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Game Theory — Based Network Selection: Solutions and Challenges

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***Abstract*—In order to cater for the overwhelming growth in bandwidth demand from mobile Internet users operators have started to deploy different, overlapping radio access network technologies. One important challenge in such a heterogeneous wireless environment is to enable network selection mechanisms in order to keep the mobile users Always Best Connected (ABC) anywhere and anytime. Game theory techniques have been receiving growing attention in recent years as they can be adopted in order to model and understand competitive and cooperative scenarios between rational decision makers. This paper presents an overview of the network selection decision problem and challenges, a comprehensive classification of related game theoretic approaches and a discussion on the application of game theory to the network selection problem faced by the next generation of 4G wireless networks.**

***Index Terms*—game theory, network selection, heterogeneous environment.**

I. Introduction

In an ever-evolving telecommunication industry, smart mobile computing devices have become increasingly affordable and powerful, leading to a significant growth in the number of advanced mobile users and their bandwidth demands. People can now connect to the Internet from anywhere at any time, when on the move or stationary. According to Cisco [1], these high-end devices - smartphones, netbooks, and laptops - generate more than 90% of the entire mobile broadband traffic which is expected to reach 3.6 exabytes per month by 2014. Mobile video has the highest growth rate of any application category, expected to reach almost 66% of the world's mobile data traffic by 2014 [1]. This is due to the growing popularity of video-sharing websites like: YouTube, social networks (Twitter, Facebook, MySpace, etc.), mobile TV and entertainment services.

No single network technology will be equipped to deal with this explosion of data, making the coexistence of multiple radio access technologies (RATs) a necessity. In order to accommodate more mobile users and keep up with the traffic demand, network operators have started to deploy different overlapping radio access technologies, such as: WLAN (Wireless Local Area Network), WiMAX (Worldwide Interoperability for Microwave Access), UMTS (Universal Mobile Telecommunications System), and most recently, LTE (Long Term Evolution). LTE is designed to ensure enhanced data throughput speeds, to increase the capacity and to improve user experience. It is built on the concept of self-organizing and self-optimizing networks which relies on breaking the network into smaller pieces and making use of femtocells [2]. While femtocells improve the capacity and coverage area, especially indoors, more small-size cells mean an increase in handover rate which translates into difficulties in guaranteeing Quality of Service (QoS) for multimedia applications.

Fig. 1 illustrates an example heterogeneous wireless scenario, where a mobile user in an area of overlapping Radio Access Network (RAN) coverage has a choice of RAN to use, ideally his mobile terminal should auto-detect this and dynamically and seamlessly select and connect to the best available network dependent on his current needs. This multi-user multi-technology multi-application multi-provider environment requires the development of new technologies and standards that seek to provide dynamic automatic network selection decision. Many previous solutions in this area have focused on multi-criteria decision making algorithms to make this decision. Game theory can also be used to study the interaction between the competitive and/or cooperative behaviour that can be identified among service providers and/or users in this domain.

The focus of this paper is to provide a comprehensive survey of the current research on game theory approaches in relation to network selection solutions. The main contributions are: an overview of the network selection decision problem and challenges, including discussion on supporting standards, current industry implementations, and some different approaches taken in the literature categorised in terms on the mathematical technique they use for multiple criteria decision making; a categorisation, comparison and analysis of the state-of-the-art game theory solutions on this topic; and an outline of the main challenges to be solved in the evolution towards a 4G mobile wireless environment.

The survey is organized as follows: The aim of section II is to familiarize the readers with the network selection problem. Section III introduces basic game theory concepts and their mapping to the network selection problem. Section IV proposes a comprehensive classification, comparison and analysis of the state-of-the-art game theory approaches in relation to network selection. The solutions are classified based on the players' interactions: users vs. users, network vs. users, and networks vs. networks. Each game theory approach is briefly described and the adopted solution concepts (Nash Equilibrium, Pareto Optimality, etc.) are presented (where

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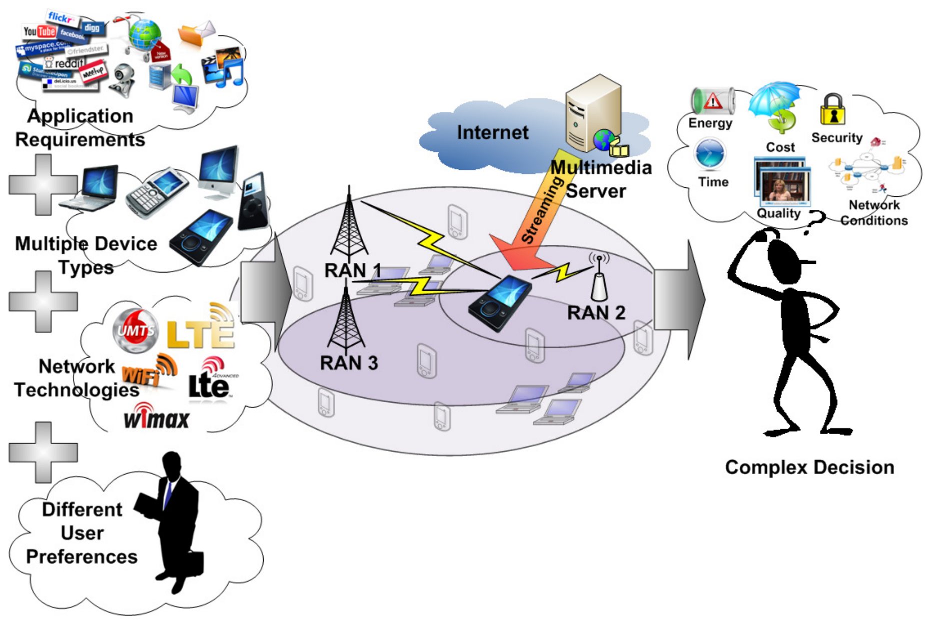

Fig. 1. Heterogeneous Wireless Networks Environment - Example Scenario

available). Section V provides a discussion on the main challenges of applying game theory to 4G mobile wireless systems. Finally, the conclusions and future work directions are presented in section VI.

II. Network Selection Concept

As illustrated in Fig. 1, the next generation of wireless networks is represented as a heterogeneous environment with a number of overlapping RANs. The user device faces the problem of selecting from a number of RANs that differ in technology, coverage, bandwidth, latency, pricing scheme, etc., belonging to the same or different service providers. These service providers may be competing for customers, each trying to maximize its own revenue, or they may be collaborating, similar to roaming, seeking social welfare maximization. From the user's perspective, the variety of portable devices (such as smartphones, netbooks, or laptops) with support for multiple radio network interfaces, enable the option of connecting to the Internet anywhere and anytime. In this setting, users are able to freely migrate from one RAT to another or from one service provider to another.

In this context, a network selection decision is made at call setup and subsequently the decision is re-made in the case of a handover trigger. The process consists of three main steps:

- Monitoring - this step can play different roles: monitoring the network conditions, listing the available RANs, predicting/estimating the characteristics for each RAN, etc.; and, using the monitored data to trigger a HO decision.
- Network selection/HO decision - handles the Network Selection process and is initiated either by an automatic trigger for a HO for an existing call or by a request for a new connection on the mobile device. The selection of the best network is decided based on the decision criteria provided by the device, the application and the monitoring process. After the target network is selected the call is set up on the target candidate network. Traditionally, this decision was made by network operators both for mobility and load balancing reasons, and mainly based on a single (Received Signal Strength (RSS)) parameter
- Call setup or HO execution - after the target network is selected, the connection is set up on the target candidate network. In the case of an existing connection, HO is executed and the original connection is torn down and the call data re-routed to the new connection. If the first choice network is unavailable, then the next listed candidate is chosen as the target network. Connection setup (and teardown in the case of handover) will be handled by a mobility management protocol such as MobileIPv6.

In today's mobile and wireless environments, where user quality of experience is key, the main challenge is to have a handover (HO) process which is smooth, fast, seamless, and transparent to the user. From the network operators' point of view, maximising revenue is the main focus. From the user perspective, the main challenge is to ensure that the best network, that satisfies his interests, has been chosen. But how can an ordinary user, without any background knowledge in wireless networks, know which is the best deal for him?

A good tutorial on the network selection problem is introduced by Charilas et al. in [3]. The authors describe the network selection concept and the basic processes involved in the network selection process (e.g., selecting the decision criteria, collecting the alternatives' values, defining the weights, and ranking the alternatives). The aim of their tutorial is to give an insight to the key elements of the network selection problem for researchers and engineers who are unfamiliar with this area.

A. Standards which support Network Selection

The "optimally connected anywhere, anytime" vision was introduced by ITU in Recommendation ITU-R M.1645 [4] in June 2003 and consists of different radio access networks connected via flexible core networks. The aim is to provide seamless, transparent and QoS-enabled connectivity to the user by taking into account the limitations of the underlying wireless access technology and user preferences.

The Media Independent Handover Working Group IEEE 802.21 [5] (Jan 2009), considers the interoperability aspect between heterogeneous networks, and has developed a standard referred to as IEEE 802.21. The standard enables the optimization of handover between heterogeneous IEEE 802 networks and facilitates handover between IEEE 802 networks and cellular networks by providing a media-independent framework and associated services. However IEEE 802.21 only facilitates handover and does not specify the network selection algorithm, which is a major part of the handover process.

The third-Generation Partnership Project (3GPP) are currently defining a novel entity for access network discovery and selection referred to as Access Network Discovery and Selection Function (ANDSF) [6] which enables the interworking of 3GPP (e.g., GSM, UMTS, LTE) and non-3GPP networks (e.g., CDMA, WiFi, WiMAX). ANDSF provides information about the neighbouring access networks to the mobile device through Discovery Information and assists the device in the handover process through rule based network selection policies. Two categories of policies are being defined: Inter-System Mobility Policy (ISMP) which guides the selection decision for devices with single links; and the Inter-System Routing Policy (ISRP) which directs the distribution of traffic for devices with multiple simultaneous links.

A study on the network selection requirements for non-3GPP (e.g., Bluetooth, WLAN, and wired connections) access types is provided in 3GPP TR 22.912 specifications [7]. The study identifies the potential requirements for automatic and manual selection as well as operator and end-user management requirements. The aim of the study is to ensure predictable behaviour and enable the user or application to select the best type of access that fulfils the requested service requirements.

B. Industry Solutions

In the current environment network operators are trying to cope with the explosion of data traffic by adopting different solutions to expand their networks. One category of network selection solutions include those from operators with multiple converged networks (i.e. multiple radio access technologies) - where existing mobile operators expand their network capacity by adding next generation wireless networks (e.g., HSDPA, LTE, WiMAX). Many of these upgrades involve closely interworking the existing 2G/2.5G/3G network with the new next generation network in terms of handover and network selection. For example Verizon upgraded their wireless network to offer commercial LTE-based services in the United States[1].

Another category of commercial network selection solution is for network operators who offload the mobile data traffic onto Wi-Fi networks. This solution enables transfer of some traffic from the core cellular network to WiFi at peak times. AT&T adopted this solution and launched the Wi-Fi Hotzone project[2] which aims to supplement their macro cellular coverage with additional Wi-Fi capacity (over 24,000 WiFi hotspots) in areas with high 3G traffic and mobile data usage. The Wi-Fi offload solution is already adopted by many other service providers including: Swisscom with its ”Mobile Unlimited”[3] service which provides automatic connection to the fastest available mobile broadband (on Swisscoms EDGE/HSPA networks which are supplemented with more than 1,200 WLAN hotspots); T-Mobile's ”Hotspot@Home”[4] solution which offers connectivity on the home WiFi, on all T-Mobile hotspots and on the T-Mobile cellular network; the British Telecom ”BT Fusion”[5] service which works on the user's home wireless network, BT Openzone WiFi hotspots, and on the BT cellular network; Deutsche Telekom and iPass WiFi Mobilize[6] solution; and Wi-Fi network database provider WeFi[7] who launched WeANDFS, an offload solution (to over 80 million hot-spots) which is ANDSF 3GPP compliant.

In the Enterprise Fixed Mobile Convergence service space, the advantages of fixed mobile convergence for business are well established, with one mobile device using a single number, mailbox, address book and always the lowest cost network for connectivity, all without burdening the user with the responsibly to choose the appropriate network. Solutions in this area, include: Siemens with its ”Highpath MobileConnect”[8] solution and AT&T with its ”Global Network Client”[9].

