrey-Clarke-Groves (VCG) auction to prevent players from lying and to route messages along	All the network nodes	A strategy is a combination of strategies from the following base space: 1. a node can declare any value for its type;	Maximizing the node's utility. The sender's node utility is the difference between the amount of money it is willing to pay for the connection and the

	the most energy-efficient paths (as defined by the topology control protocol)		2. a node can drop control messages that it should forward; 3. a node can modify messages before forwarding, and 4. a node can create bogus messages.	amount it effectively pays for that; the intermediate's node utility is the difference about the amount of money received from the sender and the total cost incurred by relaying the sender's packet.

Reliable Wireless Backhaul

In FN environments wireless multi-hop backhaul links are expected to be very popular deployments. In this case, the channel quality between relay stations can fluctuate because of fading. Therefore, the users (players) at the source node must be able to observe, learn, and change the routing strategy to achieve the most reliable path from source node to the Internet gateway, as summarized in Table 10.

Table 10: Summary of Relevant Characteristics of Game to Study Traffic Routing through Multi-hop Wireless Backhaul Links (Anastasopoulos et al., 2008)

Scenario	Game Type	Player	Player's Strategy	Payoff
Multi-hop Wireless Backhaul Links	Evolutionary game	Users	Users periodically and randomly sampling different wireless backhaul links to select a convenient path between a source node and an Internet gateway	Find a backhaul link that ensures the smallest number of packet errors due to rain attenuation

Computing and Storage at the Network Edge

The paradigm of Multi-Access Edge Computing (MEC) (Yi et al., 2015) (Abbas, Zhang, Taherkordi, & Skeie, 2018) (Hang Liu et al., 2017) is finally possible to deploy because foundational technologies such as virtualization (e.g. docker, Linux Containers) and communications (e.g. 5G) are becoming a reality now more than ever. Edge computing aims to provide more compute and storage power at either Base Stations or Access Points. The potential benefits to the data traffic are: i) diminish the data access latency; ii) decrease the load on the backhaul links; iii) save users' cost because less traffic is exchanged with remote clouds. Nevertheless, this new paradigm can increase the battery consumption on mobile nodes. To overcome this potential problem, computation offloading from mobile devices to edge devices (APs or BSs) can be a viable solution.

The authors of (Nawab, Agrawal, & El Abbadi, 2018) propose extending edge computing technology with dynamic, mobile edge datacenters, which they designate as nomadic datacenters. Nomadic datacenters are small and portable edge datacenters that can be easily moved around according the traffic load needs. In this way, nomadic datacenters can replace a damaged communications infrastructure by a natural disaster. Alternatively, nomadic datacenters can temporarily extend the capacity of a mobile network in the case of a public event that concentrates several hundreds of thousands of people (e.g. musical concert within a stadium).

There is a huge number of recent literature contributions on MEC, namely covering the next topics: i) the communication perspective (Mao, You, Zhang, Huang, & Letaief, 2017); ii) computation offloading (Mach

& Becvar, 2017); iii) convergence of computing, caching and communications (S. Wang et al., 2017); iv) emerging 5G network edge cloud architecture and orchestration (Taleb et al., 2017); v) software-defined networking (Kumar, Chilamkurti, et al., 2015); vi) architecture harmonization between cloud radio access networks and fog networks (Hung, Hsu, Lien, & Chen, 2015); vii) Internet of Things (Chiang & Zhang, 2016); and viii) latency control in software-defined mobile-edge vehicular networking (Deng, Lien, Lin, Hung, & Chen, 2017). None of the previous surveys comprehensively analyzes GT into MEC. Nevertheless, there is a very work (Moura & Hutchison, 2018) that tries to discuss in a comprehensive way those two pertinent areas, in the sense to understand how GT can address in a successful way the emerging requirements of MEC use cases. They also discuss GT research topics related to MEC, namely on wireless sensor networks, cognitive small cells, vehicular networks, and unmanned vehicles.

1.7. BUSINESS PERSPECTIVE

From a business viewpoint, collaboration may be positive or negative – if a certain company plans to take over the market, it would engage in an open competition with its competitors in the hope to conquer most of the market, but in doing so it would have to pay the price of being competitive; be it by lowering their prices or by increasing their quality. If the company would engage in collaboration with its competitors, they would assess the market needs together and become more efficient, operating at a point where all would maximize their profit. In this case, assuming a total of n companies, and taking Pm as the maximum price for the product that all the companies manufacture, we can build an inverse demand curve (the demand curve solves for Quantity, whereas the inverse for Price), where the price charged for one of those products is equal to the Pm minus the quantity Q, multiplied by a factor α (assuming a linear relationship for simplicity, as shown in (15); more detailed curves can be found in (O'Sullivan, Sheffrin, & Perez, 2003).

$$P = P_m - \alpha Q \tag{15}$$

In the case of n competing companies, we have the total quantity given by (16).