Another player category in this space is softphone service providers, such as CiceroPhone[10] whose software (which works over SIP and IMS) allows roaming between WLAN and cellular networks.

Many existing commercial solutions are proprietary and involve rudimentary static network selection decisions (e.g., always select the WLAN, always select the cheapest or the fastest network). They do not account for the varying network characteristics or for the various user context-based preferences and may often result in lower quality of service. User mobility, as well as the heterogeneity of mobile devices (e.g., different operating systems, display size, CPU capabilities, battery limitations, etc.), and the wide range of the video-centric applications (e.g., VoD (Video On Demand), video games, live video streaming, video conferences, surveillance, etc.) opens up the demand for user-centric solutions that adapt the application to the underlying network conditions and device characteristics.

[1] Verizon - www.network4g.verizonwireless.com

[2] AT&T, Wi-Fi Hotzone project - www.fiercewireless.com

[3] Swisscom 'Mobile Ultimited' Service - http://www.swisscom.ch/solutions/Solutions-products/Mobile-Unlimited

[4] T-Mobile 'Hotspot@Home' - https://content.hotspot.t-mobile.com /Asset-Process.asp?asset=com.default.main.001

[5] British Telecom 'BT Fusion' - http://www2.bt.com/static/i/btretail/consumer/btbenefits/fns/fusion.html

[6] Deutsche Telekom and iPass 'WiFi Mobilize' - http://www.telekom-icss.com/dtag/cms/content/ICSS/en/1508330

[7] Wi-Fi Network Database Provider -WeFi 'WeANDFS' - www.wefi.com /carriers/weandsf/

[8] Siemens 'Highpath MobileConnect' - http://www.midlandtelecom.co.uk /SiemensHiPathMobileConnect.aspx

[9] AT&T 'Global Network Client' - http://attnetclient.com/

[10] CiceroPhone - http://www.electronista.com/articles/06/11/02/cicero.cell.wifi.roaming/

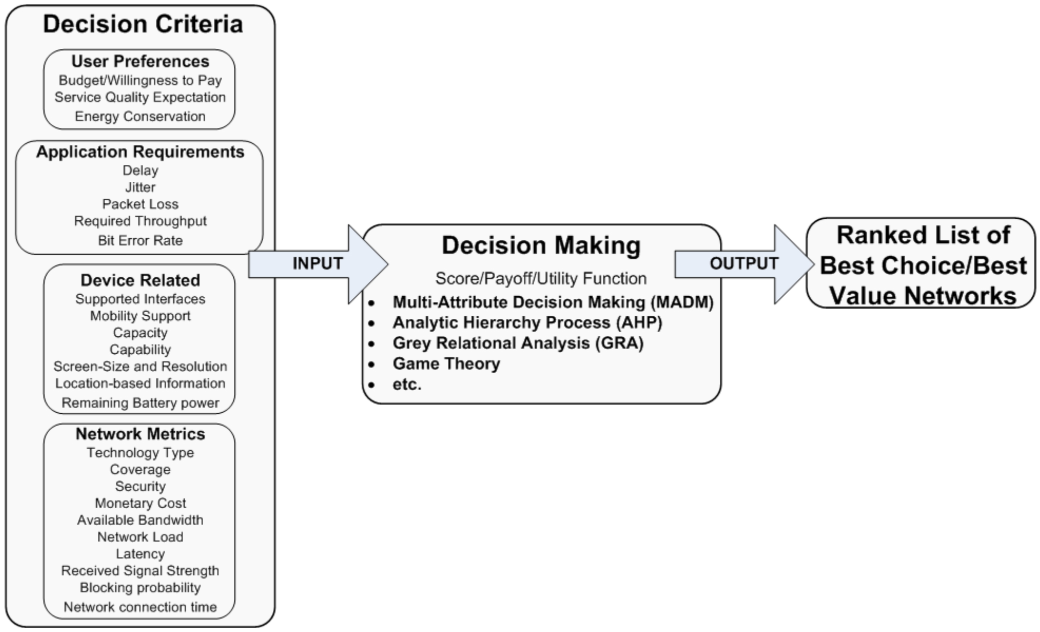

Fig. 2. Decision Making Process

C. Network Selection Decisions - Related Works

In order to strengthen the ABC vision, various network selection mechanisms have been proposed in the research literature. In general the network selection problem is part of the HO decision process and is modelled using either a centralized or a decentralized approach. Most centralized approaches are network-centric, and consist of a centralized, operator-controlled policy that decides the users' distribution among the networks. These network-centric approaches are based on the cooperation of subscribed user devices in obeying the decision made by the controller. For the decentralized approach the decision is made at the user side either by the user or automatically by the user's device. This automation may be based on policies/rules set by the user or downloaded to the device from an operator or service provider. Many of the considered decentralised user-centric approaches consider the case of users who are not solely subscribed to one network, but instead have multiple subscriptions/agreements in place and wish their device to choose the most suitable available RAN. For example an enterprise user who uses the same mobile device for personal and business use, may have access to home and work WLANs, and minutes/data from a number of operators.

In this work we consider a decentralized network selection approach. The network selection problem is considered to be a complex problem, because of the multiple mix of static and dynamic, and sometimes conflicting parameters/criteria involved in the process. An illustration of the decision making process is illustrated in Fig. 2.

1) Decision Criteria: Every decision making mechanism requires essential and relevant input information in order to choose the best value network. The decision criteria that may be used in the network selection process can be classified in four categories depending on their nature:

- Network metrics - includes information about the technical characteristics or performance of the access networks, such as: technology type, coverage, security, pricing scheme, monetary cost, available bandwidth, network load, latency, received signal strength, blocking probability, network connection time, etc.
- Device related - includes information about the end-users' terminal device characteristics, like: supported interfaces, mobility support, capacity, capability, screen-size and resolution, location-based information, remaining battery power, etc.
- Application Requirements - includes information about the requirements (minimum and maximum thresholds) needed in order to provide a certain service to the end-user: delay, jitter, packet loss, required throughput, Bit Error Rate, etc.
- User Preferences - includes information related to the end-users' satisfaction: budget (willingness to pay), service quality expectations, energy conservation needs, etc.

Note that the parameters presented above do not represent an exhaustive list and are possible choices that can be used as input information for the decision mechanism. Different approaches may use only a subset of the parameters, or may include additional parameters. An important aspect is what information is available to the decision maker and how accurate and/or dynamic that information is. For example, because of the dynamics of the wireless environment the received signal strength or the available bandwidth can present major fluctuations for short periods; while coverage and pricing schemes are less dynamic as in they do not present changes on a daily basis; and technology type, security level and application requirements are more static parameters.

Depending on the type of architecture, and protocol in use, and whether it is a centralized or decentralized decision, different information will be available in different forms and accuracy levels. For example, for a decentralized approach, the mobile device could collect the network state information as statistics, usually represented by mean values

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of previous sessions, or could estimate network bandwidth, for example, through the use of IEEE 802.21 Hello packets. A mobile station can collect authentication, routing, and network condition (e.g., available throughput, average delay, average packet loss, etc) information through advertisement Hello packets sent by a gateway node. This information can be collected from the link layer by using the IEEE 802.21 reference model [5]. Another option would be to predict the future network state based on past history. For example, based on location (e.g., home/office/airport/coffee bars, etc.), time of day (e.g., peak/off-peak hours), day of week (e.g., working days/weekends), year periods (e.g., holidays) many QoS parameters (e.g., availability, utilisation, etc.) of different hot-spots can be predicted depending on their usage pattern statistics. The accuracy in collecting network state information is very important as the selection of the best value network depends on it. However, a trade-off between accuracy and overhead needs to be taken, as keeping accurate estimates for the more dynamic parameters depends on their frequency of change and can be data intensive, adding to signalling, processor and memory burden.

The user preferences play an important role in the decision mechanism and they may be used to weight the other parameters involved. There are many ways of collecting data from the user. Some of the existing weighted solutions obtain the weights through questionnaires on user and service requirements. Other solutions integrate a GUI in the user's mobile terminal in order to collect the user preferences. An important aspect is to find a trade-off between the cost of involving the user and the decision mechanism. One solution for minimizing the user interaction may be implementing an intelligent learning mechanism that could predict the user preferences over time.

2) Decision Making: Due to the different possible strategies and the numerous parameters involved in the process, researchers have tried many different techniques in order to find the most suitable network selection solution. Some of the more formal techniques used in the literature are outlined below.

(a) *The Simple Additive Weighting Method (SAW)* [8] (also known as the weighted sum method) is one of the most widely used Multi Attribute Decision Making (MADM) methods used in the network selection literature. The basic logic of SAW in this context is to obtain a weighted sum of the normalized form of each parameter over all candidate networks. Normalization is required in order to have a comparable scale among all parameters. Depending on the formulation of the problem, the network which has the highest/lowest score is selected as the target network. For example if we consider a list of candidate networks and for each network we have a list of n parameters, then for each candidate network i a score is obtained by using eq. (1).

$$SAW_i = \sum_{j=1}^{n} w_j r_{ij} \tag{1}$$

where r_{ij} is defined as the normalized performance rating of parameter j on network i, and w_j is the weight of parameter j. Usually, the greater the score value the more preferred the candidate network.

One of the first researchers to apply the SAW method in the area of network selection strategy was Wang et al. in 1999 [9]. They describe a policy-enabled handover system used to select the "best" wireless system at any moment. They define the cost of using a network at a certain time as a function of several parameters: the bandwidth it can offer, the power consumption of the network access and the cost of this network. The function is the sum of a weighted normalized form of the three parameters. The weights may be modified by the user or the system at run-time. The cost is limited by the maximum sum of money a user is willing to spend for a period of time and the power consumption is limited by the battery lifetime. The network that has the lowest value for the score function is chosen as the target network.

Since 1999 a number of other papers offering variations of this SAW method, have been produced, e.g., [10]. In order to scale different characteristics of different units to a comparable numerical representation, different normalized functions have been used, such as: exponential, logarithmic and linear piecewise functions [11]. One of the main drawbacks with SAW is that a poor value for one parameter can be heavily outweighed by a very good value for another parameter, so, for example, if a network has a low throughput but a very good price, it may be selected over a slightly more expensive network with a much better throughput rate.

(b) *The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)* [8] is based on the concept that the selected candidate network is the closest to the ideal possible solution and the farthest from the worst possible solution. The ideal solution can be obtained by giving the best possible values to each parameter. For each candidate network i a score is obtained by using eq. (2). The greater the score value, the more preferred the candidate network.

$$TOPSIS_i = \frac{worstsolution_i}{idealsolution_i + worstsolution_i} \tag{2}$$

The authors in [12] propose a network selection algorithm based on TOPSIS method. The networks are ranked based on the closeness to the ideal solution using TOPSIS method. The proposed solution is evaluated using numerical examples. The parameters considered in the decision matrix are: available bandwidth, QoS level, security level, and cost. The results show that TOPSIS is sensitive to user preference and the parameter values.

(c) *The Multiplicative Exponential Weighting Method (MEW)* [8] (also known as the weighted product (WP) method) uses multiplication for connecting network parameters ratings. For example, for each candidate network i a score is obtained by using eq. (3).

$$MEW_i = \prod_{j=1}^{n} r_{ij}^{w_j} \tag{3}$$

TABLE I
MADM METHODS - SUMMARY

MADM Method	**Advantages**		**Disadvantages**	
SAW	-easy to use and understand -good performance for voice connections [16]	-can accommodate multiple criteria -easy to implement	-poor value parameter can be outweighed by a very good value of another one	-imprecise data cannot be handled -normalization issues
TOPSIS	-the concept is simple and comprehensive -good performance for voice connections [16]	-accurate result and scalability -high efficiency -high flexibility	-most sensitive to user preferences and parameter value [12]	
MEW	-the least sensitive method [11] -good performance with data connections [16]	-medium implementation complexity	-penalizes alternatives with poor attribute values more heavily [11]	
ELECTRE	-good performance with data connections [16]	-integrate subjective judgments with numerical data	-complicated, uses pair-wise comparison	
AHP & GRA	-can handle many parameters, giving a precise solution -good performance for data connections [16]		-complicated -length of the process increases with the number of levels and pair-wise decisions	

where r_{ij} is defined as the normalized performance rating of parameter j on network i,and w_j is the weight of parameter j. The greater the score value the more preferred the candidate network. In [11] the authors examine the disadvantages of previously proposed SAW algorithms and instead they propose the use of a weighted multiplicative method in the decision mechanism. Their results show the inaccuracy of the SAW method and the benefits of using their proposed utility function together with a weighted multiplicative method.

(d) *The Elimination and Choice Expressing Reality (ELECTRE)* method [13] is based on a pair-wise comparison amongst the parameters of the candidate networks. The concepts of concordance and discordance are used in order to measure the satisfaction and dissatisfaction of the decision maker when comparing the candidate networks.
The authors in [14] propose a modified version of ELECTRE in order to solve the network selection problem. They compute the concordance set (CSet) which consists of a list of parameters indicating that the current network is better than the other candidate networks. On the other hand a discordance set (DSet) is defined which provides a list of parameters for which the current network is worse than the other candidate networks. Two corresponding matrices are constructed using CSet and DSet. In order to indicate the preferred network, the elements of each matrix are compared against two thresholds: $C_{threshold}$ and $D_{threshold}$.

(e) *Analytic Hierarchy Process (AHP) and Grey Relational Analysis (GRA)* The authors in [15] proposed a user-centric network selection scheme using two mathematical techniques: AHP and GRA. AHP is used in order to compute the relative weights of the various parameters used in the decision model, such as: availability, throughput, timeliness, reliability, security, and cost. GRA is used to rank the networks.

- Analytic Hierarchy Process (AHP): The idea behind AHP is to decompose a complicated problem into a hierarchy of simple and easy to solve sub-problems. According to [15] there are four steps involved in the process: (1) decomposition - the problem is structured as a hierarchy of multiple criteria, where the top level is the problem to be resolved, the subsequent levels are the decision factors, and the solution alternatives are located at the lowest level. (2) pair wise comparison - at each level the elements within the same parent are compared to each other, the results are translated into numerical values on a scale from 1 to 9 and presented in a square matrix, referred to as the AHP matrix. (3) local weight calculation - the weights of the decision factors are computed by calculating the eigenvector of the AHP matrix. (4) weight synthesis - the overall weights of the decision factors are computed by multiplying the local weights from each level.
- Grey Relational Analysis (GRA):The GRA method is used to rank candidate networks and select the one which has the highest rank. There are three steps involved in the process: (1) normalization of data - is performed considering three situations: larger-the-better, smaller-the-better, and nominal-the-best. (2) definition of the ideal sequence - the ideal sequence will contain the upper bound, lower bound and moderate bound respectively in the three considered situations. (3) computing the grey relational coefficient (GRC) - the larger the GRC is, the more preferable the sequence is.

An in-depth comparison study of the MADM methods is presented by Martinez-Morales et al. in [16]. The authors analyze the performance of SAW, TOPSIS, MEW, ELECTRE and GRA through simulations considering a 4G environment with three network types (e.g., WLAN, UMTS, and WiMAX) and six decision criteria (available bandwidth, total bandwidth, packet delay, packet jitter, packet loss, and monetary cost per byte). In order to differentiate the services, the authors considered three cases with different values of the parameter weights corresponding to a specific service type: a baseline case in which all the parameters have the same assosciasted weights, a voice connection-based case in which the delay and packet jitter weight is 70% while the rest of the parameters are considered equally important, and a data connection-based

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TABLE II
MAPPING OF GAME THEORY TO NETWORK SELECTION ENVIRONMENT

Game Component	Network Selection Environment Correspondent
Players	The agents who are playing the game: users or/and networks
Strategies	A plan of actions to be taken by the player during the game: available/requested bandwidth, subscription plan, offered prices, available APs, etc.
Payoffs	The motivation of players represented by profit and estimated using utility functions based on various parameters: monetary cost, quality, network load, QoS, etc.
Resources	The resources for which the players involved in the game are competing: bandwidth, power, etc.

case in which the available and total bandwidth have the highest importance (70%). The results show that SAW and TOPSIS are suitable for voice connections resulting in low jitter and packet delay, while GRA, MEW, and ELECTRE are suitable for data connections obtaining high throughput. A summary of the advantages and disadvantages of each of the MADM methods, as identified in this section, is illustrated in Table I.

III. Game Theory and Network Selection

Game theory is a mathematical tool used in understanding and modelling competitive situations which imply the interaction of rational decision makers with mutual and possibly conflicting interests. It was originally adopted in economics, in order to model the competition between companies. Nowadays game theory is widely applied to other areas, such as: biology, sociology, politics, computer science, and engineering. Game theory has been adopted in the telecommunication environment, especially in wireless sensor networks [17], cognitive radio networks [18], and ad-hoc networks [19]. Game theory is used as a tool for studying, modeling, and analyzing the interactions between individuals strategically. In the wireless environment, game theory has been used in order to solve many distributed power control [20], resource management and allocation, and dynamic pricing [21] related problems. A more comprehensive survey on general game theory application in wireless networks is offered by Charilas et al. in [22]. They present a categorization, under the corresponding OSI Layer (e.g., Physical, Data link, Network, and Transport), of a collection of game theoretic approaches applicable to various telecommunication fields (e.g., power control, spectrum allocation, MIMO systems, medium access control, routing, load control, etc.). The aim of their survey is to show that game theory can be used to solve problems in all aspects of telecommunications. The recently released book [23] presents a collection of fundamental issues and solutions in applying game theory in different wireless communications and networking domains (e.g., wireless sensor networks, vehicular networks, power control games, economic approaches, and radio resource management).

The focus of this review is on the state-of-the-art game theory solution approaches in relation to network selection. The main contribution is a comprehensive survey of the current research on this topic in the form of a categorisation, comparison and analysis of the existing solutions.

A. Basic Concepts of Game Theory

The main components of a game are: the set of players, the set of actions, and the set of payoffs. The players seek to maximize their payoffs by choosing strategies that deploy actions depending on the available information at a certain moment. Each player chooses strategies which can maximize their payoff. The combination of best strategies for each player is known as equilibrium. When each player cannot benefit anymore by changing his strategy while keeping the other players' strategies unchanged, then we say that the solution of the game represents Nash Equilibrium. The payoff for each player can be represented as the actual or expected utility a player receives by playing the current strategy. When the payoffs cannot be further enhanced with any other strategy combination, the game is said to have reached a Pareto Optimal Nash Equilibrium.

- *Nash Equilibrium Definition*: Let N be the number of players in a game and i be an index of a player such that $0 < i \leq N$. Let S_i denote a set of available mixed strategies for player i with $s_i \in S_i$ being any possible strategy of player i. The Nash Equilibrium satisfies the condition given in eq. (4).

$$\pi_i(s_i^*, s_{-i}^*) \geq \pi_i(s_i, s_{-i}^*) \forall 0 < i \leq N \forall s_i \in S_i \tag{4}$$

  where $\pi_i()$ is the payoff function of player i, s_i^* denotes a Nash Equilibrium strategy of player i, and s_{i-1}^* denotes the Nash Equilibrium strategies of all players other than player i. However, some games might not have a Nash Equilibrium or they can have more than one Nash Equilibrium.
- *Pareto Optimality Definition*:Let N be the number of players in a game and i be an index of a player such that $0 < i \leq N$. Let S_i denote set of available mixed strategies for player i with S_i^* being the set of Nash Equilibrium strategy of player i, $s_i^* \in S_i^*$. The Pareto Optimality satisfies the condition give in eq. (5).

$$\pi_i(s_i^p) > \pi_i(s_i^*) \forall 0 < i \leq N \forall s_i^* \in S_i^* \tag{5}$$

  where $\pi_i()$ is the payoff function of player i and s_i^p denotes the strictly Pareto Optimal strategy.

TABLE III
GAME THEORETIC APPROACHES FOR NETWORK SELECTION

Players Interaction	Game Theoretic Approach	Objective
Users vs. Users	**Non-cooperative**	users compete against each other seeking to maximize their own utility
	Cooperative	users cooperate in order to obtain mutual advantage (maximize social welfare)
Networks vs. Users	**Non-cooperative**	users compete against networks, each seeking to maximize their own utility. On one side the users try to maximize their cost-benefit performance. On the other side the networks aim to maximize the profit for the provided services.
	Cooperative	both sides cooperate in order to achieve mutual satisfaction
Networks vs. Networks	**Non-cooperative**	the networks compete against each other seeking to maximize their individual revenues
	Cooperative	networks cooperate in order to achieve global welfare maximization

B. Game Theory to Network Selection Mapping

A mapping of game theory components to network selection environment is given in Table II. The players in the game are the mobile users and/or the networks. Players seeking to maximize their payoffs can choose between different strategies, such as: available bandwidth, subscription plan, or available APs. The payoffs can be estimated using utility functions based on various decision criteria: monetary cost, energy conservation, network load, availability, etc. The games can be formulated so that they can target different objectives, such as maximizing or minimizing different resources - bandwidth, power, etc.

Different categorisations of the various game types are possible. In this work the solutions are classified firstly by the players involved (Users vs. Users, Users vs. Networks, Networks vs. Networks) with a further sub-classification under two broad major game theoretic approaches:

- cooperative approaches - which implies the joint considerations of the other players.
- non-cooperative approaches - in which each player selects his/her strategy individually.

In this context, game theory is used to model and analyze cooperative or non-cooperative behaviors of users and networks during their interaction in a heterogeneous wireless environment. For example consider a group of users that are located in an area with a number of available networks. Each user is seeking to select the best network that will maximize its utility. In this particular case we can identify six different game theoretic approaches, as illustrated in Table III.

C. Game Theoretic Models

Different types of games are used to model various cooperative or competitive situations between rational decision makers. Some of the most widely used game theoretic models are outlined below.

1) Strategic Game: Prisoner's Dilemma: A Strategic Game is an event that occurs only once with each player being unaware of the other player's action. The players choose their action simultaneously and independently. One of the most well-known strategic games is Prisoner's Dilemma [24].

TABLE IV
PAYOFF TABLE FOR PRISONER'S DILEMMA

	Cooperate	**Defect**
Cooperate	1,1	4,0
Defect	0,4	3,3

Prisoner's Dilemma models a situation in which there are two suspects in a major crime held in separate cells. The payoffs for this game are illustrated in Table IV and the idea is that the players are seeking to minimize their jail sentence. If they both remain silent (Cooperate with each other), each will be sentenced to 1 year in prison. If they both confess (Defect), each will be sentenced to 3 years in prison. If only one of them confesses, he/she will be freed, and used as a witness against the other, who will be sentenced to 4 years in prison. The best outcome for the players is that they both cooperate, meaning that neither confesses, but each of them has an incentive to "free ride" (Defect) seeking to get out of jail. In isolation both players will prefer Defect to Cooperate, leading to the game's unique Nash equilibrium (Defect, Defect).

2) Repeated Game: The main idea of the Repeated Game is to examine the logic of long-term relationships and show that repeated interaction leads to cooperation [24]. Usually in repeated games, a set of players will repeatedly play the same strategic game taking into account the history of the past behaviour. Let us consider the repeated Prisoner's Dilemma game with the same payoff table as illustrated in Table IV. For each player, playing Defect strictly dominates playing Cooperate, despite the fact that both players are better off cooperating. Therefore, the game has a unique Nash equilibrium when each player Defects. When the game is played repeatedly, the mutual desirable outcome is when they both cooperate in every period (long-term gain). This becomes stable if each player believes that by Defecting they will cause the Cooperation to end, which results in short-term gain but long-term loss.

3) Bargaining Game: The Bargaining Game [25] is a game theoretic approach in which players bargain for an object or service. The most common example is where one of two players splits a pie of a certain size. The first player proposes

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a division of the pie and the second player has two options: to accept - in which case he might end up with no pie if player 1's division is selfish (i.e., he leaves no pie for player 2) leading to a unique subgame perfect equilibrium, or to refuse the division - in which case neither player gets any pie. In the extended game where the players alternate the offers over many periods, the player who makes the offer in the last period will end up with the entire pie considering the case of subgame perfect equilibrium.

4) Trading Market: The Trading Market game [24] models the scenario in which a single seller can negotiate to trade a certain good with multiple buyers. The basic idea behind this game is to analyze how the presence of a second buyer affects the negotiated price. The buyers know that by rejecting the seller's offer there is a 50% probability that another buyer will be trading in the next period.