$$Q = Q_1 + Q_2 + \cdots + Q_n \tag{16}$$

The total revenue is given by the product price x quantity. The total revenue for all companies can thus be calculated as shown in (17).

$$TR = P \times Q = (P_m - \alpha Q) \times Q = P_m Q - \alpha Q^2 \tag{17}$$

The derivative of TR with respect to Q gives us the Marginal Revenue (MR), which in our simple linear model is given by (18).

$$MR = P_m - 2\alpha Q \tag{18}$$

In Figure 10, we have an illustration of the above formulas. Note that the MR curve represents the slope of the TR curve (which is drawn at a different scale, for practical reasons), and that maximum total revenue is obtain when MR=0.

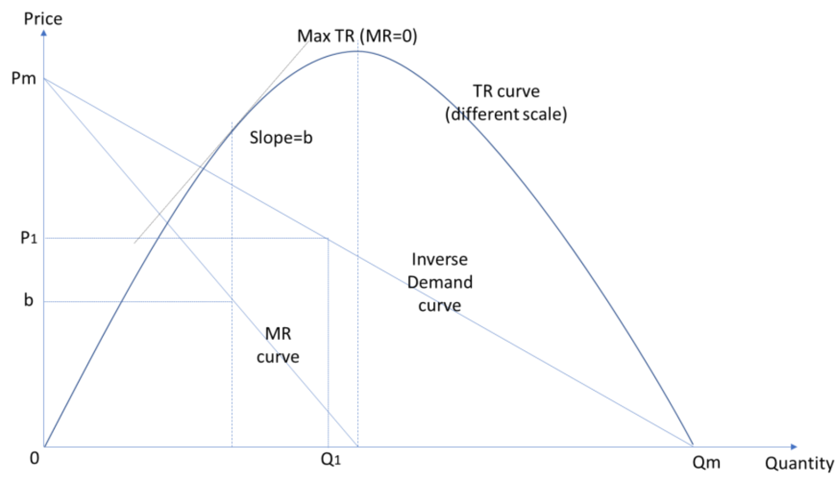

Figure 10: Inverse Demand curve, Total Revenue and Marginal Revenue.

Since the objective is to maximize profit, we must check at which point MR equals the Marginal Cost (MC), to find the ideal price and quantity to produce, as we evaluate below:

$$MR = MC \rightarrow P_m - 2\alpha Q - MC = 0 \Leftrightarrow$$
$$\Leftrightarrow Q = \frac{P_m - MC}{2\alpha} \Leftrightarrow$$
$$\Leftrightarrow P = \frac{P_m + MC}{2}$$

The Figure 11 illustrates the trend's point in which MC=MR (point b), and the corresponding Price and Quantity (P_1 and Q_1). From the previous figure, notice also that Q_0 denotes the free market equilibrium quantity, in which the marginal cost of producing a unit equals its price – in a hyper competition setting, companies may operate close to this point, ideally a bit more to the left to obtain some (minimal) profit. The difference between quantities Q_1 and Q_0, and between prices P_1 and C_0, can be regarded as the difference between operating collaboratively (or in a monopoly) and competitively (the area of the triangle *abc* is also referred to as the deadweight loss of monopoly). It is up to each company's strategy if it should consolidate or invest/risk to (try to) conquer market (operating close to C_0 will lead many less cost-effective companies to file for bankruptcy, allowing for the bigger companies to take over their market-share).

Should the companies engage in competition, all would be losing out, operating with a higher quantity each, and subsequently lower prices and profit margins. There is a clear incentive to appeal to collaboration, although all companies want the best possible deal for themselves, which sometimes might hinder the collaboration attempts. Game theory models try to assess the best possible solution for all parties, quantifying the possible gains and losses predicted by the used model. Collaboration goes beyond revenue sharing (Bhaskaran & Krishnan, 2009); it may include the sharing of knowledge about the markets and technologies, setting the market standards, the sharing of facilities, etc. (Goyal & Joshi, 2003). To reap the full benefits of collaborating, one must analyze the collaborative conditions beforehand, hence negotiating the collaboration terms is of paramount importance. Important decisions need to be taken, such as the level of investment, profit sharing, knowledge and trust.

There has been some interesting work on the field to obtain win-win solutions for collaborative partners, and the authors would like to highlight (Arsenyan, Büyüközkan, & Feyzioğlu, 2015) for the proposed mathematical model integrating trust, coordination, co-learning and co-innovation for collaborative product development using Nash bargaining, as well as work in Hospital Information Exchange (HIE) networks that attempt to quantify the benefits and losses from the exchange of patient information both to the hospitals and patients (Martinez, Feijoo, Zayas-Castro, Levin, & Das, 2018). In the same field, Desai developed a game theoretical model to analyze the potential loss of competitive advantage due to HIE adoption (Desai, 2014).