5) Auction Game: The Auction Game [25] is a game theoretic approach that models the situation in which bidders submit bids to an auctioneer in order to obtain a certain object or service. The good is sold to the bidder that submits the highest bid. There are two main auction games:

- the first-price auction game - in which the winning bidder will pay an amount equal to his bid;
- second-price sealed-bid auction game - in which the bidder with the highest bid wins but pays an amount equal to the second highest bid.

6) Cournot Game: The Cournot Game [24] models the competition among firms for the business of consumers. It considers the case where a good is produced by multiple firms. Each firm has a cost of producing a certain amount of good units. More output means more cost to produce. The profit of each firm is computed as the difference between the firm's revenue and the cost incurred. The price decreases as the total output among the firms increases. The aim is to analyze the impact of several factors (i.e., market demand, the nature of the firms' cost functions, or the number of firms) on the outcome of competition among firms.

7) Bankruptcy Game: The Bankruptcy Game [24] is a game theoretic approach used to model distribution problems. This usually involves the scenario in which a perfectly divisible good has to be allocated among a group of agents. The bankruptcy game considers the case in which the amount is insufficient to satisfy all parties' demands.

8) Stackelberg Game / Leader-Follower Game: The Stackelberg Game [26] is a strategic game also known as the Leader-Follower Game in which the player acting as the leader moves first and then the follower players move sequentially. It is assumed that the followers are rational and they will try to optimize their outcome given the leader's actions. Given this, the aim is to find an optimal strategy for the leader.

9) Bayesian Game: Bayesian Games [24] represent a combination of game theory and probability theory, offering the possibility to take into account incomplete information. Each player involved in the game can have some private information which is unknown by the other players but it can affect the overall game play. In these situations the players act optimally according to their private information and their beliefs which are represented through probability distributions.

10) Coalition Game: Usually cooperative games explore the formation of coalitions between various players [24]. For example considering a N-player cooperative game, where N = 1, ..., n is the set of n players, the coalition form would be given by the pair (N,v) where v is the characteristic function. The characteristic function assigns the maximum expected total income of the coalition. The core represents the solution concept of the cooperative game, and is usually used in order to obtain the stability region. It gives the set of all feasible outcomes that cannot be improved by the coalition members when acting independently. Another concept which represents a measure of efficiency is Pareto Optimality. By definition, an agreement is said to be Pareto efficient if and only if there is no other feasible agreement that all the players prefer.

11) Evolutionary Games: The Evolutionary Game [27] is a game theoretic approach that has been applied most widely in the area of evolutionary biology. The main idea behind evolutionary game theory is that many behaviours are involved in the interaction of multiple entities/organisms in a population and the success of any of them depends on how their behaviour interacts with that of the others. In these types of games, an individual entities/organism has to be evaluated considering the context of the entire population in which it is living.

12) Mechanism Design: Mechanism Design [28] is an area of Game Theory that concerns defining incentive mechanisms which will induce desirable equilibrium. The incentives can be defined through the use of utility functions or by using pricing or virtual currency mechanisms.

IV. Classification of Game Theory Approaches

The network selection problem can be a very complex problem, and various game theoretic approaches that try to solve the network selection problem are proposed in the literature. Different game models are used to model the problem as non-cooperative or cooperative game between users and/or networks. Fig. 3 illustrates a classification of the existing approaches into three broad categories based on the interaction between players: users vs. users (non-cooperative [29] - [35] and cooperative [36]), networks vs. users (non-cooperative [37] - [41] and cooperative [42]), and networks vs. networks (non-cooperative [43] - [49] and cooperative [50] - [54]). It is noticeable that most related works formulate the problem as non-cooperative games. Few of the works look at cooperative behavior, and of those that do, most are based on cooperation between networks.

The approaches differ in terms of: game model (Evolutionary Game, Auction Game, Bargain Game, Repeated Game, etc.), players (users and/or networks), strategies (transmission rates, available APs, service requests, etc.), pool of parameters (delay, jitter, throughput, packet loss, monetary cost, etc.), single or multiple operators, use of single or multiple simultaneous RAN connections, pricing scheme (dynamic or flat rate pricing), used RATs (WLAN, WiMAX, Cellular), etc. However, the main objective of the games is more or less the same: network selection, which is in fact a resource allocation problem.

Table V provides a comparative summary of the latest proposed game theoretic solutions in terms of related category, game type, game model, objective, strategy set, payoffs,

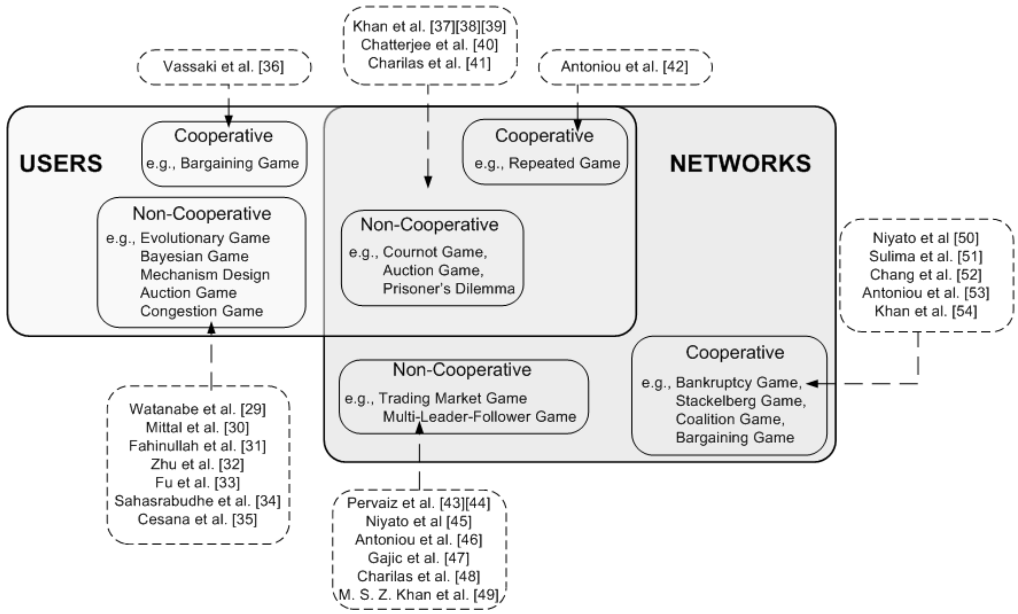

Fig. 3. Classification of Related Works Based on Players' Interactions

considered parameters, resource, Radio Access Technology (RAT), and number of operators.

A. Game players: Users vs. Users

1) Users vs. Users - Non-Cooperative Approach: In the non-cooperative users vs. users scenarios, users compete against each other while seeking to maximize their own utility.

The behaviour of selfish users who compete for access in a WLAN is studied by Watanabe et al. in [29]. The authors make use of evolutionary game-theory in order to model the interaction between users. The players are the mobile users and the available transmission rates represent the set of strategies. The payoff for each user is modelled as a utility function which determines the voice quality received by each user in each state. The role of the utility function is to map the wireless characteristics, such as delay and loss rate into the Mean Opinion Score (MOS) which represents a measure for voice quality. The authors show that by having free users, equilibrium close to optimal, from the system perspective can be reached but the equilibrium is very unfair

Another approach which studies the interaction between selfish users, is proposed in [30] by Mittal et al. The authors look at the problem faced by mobile users of selecting the least congested Access Point (AP) when they are located in an area with a number of deployed WLANs. The aim is to find the best trade-off between the bandwidth gained by the user and the effort incurred by the user when travelling to the new location. The AP selection system is modelled as a non-cooperative game between selfish users. The set of strategies for the user is represented by the set of available APs in the network and involves physically relocating to within close range of the chosen AP. The authors show that the stability of the system is high when users' arrivals and exits are evenly intermingled. The necessary condition to attain a Nash Equilibrium is examined and the Nash condition is used in order to evaluate the stability of the distribution. The outcome of the game is the users' distribution among the APs.

Fahimullah et al. in [31] extended the work proposed in [30] by considering the case of multiple operators. The authors define a weighted sum score function based on the AP's load, the price and the distance that the user must travel to reach the new AP. The authors argue that the results prove the existence of the Nash equilibrium.

A Bayesian game is used by Zhu et al in [32] in order to model the network selection problem. The players are the users, and their action set is represented by the selection of an available access network. Each user has partial information about the preferences of other users. The authors show that a Bayesian Nash equilibrium can be reached in an environment with incomplete information.

Fu et al. [33] model the wireless resource allocation problem as a non-cooperative game between rational and selfish users. The users compete against each other in order to stream real-time video traffic. The authors make use of mechanism design in order to ensure that the players declare their resource requirements truthfully and the resources are fairly allocated.

An auctioning game is used by Sahasrabudhe et al. in [34] to model the resource allocation problem between the wireless users. Considering the scenario of multiple wireless users located in the coverage area of a number of base stations (BSs), each user is interested in buying a certain amount of bandwidth owned by the BS. Every user has a total amount (budget) that he can spend, and from which he bids for a BS allocation. Each BS will allocate its available bandwidth among the wireless users in a proportionally fair manner, based on the users' bids. The authors argue the existence of Nash Equilibrium for the case where each user can access all BSs. However, in the case of constrained users (users that can access only a subset of all BSs) the existence of Nash Equilibrium is not guaranteed.

In [35] Cesana et al. consider the scenario where there is only one WiFi network with multiple APs and the users within the system can choose the AP to connect to. In this scenario the users are the players of a non-cooperative game and their

TABLE V
SUMMARY OF SURVEYED APPROACHES

Category	Game type	Game Model	Objective	Strategy Set	Payoffs	Parameters	Resource	RAT	Op.	Ref.
Users vs. Users	**Non-Cooperative**	*Evolutionary Game*	**resource sharing** - study the behavior of selfish users who compete for medium access in a WLAN.	available transmission rates	utility function	loss rate, mean burst size, delay, jitter	bandwidth	WLAN	single	[29]
		Evolutionary Game	**network selection** - fair users' distribution among the APs.	all available APs in the network	utility function	distance from AP and network load (number of connected users)	bandwidth	WLAN	single	[30]
		Evolutionary Game	**network selection** - fair users' distribution among the APs.	all available APs in the network	utility function	distance from AP, network load (number of connected users), price	bandwidth	WLAN	multiple	[31]
		Bayesian Game	**network selection** - choosing the best value network	the probability of choosing one of the available networks	utility function	bandwidth, price	bandwidth	WLAN, CDMA, WiMAX	multiple	[32]
		Mechanism Design	**resource management** - fair resource distribution among users.	requested bandwidth	utility function	SNR, video source characteristics, price	bandwidth	WLAN	single	[33]
		Auction Game	**resource allocation** - resource distribution among users	bids representing the willingness to pay	utility function	bandwidth, user's budget	bandwidth	not specified	multiple	[34]
		Congestion Game	**network selection** - select the network that minimizes the selection cost	available APs in the network	cost function	congestion of the AP (number of interferences)	bandwidth	WLAN	single	[35]
	Cooperative	*Bargaining Game*	**resource allocation** - optimal bandwidth distribution.	requested bandwidth	utility function	bandwidth, transmitted power, path gain, noise spectral density	bandwidth	Cellular	single	[36]
Users vs. Networks	**Non-Cooperative**	*Auction Game*	**network selection** - select the network which fulfils the user requirements.	requested bandwidth with associated attributes	utility function	bandwidth, MOS, Delivery Response Time, application requirements	bandwidth	HSDPA, WLAN	multiple	[37] [38] [39]
		Cournot Game	**resource allocation** - allocate the available resources among users within user classes.	subscription plan (Premium, Gold, or Silver)	utility function	cost per byte, cost for up time per unit time, cost of coverage of services	power	CDMA	single	[40]
		Prisoner's Dilemma	**resource management** - admission and load control.	network: admit or reject; user: stay or leave;	utility function	delay, jitter, throughput, packet loss, cost	bandwidth	not specified	multiple	[41]
	Cooperative	*Repeated Game*	**network selection** - achieve a user-satisfying and network-satisfying solution.	**network**: tit-for-tat or cheat-and-return; **user**: Grim, Cheat-and-Leave, Leave-and-Return, or Adaptive return	utility function	perceived quality, price (not defined)	bandwidth	not specified	multiple	[42]
Networks vs. Networks	**Non-Cooperative**	*Strategic Game*	**network selection** - select the network which fulfils the user requirements.	offered prices	utility function	reputation, degradation, price and availability	bandwidth	WiMAX, WLAN	multiple	[43] [44]
		Trading Market	**resource allocation** - allocate bandwidth from each available RAN to an incoming connection in a fair manner.	amount of offered bandwidth	utility function	bandwidth, number of ongoing connections	bandwidth	WLAN, CDMA, WMAN	single	[45]
		Strategic Game	**network selection** - select the best network to satisfy a service request	the service requests	utility function	delay, jitter	bandwidth	4G system	multiple	[46]
		Multi-Leader-Follower Game	**network selection** - select the best value network for the user	offered prices	utility function	spectral efficiency, allocated time fraction, and the willingness to pay	bandwidth	not specified	multiple	[47]
		Non-Zero-Sum	**admission control** - service requests distribution among the available access networks	the service requests	utility function	network efficiency and network congestion	bandwidth	WLAN	multiple	[48]
		Strategic Game	**network selection** - select the best access network	the service requests	utility function	service type, user preferences, signal strength, mobility, battery level	bandwidth	WCDMA, WLAN, WiMAX	multiple	[49]
	Cooperation	*Bankruptcy Game*	**admission control** - guarantee the total transmission rate requested by the new connection; **bandwidth allocation** - allocate bandwidth from each network in a fair manner.	coalition form	characteristic function	available bandwidth	bandwidth	WLAN, CDMA, WMAN	single	[50]
		Stackelberg Game	**resource allocation** - allocate resources by splitting the user's application over the available networks.	coalition form	characteristic function	congestion factor, available bandwidth	bandwidth	not specified	single	[51]
		Strategic Game	**network selection** - compute the preference value from the network point of view, seeking to decrease the number of handoffs and achieve load balancing.	preference value for each network	utility function	network load, call holding time, the dwell time, mobility	bandwidth	not specified	single	[52]
		Coalition Game	**resource allocation** - allow individual access networks components to cooperate and share resources.	coalitions	characteristic function	available bandwidth	bandwidth	not specified	multiple	[53]
		Bargaining Game	**resource allocation** - allocate bandwidth from each network in a fair manner.	offered bandwidth	utility function	available bandwidth	bandwidth	not specified	multiple	[54]

actions are the selection of an AP within their area. For every user, a cost function is defined based on the AP the user will connect to and on the congestion level of that AP. The solution of the game is the existence of the Nash equilibrium.

2) Users vs. Users - Cooperative Approach: In cooperative users vs. users situations, users cooperate in order to obtain mutual advantage and maximize the global welfare of the group.

Vassaki et al. [36] look at the scenario of a single cell network with one base station (BS) and multiple users having certain capacity demands. The authors model the bandwidth sharing problem using two different approaches. The first approach models the allocation problem as a cooperative N-person bargaining problem and the Nash bargaining solution (NBS) is found. The users' strategies are the bandwidth demands, and users are assumed to be free to bargain in order to achieve mutual advantage. The second approach models the problem as a bankruptcy game, solved using three different division rules: Constrained Equal Awards (CEA) rule - assigns awards as equal as possible, Random Arrival (RA) rule - follows the first-come first-served principle, and Talmud rule - if the amount to divide (bandwidth) is smaller than the sum of the half-claims then the CEA rule is used and applied to the half-claims, else, if it is greater, the Constrained Equal Losses (CEL) rule is used - equalizes the losses. The results show that the maximization of total capacity is reached by using CEA or NBS, but in terms of maximum fairness the RA and Talmud rules act better.

B. Game players: Networks vs. Users

1) Networks vs. Users - Non-Cooperative Approach: In non-cooperative networks vs. users situations, users compete against networks, each seeking to maximize their own utility. On one side, the users try to maximize their benefits from the service for the price they pay. On the other side, the networks try to maximize the profit for the provided services.

The interaction between networks and users is studied by Khan et al. in [37] - [39]. The authors model the network selection problem as a non-cooperative auction game which has three components: bidders, sellers, and an auctioneer. The buyers are represented by the users, sellers/bidders are analogous to available network operators and the auction item is represented by the requested bandwidth with associated attributes. The winning bid is computed such as it will maximize the user's utility.

A non-cooperative game is also used in [40] for service differentiation in CDMA systems. In order to define the utility function for the provider, the authors use the Cournot game played between a provider and their customers. The dominant strategies for the provider and customer are defined as: the provider is looking to serve only customers who bring high revenue, while the customers will opt to leave the network if the received service quality does not fulfil their expectations. Users are accepted into the network if the provider's utility value is less than the value of the new utility computed for each of the service classes when a new customer arrives. The authors categorized the users into three classes: Premium, Gold, and Silver. The resource allocation is done in two steps: (1) at the macro level, where the available resources are split between different user classes by the admission control algorithm which meets the Nash equilibrium; (2) at the micro level, where the resources are split between active users within the same class. Using a variant of the Cobb-Douglas utility function, the authors find the equilibrium for resource distribution.

Charilas et al. [41] propose a congestion avoidance control mechanism which models the competitive customer-provider scenario as a non-cooperative two-player game. The proposed framework consists of two games, namely the Admission Control (AC) game and the Load Control (LC) game. The AC game is modelled using the classical Prisoner's Dilemma game and is played between each user-provider combination. Each service request represents an instance of the game with both players having two strategies. The provider either admits or rejects the service request, while the customer can decide to leave or to stay with the service provider. The authors argue the existence of a pure strategy Nash equilibrium. The LC game is similar to the AC game and is played periodically while the sessions are running. In this way, users can decide to leave the network even though their session is still running, or providers can decide to terminate a session, if that session is causing QoS degradation to the on-going sessions. The authors show that when both proposed mechanisms are used the provider achieves the best revenue.

2) Networks vs. Users - Cooperative Approach : In co-operative networks vs. users situations, users and networks cooperate in order to achieve mutual satisfaction.

Antoniou et al. in [42] look at the network selection problem and model the user-networks interaction as a cooperative repeated game where the user has four strategies: Grim strategy dictating that the user is participating in the relationship but if dissatisfied he will leave the relationship forever, Cheat-and-Leave strategy gives the user the option to cheat and then leave the network after cheating, Leave-and-Return strategy dictates that in case the network cheats the user leaves for only one period and returns in the subsequent interaction, and Adaptive Return strategy in which the user returning is dictated by the normalized weight of network's past degradation behaviour. The network can choose between two strategies: Tit-for-Tat strategy which mimics the action of the user, and Cheat-and-Return strategy which gives the option to the network to cheat and return accepting the user's punishment. The authors show that employing the proposed Adaptive Return strategy can motivate cooperation, resulting in higher payoffs for both players.

C. Game players: Networks vs. Networks

1) Networks vs. Networks - Non-Cooperative Approach: In non-cooperative networks vs. networks situations the networks compete against each other, seeking to maximize their individual revenues.

Pervaiz et al. in [43] [44] use a non-cooperative game approach in order to formulate the network selection problem as an interaction game between network service providers aiming to maximize their rewards. Dynamic pricing is used and the prices set are considered to be the players' strategies. The payoff for each provider represents the gain from users selecting that provider's network.

Another study which looks at the interaction between networks is presented by Niyato et al. in [45]. The authors propose a radio resource management framework based on non-cooperative game theory and composed of four main components: network level allocation, capacity reservation, admission control and connection-level allocation. The bandwidth allocation problem is modelled as a non-cooperative game between different access networks and the solution is obtained from the Nash equilibrium showing that the total network utility is maximized. A bargaining game is used in order to model the capacity reservation problem. The connection level allocation is modelled as a trading market game and a Nash equilibrium is found as the solution of the game.

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Antoniou et al. [46] model the network selection problem as a non-cooperative game between the networks which compete against each other in order to maximize their own payoff. The payoffs are defined based on a utility function which models the user preferences. The utility function follows a three zone-based structure, which was previously proposed in [55], that defines the user's level of satisfaction relative to delay: satisfied, tolerant, and frustrated. The authors argue the existence of Nash Equilibrium and observe that under Nash equilibrium the networks' payoffs are maximized when the users with higher preferences for the specific network are selected.

In [47] Gajic et al. propose a provider competition game that makes use of a two-stage multi-leader-follower game, where networks are the leaders and users are the followers. The game consists of two stages. In the first stage the providers announce their prices per resources and in the second stage the users announce their resource demands. The users are allowed to have simultaneously connections with different providers. The authors consider a social welfare optimization problem (SWO) which aims at maximizing the sum of payoffs of the users and providers. They demonstrate the existence of an unique equilibrium corresponding to the unique social optimal solution of the SWO problem.

Charilas et al. in [48] propose a non-cooperative multi-stage game between two independent WLANs to model the admission control problem. The players in the game are the two networks and their strategy set is the users' service requests. The outcome of the game is the distribution of the service requests among the networks, so that each network gains the maximum payoff.

Another study that models the network selection as a non-cooperative multi-stage game is provided by Khan et al. in [49]. The players are three wireless access networks: WCDMA, WLAN, and WiMAX. The set of strategies is represented by the users' service requests, and the payoffs for each network are computed based on the type of service (streaming video, internet surfing, or voice call), user preferences (cost and quality), traffic state and signal strength of the network (bad, medium, or good), speed of the user (high, low, or stable), and drainage rate of the battery. The outcome of the game is the distribution of the service requests among the networks while each network tries to maximize its own payoff.

2) Networks vs. Networks - Cooperative Approach: In cooperative networks vs. networks situations, networks cooperate in order to achieve global welfare maximization.

A cooperative approach which looks at the interaction between networks was proposed by Niyato et al. in [50]. The authors look at the scenario where a wireless multi-mode terminal can be served simultaneously by three different access networks owned by different cooperating network operators. In this context, the bandwidth allocation and admission control problems are modelled using a bankruptcy game. In this game the mobile user who initiates a connection request is seen as the bankrupt company, the bandwidth requirement is the money that has to be distributed among different networks. The access networks involved cooperate in order to provide the required bandwidth to the mobile user by using a coalition form and a characteristic function which is used to express the payoff of the coalition. The solution of the bandwidth allocation problem is computed by using the Shapley Value and the core concept is used in order to analyze the stability of the allocation.

Another cooperative approach that models the problem of resource allocation in heterogeneous wireless networks as a cooperative Stackelberg game, using coalitions between individual wireless networks is studied by Sulima et al in [51]. When a user cannot be served by a single network, the proposed model will enable the user to split its application traffic between the coalition members. The authors define the characteristic function which is used to express the payoff of the coalition, and the core concept is used in order to analyze the stability of the allocation.

A combination of utility and game-theory network selection scheme is proposed by Chang et al. in [52]. Considering the scenario of a mobile user located in a area with a number of available wireless networks, the authors propose the use of a cooperative game modelled between the candidate networks in order to achieve load balancing and reduce the handoff occurrence frequency. The strategies in the game are the set of preference values for each network. The payoff for each candidate network is a function of the current load intensity before accepting the call request, the predefined load intensity threshold and the penalty weight of the network. The goal of the game would be to maximize the payoff function for each candidate network.

Antoniou et al. in [53] explore the formation of a coalition between individual access networks which is done based on the available resources and the payoffs' allocation method. The authors propose the use of two types of payoffs: transferable payoffs, where a network can transfer a certain amount from its own payoff to other members of the coalition, as long as its final payoff is greater than zero; and non-transferable payoffs which are the payoffs obtained for each member's resource contribution. The authors study the stability of coalitions for the two types of payoffs, using the core concept. Using analysis they have shown that when considering transferable payoffs only winning coalitions, which are minimal in size for at least one player, are in the core. On the other side, the coalitions which are by-least winning for at least one player, are located in the core when considering the non-transferable payoffs. Another approach, which considers cooperation between networks, was proposed by Khan et al. in [54]. The authors considered a multi-operator environment where a network sharing agreement has been established between the operators. The interaction between networks is modelled by defining two games: intra-operator and inter-operator games. In the case of the intra-operator game, the networks within a single operator play a bargaining game in order to share the bandwidth requested by an application. If that single operator cannot satisfy the requirements, then a second game is played (this time an inter-operator game). The inter-operator game is played between operators who are willing to share extra bandwidth.