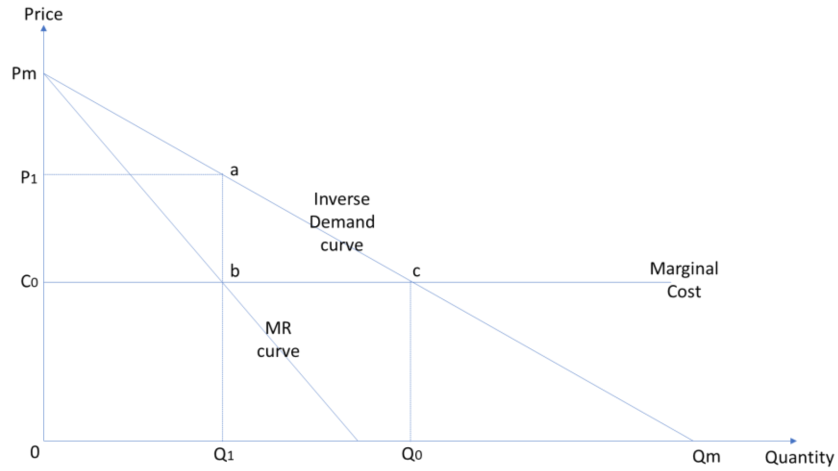

Figure 11: Collaboration and competition operating points.

1.8. CONCLUSION

Cooperation: Current Status and Open Issues

Cooperation is a revolutionary wireless communication paradigm that can achieve much higher network performance and spectrum utilization in future networking environments. Many technical challenges, however, need to be addressed to make this vision a reality. In particular, the distributed and dynamic nature of the sharing of information about node cooperation requires a new design and analysis framework. GT provides a very solid solution for this challenging task. In this book chapter, we describe several GT models that have been successfully used to solve various problems associated with node cooperation.

The most part of discussed models relies on the concept of Nash Equilibrium (NE) in games with complete information and static strategies. Although mathematically convenient, this may not be the most suitable GT model in practice. For example, the complete information assumption is difficult to be satisfied in practice, due to the dynamic and uncertain environment associated to FNs (or MEC / FC) formed by heterogeneous wireless access technologies and a huge variety of flow types. A model of incomplete games will be more suitable. Moreover, NE assumes rational players and static strategies but the players in FNs aren´t completely rational; the players have limited information about available choices and consequences of others; the game strategies are not static (in fact, the strategies are highly dynamic). A recent branch of GT - Evolutionary GT (EGT) seems a very promising alternative to the traditional GT to be applied in FNs. Some preliminary work has been reported along these directions (M. A. Khan et al., 2012a) (Nazir et al., 2010) (Bennis et al., 2011) (Eitan Altman et al., 2009) and definitely much more is required. As a pertinent example, evolutionary network models can provide useful guidelines for upgrading protocols/algorithms to achieve stable infrastructure functionality around preferred status/configuration in FNs. Other interesting models are Stackelberg and Bayesian ones. Finally, in Table 11, some relevant contributions found in the literature, which can be the foundations for new work in the FN area, are listed together with some associated open issues.

Table 11: Open Issues in Applying GT to Future Wireless Networking Scenarios

Scenario	Reference	Open Issue
Network planning	(Guruacharya et al., 2010)	Due to the notorious computational burden of estimating the Stackelberg equilibrium, a low complexity algorithm based on Lagrangian dual theory was chosen. However, the numerical results show that the adopted algorithm is suboptimal.

Multi-technology wireless networks	(Zhu et al., 2010)	Future work can study based on the Equilibrium distribution, how the service providers can adjust the system capacity and price accordingly to maximize the profits
Network management	(Watanabe et al., 2008)	The experiments were performed with small populations. Future work can devise more scalable experiments.
Internet of things (multi-hop reliable networks)	(Hua Liu & Krishnamachari, 2006)	Add the destination as a player; consider scenarios where the destination can choose from several source nodes for a given piece of information. This will allow for an auction to be held among the source nodes to optimize destination's payoff
Internet of things (multi-hop reliable networks)	(Eidenbenz et al., 2008)	Enhance previous protocol to be robust against malicious nodes and collusion
Reliable wireless backhaul	(Anastasopoulos et al., 2008)	Extend previous work in the direction of IEEE 802.11s (wireless mesh networking)
Computing and Storage at the Network Edge	(Moura & Hutchison, 2018)	Low data/service access latency; distributed offloading computing hierarchical mobile environments; proactive data caching at the network edge managed by data popularity, social links, and available node battery energy; low-power wireless communications and networking for IoT; fingerprinting localization technology to support indoor location-based services; and understand emerging security and privacy problems in cyberspace and potential solutions.

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KEY TERMS & DEFINITIONS

Game Theory, cooperation, future networks, network management, network collective intelligence, evolutionary algorithms, business perspective.