V. GAME THEORY AND 4G - CHALLENGES

When using game theory in the heterogeneous wireless environment, several challenges and issues can be identified

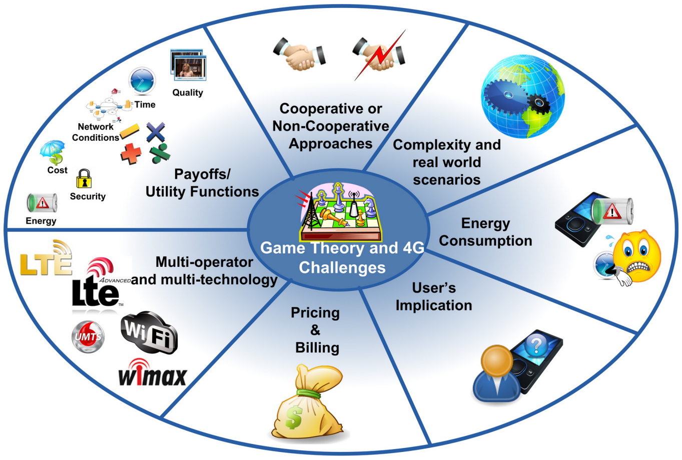

Fig. 4. Challenges in Game Theory and 4G

as illustrated in Fig. 4 and highlighted in this section.

A. Cooperative or Non-cooperative Approach

The 4G environment aims to provide a combination of network and terminal heterogeneity as well as heterogeneous services. In this multi-user multi-provider heterogeneous environment, users equipped with multi-mode wireless mobile devices will have the option to connect to one or more access networks, which differ in technology, coverage range, available bandwidth, service provider, monetary cost, etc. In this context, game theory approaches have been used in order to model and analyze the cooperative or competitive interaction between rational decision makers, which represent users and/or network operators.

One of the first challenges is to identify the players and model the problem with the appropriate cooperative or a non-cooperative game. The players, the strategies available to each player and their objectives must be clearly defined as they represent the main components with crucial roles in the game. In section 4 we classified the existing approaches based on players' interaction as: users vs. users, users vs. networks, and networks vs. networks. Game theory works on the assumption of rationality, meaning that it is assumed that players are rational individuals who act based on their best interest. While the service providers' main interest is in trying to increase their revenues by increasing their number of customers, the users expect to get the service quality they are paying for. When considering the heterogeneous wireless environment, the players are represented by entities in the networks or by users' terminals, which are assumed to be rational. However, it cannot be always guaranteed that these entities will act in a rational manner.

As we have seen in this survey, various game models (strategic games, bargain game, auction game, etc.) have been considered under different scenarios (users vs. users, network vs. users, networks vs. networks). Most of the presented solutions used non-cooperative game theory in order to define the interaction between players. Users compete against each other by adopting different strategies, such as: available transmission rates [29], available APs [30] - [32] [35], requested bandwidth [33] or by submitting bids representing the willingness to pay [34]. The cooperative approach is modeled as a bargain game [36] where users are free to bargain in order to obtain mutual advantage. Networks compete against each other in order to increase their individual revenue by employing different strategies, such as: offered prices [43] [44] [47], offered bandwidth [45], and service requests [46] [48] [49]. Most of the related works that explore the cooperation between networks look at the scenario in which a number of different access networks form coalitions [50] [51] [53] [54] in order to handle the service requests when a single access network cannot. In this scenario, the cooperation is built on the assumption that the wireless networks may cooperate either because their service demand overwhelms the network capacity or because they can reduce some of their cost by cooperation.

By using game theory we can model realistic scenarios in which players compete against each other, each of them seeking to maximize their own profit. In the cooperative games, players are assumed to be collaborating in order to maximize their payoffs, but in some cases they may act selfishly and refuse to cooperate in order to optimize their own profit or to conserve their own limited resources (e.g., energy). In these situations, in order to avoid an overall QoS degradation, incentive mechanisms can be adopted. The aim of using incentive mechanisms is to motivate the players to cooperate for the social welfare maximization. An important aspect that appears due to the dynamics of the wireless environment, is that some of the cooperative players can be perceived as selfish because of random wireless errors, interference, or packet collisions. This situation can lead to players ending their cooperation thus decreasing the overall network performance.

Another important aspect is the way the players make their decisions: distributed or centralized manner. The centralized approach is rarely used in solving the problem of multiple access networks. This may be due to the computational expense increasing with increase in network size, increasing the network control overhead as well. In general, game theory is more suitable for distributive approaches with self-configuration features and a lower communication overhead. The common aim of these game theoretic approaches is to improve the overall system performance (e.g., efficient resource utilization, throughput maximization, QoS guarantee).

B. Payoffs/Utility Functions

The choice of payoff or utility function is another challenge as it impacts on how the players will choose their actions. Utility functions have been introduced to describe the player's perception of performance and satisfaction. They usually express the trade-off the user is willing to accept between acquiring more resources (manly bandwidth) and saving resources (mainly money, energy, etc.). All the existing approaches have a common goal of optimising the network performance by maximizing the utility function. Because of the traffic heterogeneity, that brings a huge number of different applications with different requirements, a precise definition of a utility function becomes very complicated.

An example of some popular utility function shapes are those defined by Rakocevic et al. in [56]. They differentiate

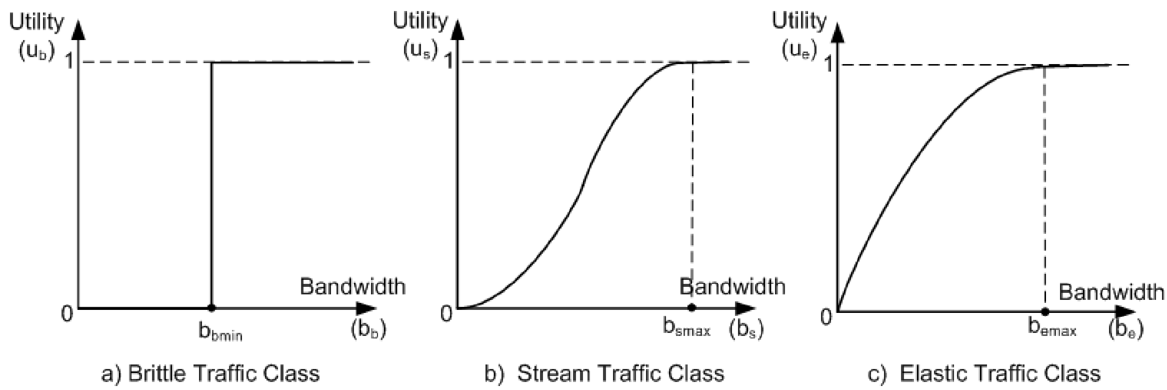

Fig. 5. Utility Functions for Different Traffic Classes

the traffic into three broad classes (brittle, stream and elastic traffic) and propose the use of a utility function for each traffic class, as illustrated in Fig. 5.

The traffic in the brittle class is real-time traffic with strict performance requirements and includes applications like: video telephony, telemedicine, highly secure data transactions, etc. This type of traffic flow is not allowed to enter the network if any basic requirements are not met. The mathematical representation of the utility function is simple, given in eq. (6). Usually the users of this type of traffic are interested only in high level QoS, in which case the utility will be 1. If the network cannot fulfil the requirements, the utility will be 0.

$$u_b(b_b) = \begin{cases} 1 & , b_b \geq b_{bmin} \\ 0 & , b_b < b_{bmin} \end{cases} \tag{6}$$

where b_b represents the allocated bandwidth and bb min represents the minimum required bandwidth.

The stream traffic class represents real-time traffic that is adaptable to the network conditions and includes audio and video applications that requires a minimum level of network performance guarantee. The shape of the utility function is illustrated in Fig. 5b and the mathematical representation is given in eq. (7).

$$u_s(b_s) = 1 - e^{-a_{s2}\frac{b_s^2}{a_{s1}+b_s}} \tag{7}$$

where b_s is the allocated bandwidth, a_{s1} and a_{s2} are constants that determine the shape of the utility function.

The elastic traffic class represents non-real-time, elastic traffic and includes applications like data transfer (files, pictures, etc.). These type of applications have loose response time requirements and they do not need a minimum level of bandwidth requirement. The shape of this utility is illustrated in Fig. 5c and the mathematical representation is given in eq. 8.

$$u_e(b_e) = 1 - e^{\frac{a_e b_e}{b_{emax}}} \tag{8}$$

where b_e denotes the allocated bandwidth, b_{emax} represents the peak rate of the elastic flow, and a_e is a scaling constant.

Several other approaches exist that try to quantify the utility in practice. For example, the authors in [55] explore the trade-off between user's willingness to pay and file download completion time for FTP downloads. A zone-based utility function is proposed. Depending on the transfer completion

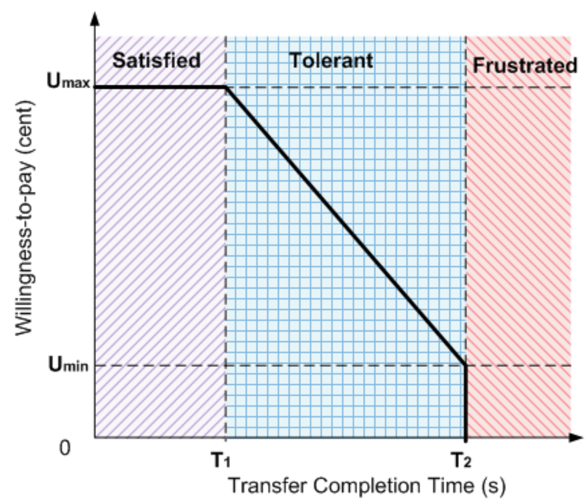

Fig. 6. User Utility Function for Non-Real-Time Applications

time, three zones are defined: satisfaction zone, tolerance zone, and frustration zone, as illustrated in Fig. 6. The zone-based utility function represents a trade-off between the user's willingness to pay and the willingness to wait for a particular data service transfer. This concept is based on the idea that a user is willing to pay a minimum amount (Umin) if the data is transferred within a maximum transfer completion time (T2), going above this threshold the data will worth nothing to the user. On the other side, each user has a preferred delay time, within which he will be willing to pay a maximum amount (Umax), this denotes the satisfaction zone.

For real-time streaming applications, the authors in [57] propose the use of a sigmoid function, similar to the one in Fig. 5b, in order to model the user satisfaction perceived for bandwidth (throughput). The utility function is illustrated in Fig. 7 and is expressed as:

$$u_q(Th) = 1 - e^{\frac{\alpha Th^2}{\beta + Th}} \tag{9}$$

where: α and β and are two positive parameters which determine the shape of the utility function and Th is the throughput. The proposed utility function is designed based on the idea that any real-time application has an essential required throughput (Th_{req}) in order to ensure an acceptable good quality. The quality level can drop until the throughput reaches

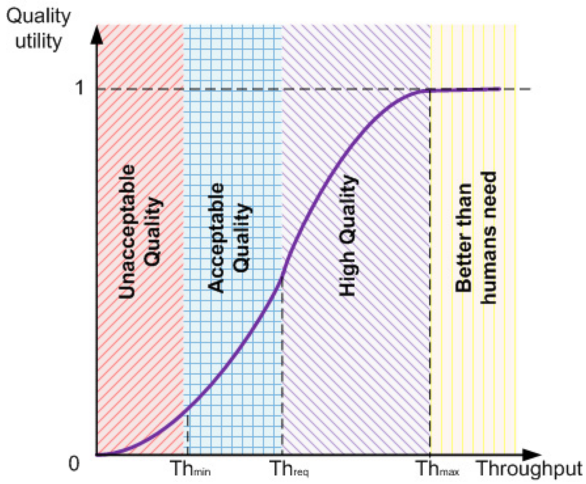

Fig. 7. User Utility Function for Real-Time Applications [57]

a minimum threshold (Th_{min}), values below this threshold translate into unacceptable quality levels. On the other side of the scale, there is a maximum threshold (Th_{max}), and values above this threshold link to quality levels which are better than humans need.

Depending on the type of service, utility functions are defined to describe the user satisfaction with certain QoS parameters. When multiple parameters are involved in the network selection process, an overall score function based on a combination of these utility functions is defined. The overall utility can be defined by using one of the multi-attribute decision making (MADM) methods, previously described. For example the authors in [31] define a score function as a simple additive weighted (SAW) function of several parameters: AP's load, price, and distance. Similarly, the authors in [49] define a SAW function considering the service type, user preferences, signal strength, mobility, and battery level. The authors in [33] introduce a pricing function (transfer) in order to prevent the users from exaggerating their resource requirements and misusing the available resources. In [41] the user's payoff is defined based on Consumer Surplus, expressed as the difference between the monetary value of the provided QoS to the user for the running service, and the actual charged price.

C. Multi-Operator and Multi-Technology

Another challenge, when designing a cooperative or a non-cooperative game, comes when considering a single or multiple operators. Some of the cooperative games in the literature explore the formation of coalitions between various networks' operators. In [53] the authors envision a unified environment where network operators would cooperate in order to combine and share their resources and provide global connectivity and transparency to the end-user. The individual access networks form a coalition and offer their available resources in return for some benefit, defined by a payoff function. In [54] the authors assume that different network operators are in contractual agreements with each other in order to share resources. A user is considered to have a contractual agreement with a home operator that handles a number of RATs. The operator will first allocate the service requests among its own RATs, if the demand exceeds the offer then he will request additional bandwidth from foreign operators that have RATs in the same area. The feasibility of such a scenario in the real regulated telecoms world, where competition among operators is intense, is questionable. Moreover, coverage range and operational characteristic information is considered to be highly confidential to the operators. For example, in [30] [31] the authors assume the existence of an information service deployed in the system which provides information about the available APs and their associated users. It would be unusual for operators to be willing to provide such information.

The existing solutions can be applied to single or multiple types of access network technologies. For example, [29] - [31] [33] [35] [48] apply only to WLAN networks, [36] applies to cellular, [40] applies only to CDMA networks, while the rest apply to two or even three different technologies.

D. Pricing and Billing

The multi-user multi-technology multi-application multi-provider environment brings increasing demands for the charging systems towards flexibility, scalability and efficiency. In today's mobile telecommunication networks the charging and billing models are relatively simple: time-based and volume-based charging. Considering the competitive market, the wireless operators followed the 'all you can eat' model by adopting flat rate pricing schemes. Flat rate pricing works well as long as the usage on the network is reasonable. Nowadays, with the exponential increase in data traffic, more wireless operators have started to re-adopt a usage-based pricing scheme (e.g., AT&T moved to a tiered model). If more and more wireless operators adopt the usage-based model, then all the flat rate wireless operators will attract the heaviest data users which will lead to a heavy traffic load on their networks. Looking at the wide pool of QoS parameters (e.g., bandwidth, packet loss, delay, jitter, etc.), only bandwidth is considered to be charge-relevant, even though other parameters could be significant as well. For example, with the increasing popularity of real-time applications, delay could be considered of relevant importance. Moving towards the 4G system brings important challenges for the pricing mechanisms:

- Multiple service providers - In the 4G vision, users will be able to roam freely between different service providers. This situation requires a more complex pricing and billing mechanism. As we have seen several works explore the formation of coalitions between service providers in order to share resources. In [53] the authors propose two cases for allocating the payoffs between the members of the coalitions. In the first case they propose the use of non-transferable payoffs meaning that the access network operators, members of the coalition, get a fixed payoff based on their resource contribution. In the second case, they make use of the transferable payoffs in which the members of a coalition can make side payments to other members in order to attract other players into the coalition.
- Multiple RATs - The coexistence of multiple RATs within the same service provider represents another challenge when it comes to pricing models. This is because the

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RATs differ in coverage area, capacity, QoS, offered data rate, mobility support, etc. Moreover users equipped with a multi-mode terminal will be able to connect simultaneously to different RATs.

The authors in [33] make use of the Vickrey-Clarke-Groves (VCG) mechanism in order to incentivize the mobile users to play truthfully. As mobile users are considered to be self-interested and rational players, it is natural to take into account the fact that they could also lie about their service requirements in order to maximize their own utilities. This could lead to decreasing the overall performance of the entire system. By using the VCG mechanism, which is a simple pricing mechanism, they introduce the cost associated with using one network which will encourage the mobile users to send the real values of the service requirements.

In [34] the authors modeled an auction-based scheme where users periodically send bids representing their willingness to pay for the radio resources. The service provider will then make a decision on resource allocation which will maximize its revenue.

Most of the works consider a flat rate pricing scheme [31] [37] [43] [47] and a few consider differentiated pricing as in [40]. The approach in [40] is based on service differentiation considering the expected QoS from the service provider and the price they are willing to pay. Three classes are defined: Premium, Gold, and Silver. The Premium class gets the highest priority but pays the most while the Silver class has the lowest priority and pays the least.

E. *Users' Implication*

Involving the user in the decision mechanism is based on the idea that in order to provide a useful solution, if not the best one to the customer, service providers should know what each customer really needs and where the real problem lies. As the user preferences play an important role in the decision mechanism another important aspect is the degree of the user's implication. There are many ways of collecting data from the user. Some of the proposed solutions probe the user for some required settings that are transformed afterwards into weightings for the networks parameters [43]. The solution proposed in [37] integrates a GUI in the user's mobile terminal in order to collect the user preferences on the following inputs: Service request class (Data, Video, Voice); Service preferred quality (Excellent, Good, Fair); and Service price preferences (Always Cheapest, Maximum service price). Asking the user for data can be annoying or even invasive to the user as the decision mechanism is no longer transparent. It is very important to find a trade-off between the cost of involving the user and the decision mechanism. One solution for minimizing the user interaction may be implementing an intelligent learning mechanism that could predict the user preferences over time.

F. *Energy Consumption*

When considering the energy consumption of a multi-interface mobile device, an important aspect is the connectivity. For example, in [47] [50] [51] [54] the authors consider

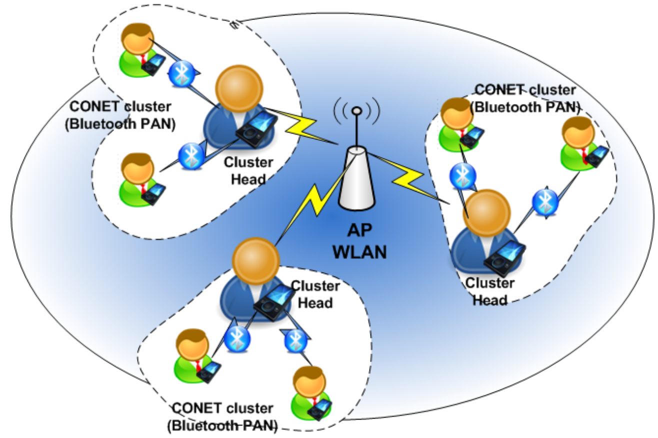


Fig. 8. Clustering Example Using CONET

that the multi-interface mobile device has simultaneous connections, with the bandwidth requirements split among multiple networks. In terms of energy consumption, simultaneous connections will drain the battery of the mobile device even faster than a single connection. In terms of monetary cost, simultaneous connections involve more complicated pricing schemes for the operators.

A concept of cooperation that aims to extend the coverage and minimize the power consumption is proposed in [58]. The authors present a distributed clustering protocol named Co-operative Network protocol (CONET). The protocol exploits the use of two interfaces of the mobile device: the WLAN interface and the Bluetooth interface. The aim is to form clusters as a Bluetooth Personal Area Network. Each cluster consists of a cluster head which acts as a gateway between the PAN and WLAN, and several regular nodes (mobile devices). The cluster head enables the regular nodes within the cluster to access the WLAN via Bluetooth with their WLAN interface switched off, conserving in this way the energy of the mobile device. The basic idea behind the protocol is illustrated in Fig. 8. The clustering and the selection of the cluster head is done periodically in a distributed manner based on the application requirements and the energy consumption of each node.

An important aspect in this type of environment is the motivation for cooperation. To this extent the authors consider two cases:

- Group networking - in which the nodes within the cluster have a common goal, to prolong the group lifetime. Considering the case of a group of friends playing network games together, their aim would be to play as much as possible. The constraint in this situation would be the node with the lowest battery level. CONET could prolong the group lifetime by rotating the cluster head role between the nodes with higher battery level.
- Individual networking - consisting of unrelated individuals without any common goal. An important aspect in this situation is defining the benefits a cluster head user may gain by spending more of his energy just to help some unrelated users. In this situation CONET distributes the gain within the cluster in a fair manner.

G. Complexity and Real World Scenarios

Generally the proposed solutions were tested through intensive numerical analysis or simulations that imply the simplification of the wireless environment. No real-world test-bed scenarios were proposed. The implementation in a real-world scenario is disputable. Some solutions require the deployment of external entities. For example, in [9] the deployment of the Central Spectrum Moderator, in the network, is required in order to divide the available resources among competing users. In [34] a central agent is used for resource allocation based on users' bids. Adding new equipment to an already complex network may not be a good solution. The authors in [30] [31] make use of the existence of a service deployed into the system that provides information about the location and the current load of the APs. In a real world scenario, considering the competitive market, operators will not be willing to provide such information without having a clear benefit from doing so.

Another important aspect when using game theory and dealing with such a heterogeneous and complex environment is the risk of users misbehaving, acting selfishly by trying to obtain the maximum performance over other users, leading to an overall system performance degradation. A survey on security threats for 4G networks is presented in [59]. In general, because of the mutually contradictory interests among service providers and/or users, different security requirements are needed. On one side, service providers compete against each other in order to maximize their own revenue by gaining more customers. On the other side, users compete against each other, each of them seeking to get the best value service/performance. In this scenario several threats can be identified: disclosure, destruction, loss, corruption or modification of information or other resources. For example, many reputation-based systems are built based on cooperation. In these types of systems a global reputation is computed based on the information gathered from multiple entities. In this context the trust level of each entity is addressed in order to avoid a fraudulent behaviour, by providing false information which could increase or decrease the reputation of an entity. Salem et al. in [60] look at the problem of selecting a Wireless Internet Service Provider (WISP) when multiple providers are available. The authors propose the integration of a Trusted Central Authority (TCA) into a Wi-Fi environment. All the WISPs will be registered with the TCA which will periodically collect feedback about each WISP in order to update the reputation records. The authors also provide a detailed threat analysis. They have identified eight specific attacks: Publicity, Selective Publicity, Denigration, Flattering, Report Dropping, Service Interruption, Refusal to Pay and Repudiation attacks. They have considered also several general attacks such as: Packet Dropping, Filtering and Replay attacks.

As the technology is advancing, network operators are looking towards adopting new architectures that come to simplify things, enabling quick deployment of services and applications.

VI. Conclusions and Future Research Directions

The Always Best Connected vision implies a heterogeneous multi-user multi-provider multi-technology environment, where users can roam in a free manner from one RAT to another or from one service provider to another. In this context, competitive or cooperating behaviour among service providers and/or users can be identified. On one side, the service providers seek to maximize their own revenue by attracting more customers, while on the other side, the users want to get the best value services/network for the money they pay. As game theory is often used to study this interaction between rational decision makers, it makes it applicable in the area of network selection strategies.

This article aims to familiarize the readers with the network selection concept and with the different game theoretic approaches used in the literature to model the network selection problem. It presents a comprehensive survey of the current research on this topic. The survey provides a useful categorization based on the players' interactions: Users vs. Users, Networks vs. Users, and Networks vs. Networks. We discuss different types of games (e.g., cooperative or non-cooperative) and the different game models adopted (e.g., Auction Game, Bayesian Game, Evolutionary Game, etc.) in order to solve the network selection problem. The major findings from these game models and the main challenges that surround the network selection problem are addressed and summarized in Table V. The survey provides a comparison and analysis of the state-of-the-art game theory solutions on network selection, and outlines the problems faced by the next generation of wireless networks.

Although this article presents a comprehensive survey on game theory solutions in relation to network selection, there are still some open issues that require further investigation. An important open issue is the impact of computational complexity of the existing solutions. Because of the wide number of factors (e.g., single or multi-technology, single or multiple operators, centralized or decentralized solution, different number of parameters, different types of utility functions, type of game, etc.) considered by different approaches, it is very difficult to compare them in terms of computational complexity. Thus, further investigation is required to evaluate the impact of the computational complexity for game theoretic-based network selection solutions.

References

[1] Cisco Visual netwokring Index, *Global Mobile data Traffic Forecast Update*, 2009-2014.

[2] A. Golaup, M. Mustapha, and L. B. Patanapongpibul, "Femtocell access control strategy in UMTS and LTE," in *IEEE Communications Magazine*, vol. 47, no. 9, pp. 117-123, 2009.

[3] D. E. Charilas, and A. D. Panagopoulous, "Multiaccess Radio Network Enviroments," in *IEEE Veh. Technol. Mag.*, vol. 5, no. 4, pp. 40-49, 2010.

[4] ITU, "Framework and overall objectives of the future development of IMT-2000 and systems beyond IMT-200," Switzerland, ITU-R M.1645, 2003.

[5] "IEEE Standard for Local and metropolitan area networks- Part 21: Media Independent Handover," IEEE Std 802.21-2008, 2009.

[6] Access Network Discovery and Selection Function (ANDFS) Management Object (MO), 3GPP TS 24.312 v10.3.0, 2011.

[7] Study into Network Selection Requirements for non-3GPP Access, 3GPP TR 22.912 v10.0.0, 2011.

[8] C.-H. Yeh, "A Problem-based Selection of Multi-attribute Decision-making Methods," *International Transactions in Operational Research*, vol. 9, pp. 169-181, 2002.

[9] H.J. Wang, R.H. Katz, and J. Giese, "Policy-enabled handoffs across heterogeneous wireless networks," in *Proc. Second IEEE Workshop on Mobile Computing Systems and Applications, (WMCSA)*, 1999.

[10] E. Adamopoulou et al., "Intelligent Access Network Selection in Heterogeneous Networks - Simulation Results," in *the 2nd International Symposium on Wireless Communication Systems*, pp. 279-283, 2005.

[11] Q.-T. Nguyen-Vuong, Y. Ghamri-Doudane, and N. Agoulmine, "On utility models for access network selection in wireless heterogeneous networks," in *IEEE Network Operations and Management Symposium, (NOMS)*, 2008.

[12] B. Bakmaz, Z. Bojkovic, and M. Bakmaz, "Network Selection Algorithm for Heterogeneous Wireless Environment," in *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, (PIMRC)*, 2007.

[13] J. Flp," Introduction to Decision Making Methods", *Computer and Automation Institute, Hungarian Academy of Sciences,* Budapest, 2005.

[14] F. Bari and V. Leung, "Application of ELECTRE to Network Selection in A Heterogeneous Wireless Network Environment", in *Proc. IEEE Wireless Communications and Networking Conference, (WCNC)*, 2007.

[15] Q. Song and A. Jamalipour, "A network selection mechanism for next generation networks," in *IEEE International Conference on Communications, (ICC)*, 2005.

[16] J. D. Martinez-Morales, U. Pineda-Rico, and E. Stevens-Navarro, "Performance comparison between MADM algorithms for vertical handoff in 4G networks," in *the 7th International Conference on Electrical Engineering Computing Science and Automatic Control, (CCE)*, 2010.

[17] R. Machado and S. Tekinay, "A survey of game-theoretic approaches in wireless sensor networks," *Elsevier Computer Networks*, vol. 52, no. 16, pp. 3047-3061, 2008.

[18] B. Wang, Y. Wu, and K.J. Ray Liu, "Game theory for cognitive radio networks: An overview," *Elsevier Computer Networks*, vol. 54, no. 14, pp. 2537-2561, 2010.

[19] V. Srivastava et al., "Using game theory to analyze wireless ad hoc networks," *IEEE Commun. Surveys & Tutorials*, vol. 7, no. 4, pp. 46-56, 2005.

[20] T. Alpcan, T. Basar, and S. Dey, "A power control game based on outage probabilities for multicell wireless data networks," *IEEE Trans. Wireless Commun.*, vol. 5, pp. 890-899, 2006.

[21] S. Sengupta et al., "Dynamic pricing for service provisioning and network selection in heterogeneous networks," *Elsevier Physical Communication*, vol. 2, no. 1, pp. 138-150, 2009.

[22] D. E. Charilas and A. D. Panagopoulos, "A survey on game theory applications in wireless networks," *Elsevier Computer Networks*, vol. 54, no. 18, pp. 3421-3430, 2010.

[23] Y. Zhang and M. Guizani, *Game Theory for Wireless Communications and Networking*, 1st ed. CRC Press, 2011.

[24] M. J. Osborne and A. Rubinstein, *A Course in Game Theory*, The MIT Press, 1994.

[25] M. J. Osborne, *An Introduction to Game Theory*, Oxford University Press, USA, 2003.

[26] D. Fudenburg and J. Tirole, *Game Theory*, The MIT Press, London, 1991.

[27] J. W. Weibull, *Evolutionary Game Theory*, The MIT Press, 1997.

[28] A. MacKenzie, *Game Theory for Wireless Engineers*, 1st ed. Morgan & Claypool Publishers, 2006.

[29] E.H. Watanabe et al., "Modeling Resource Sharing Dynamics of VoIP Users over a WLAN Using a Game-Theoretic Approach," in *the 27th IEEE Conference on Computer Communications, (INFOCOM)*, 2008.

[30] K. Mittal, E. M. Belding, and S. Suri, "A game-theoretic analysis of wireless access point selection by mobile users," *Journal of Computer Communication*, vol. 31, no. 10, pp. 2049-2061, 2008.

[31] K. Fahimullah and S. Hassan, "Game-Theory based Wireless Access Point Selection scheme," in *IEEE Silver Jubilee International Multitopic Symposium (SIMTS)*, 2010.

[32] K. Zhu, D. Niyato, and P. Wang, "Network Selection in Heterogeneous Wireless Networks: Evolution with Incomplete Information," in *IEEE Wireless Communications and Networking Conference (WCNC)*, 2010.

[33] F. Fu and M. van der Schaar, "Noncollaborative Resource Management for Wireless Multimedia Applications Using Mechanism Design," *IEEE Trans. Multimedia*, vol. 9, no. 4, pp. 851-868, 2007.

[34] A. Sahasrabudhe and K. Kar, "Bandwidth allocation games under budget and access constraints," in *the 42nd Annual Conference on Information Sciences and Systems, (CISS)*, 2008.

[35] M. Cesana, N. Gatti, and I. Malanchini, "Game theoretic analysis of wireless access network selection: models, inefficiency bounds, and algorithms," in *Proc. 3rd International ICST Conference on Performance Evaluation Methodologies and Tools, (VALUETOOLS)*, 2008.

[36] S. Vassaki, A.D. Panagopoulos, and P. Constantinou, "Bandwidth allocation in wireless access networks: Bankruptcy game vs cooperative game," in *International Conference on Ultra Modern Telecommunications & Workshops (ICUMT)*, 2009.

[37] M. A. Khan et al., "Game-Theory Based User Centric Network Selection with Media Independent Handover Services and Flow Management," in *Eighth Annual Research Conference on Communication Networks and Services (CNSR)*, 2010.

[38] M.A. Khan et al., "Auction based interface selection with Media Independent Handover services and flow management," in *European Wireless Conference, (EW)*, 2010.

[39] M.A. Khan et al., "Auction based interface selection in heterogeneous wireless networks," in *the 2nd IFIP Wireless Days, (WD)*, 2009.

[40] M. Chatterjee, H. Lin, and S. K. Das, "Non-Cooperative Games for Service Differentiation in CDMA Systems," *Journal of Mobile Networks and Applications,* vol. 10, no. 6, pp. 939-946, 2005.

[41] D. E. Charilas, A. D. Panagopoulos, P. Vlacheas, O. I. Markaki, and P. Constantinou, "Congestion Avoidance Control through Non-cooperative Games between Customers and Service Providers, " *Mobile Lightweight Wireless Systems*, vol.13, pp. 53-62, 2009.

[42] J. Antoniou et al., "Cooperative user-network interactions in next generation communication networks," *Elsevier Computer Networks*, vol. 54, no. 13, pp. 2239-2255, 2010.

[43] H. Pervaiz and J. Bigham, "Game Theoretical Formulation of Network Selection in Competing Wireless Networks: An Analytic Hierarchy Process Model," in *Third International Conference on Next Generation Mobile Applications, Services and Technologies, (NGMAST)*, 2009.

[44] H. Pervaiz, "A Multi-Criteria Decision Making (MCDM) network selection model providing enhanced QoS differentiation to customers," in *International Conference on Multimedia Computing and Information Technology, (MCIT)*, 2010.

[45] D. Niyato and E. Hossain, "A Noncooperative Game-Theoretic Framework for Radio Resource Management in 4G Heterogeneous Wireless Access Networks," *IEEE Trans. Mobile Computing*, vol. 7, no. 3, pp. 332-345, 2008.

[46] J. Antoniou and A. Pitsillides, "4G Converged Environment: Modeling Network Selection as a Game," in *the 16th IST Mobile and Wireless Communications Summit*, 2007.

[47] V. Gajic, J. Huang, and B. Rimoldi, "Competition of wireless providers for atomic users: equilibrium and social optimality," in *the Annual Allerton Conference on Communication, Control, and Computing, (ALLERTON)*, 2009.

[48] D. E. Charilas, O. I. Markaki, and P. T. Vlacheas, "Admission Control as a Non-Cooperative Multi-Stage Game between Wireless Networks," in *the 16th International Conference on Systems, Signals and Image Processing (IWSSIP)*, 2009.

[49] M. S. Z. Khan, S. Alam, and M. R. H. Khan, "A Network Selection Mechanism for Fourth Generation Communication Networks," *Journal of Advances in Information Technology*, vol. 1, no. 4, pp. 189- 196, 2010.

[50] D. Niyato and E. Hossain, "A Cooperative Game Framework for Bandwidth Allocation in 4G Heterogeneous Wireless Networks," in *IEEE International Communications Conference, (ICC)*, 2006.

[51] I. M. Suliman, C. Pomalaza-Raez, I. Oppermann, and J. Lehtomaki, "Radio resource allocation in heterogeneous wireless networks using cooperative games," *Nordic Radio Symposium I Finnish Wireless Communications Workshop, (NRS/FWCW)*, 2004.

[52] C-J. Chang, T-L. Tsai, and Y-H. Chen, "Utility and Game-Theory Based Network Selection Scheme in Heterogeneous Wireless Networks," in *IEEE Wireless Communications and Networking Conference, (WCNC)*, 2009.

[53] J. Antoniou et al., "Access network synthesis game in next generation networks," *Elsevier Computer Networks*, vol. 53, no. 15, pp. 2716-2726, 2009.

[54] M.A. Khan et al., "Cooperative game theoretic approach to integrated bandwidth sharing and allocation," in *International Conference on Game Theory for Networks, (GameNets)*, 2009.

[55] O. Ormond, G-M. Muntean, and J. Murphy, "Network Selection Strategy in Heterogeneous Wireless Netorks," in *the Information Technology and Telecommunication Conference, (IT&T)*, 2005.

[56] V. Rakocevic, J. Griffiths, and G. Cope, "Performance analysis of bandwidth allocation schemes in multiservice IP networks using utility functions," in *Proc. 17th International Teletraffic Congress, (ITC)*, 2001.

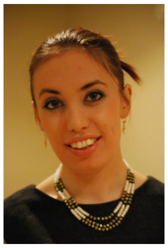
[57] R. Trestian, O. Ormond, and G-M. Muntean, "Power-Friendly Access Network Selection Strategy for Heterogeneous Wireless Multimedia Networks", *IEEE International Symposium on Broadband Multimedia Systems and Broadcasting, (BMSB)*, 2010.

[58] J-W. Yoo and K. H. Park, "A Cooperative Clustering Protocol for Energy Saving of Mobile Devices with WLAN and Bluetooth Interfaces," *IEEE Trans. Mobile Computing*, vol. 10, no. 4, pp. 491-504, 2011.

[59] Y. Park and T. Park, "A Survey of Security Threats on 4G Networks,"

in *IEEE Globecom Workshop on Security and Privacy in 4G Networks*, 2007.

[60] N.B. Salem, J.P. Hubaux, and M. Jakobsson, "Reputation-Based Wi-Fi Deployment," *ACM Mobile Computing and Communications Review, (MC2R)*, vol. 9, no. 3, pp. 69-81, 2005.



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