A Paradigm Shift Toward Satisfaction, Realism and Efficiency in Wireless Networks Resource Sharing

Symeon Papavassiliou, Eirini Eleni Tsiropoulou, Panagiotis Promponas, and Panagiotis Vamvakas

Abstract

The sheer growth of data traffic and the rising number of connected devices have highlighted and elevated the need of addressing spectral scarcity and enhancing resource utilization in 5G wireless networks. Toward this direction, the overwhelming majority of existing wireless resource management approaches and methodologies aim directly at energy efficiency maximization. In this article, we argue and demonstrate that not only the stability of these solutions depends on whether or not each user achieves the highest performance possible, but they do not properly reflect in reality the most desirable operation points from both the user and system point of view. In contrast, it is eventually more rewarding to opt for energy-awareness while targeting satisfaction of user Quality of Service (QoS) requirements, rather than targeting energy efficiency maximization itself. The proposed paradigm shift is further complemented with the introduction of a pragmatic approach in the different resource allocation paradigms in wireless networks, by integrating risk preferences in the user transmission decision making process, that traditional models fail to capture. This facilitates the inclusion and study of realistic and dynamic user behavior, under potential risks, gains and uncertainties, characteristics that are commonly present in wireless communications and networking environments. Proof of concept use cases and numerical results are presented that stress the benefits that can be obtained by this paradigm, both in terms of energy efficiency and efficient spectrum utilization, under different realizations of unlicensed and licensed spectrum sharing.

Introduction

5G Networks and Spectral Efficiency

Mobile data traffic and the number of connected devices are growing at an unprecedented pace, with this trend expected to further intensify via the emergence of 5G networks and the Internet of Things (IoT) evolution. Significant advances have been made in recent years toward increasing the number of connected users, improving throughput, and broadening network coverage and data demand, through the use of enhanced network architectures and technologies. To address the challenge of spectral efficiency, regulators (e.g., FCC) [1], are releasing several unlicensed bands for commercial purposes, hence facilitating the exploration of the use of commonly accessible and admission fee-free unlicensed spectrum, in a shared platform with closed-access, subscription-based licensed bands. Figure 1 provides an indicative illustration of a prospective network with licensed and unlicensed spectrum sharing. The absence of a supervisory body enforcing social welfare and monitoring consumption and competition of the unlicensed bands, stresses the requirement for a different approach with respect to the management, and in particular the fragility of the resource.

Moreover, the requirement for massive connectivity, high throughput and congestion management creates the need to further examine 5G ready access technologies and their deployment potential in optimizing resource allocation and operational efficiency. Consequently, Orthogonal Frequency Division Multiple Access (OFDMA) is still expected to remain an integral part of the forthcoming 5G network, while at the same time Non-Orthogonal Multiple Access (NOMA) technology and its hybrid variations gain increasing interest toward serving the objective of energy efficiency [2].

Vision and Contributions

In this article we discuss a holistic approach, in order to achieve energy efficient wireless communications in competitive multi-user heterogeneous networking environments. The envisioned framework is motivated by, and realized under, the following two fundamental observations:

- Simply targeting energy efficiency maximization does not necessarily lead to the most efficient operation points, even from the wireless transmission power and energy management point of view.
- Individuals in real life do not behave as neutral expected utility maximizers, but they exhibit risk seeking or loss aversion behavior under uncertainty, which in turn influences their wireless transmission decisions.

With respect to the first point, we evangelize that instead of maximizing the Quality of Service (QoS) in wireless networks (expressed in terms of achievable data rate per joule of consumed energy) which is generally energy costly, better ener-

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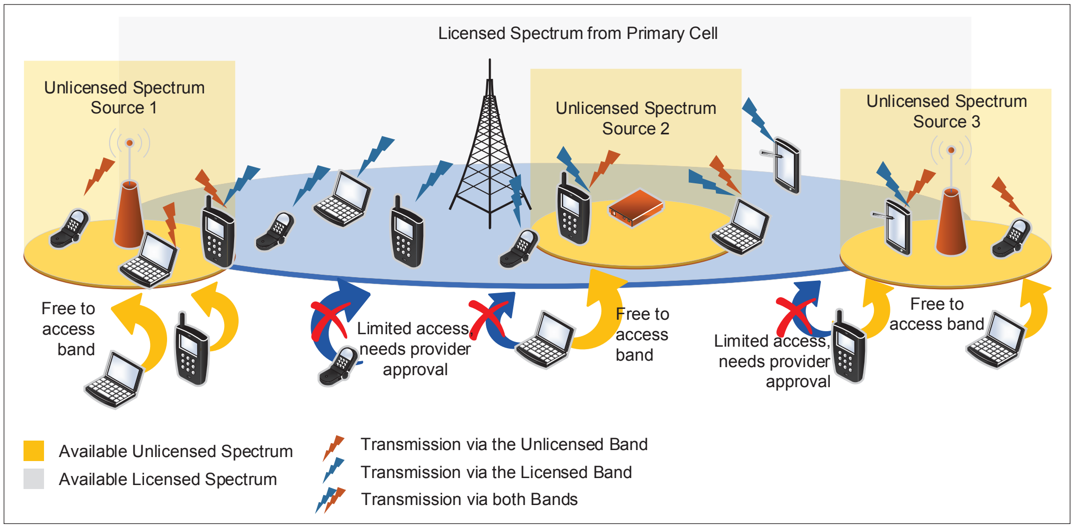

FIGURE 1. Conceptual network topology with both licensed and unlicensed spectrum access.

gy efficiency is achieved by targeting satisfactory QoS levels only. This can be treated by a novel game theoretical solution concept, referred to as *Satisfaction Equilibrium* [3]. It is noted that in the context of this article, a user is assumed to opt for a QoS expressed through the trade-off between high data rate and low power consumption, as it is indeed reflected by energy efficiency. With reference to the second point, the use of *Prospect Theory* [4] allows the introduction of realism in different resource allocation paradigms in wireless networks, by integrating risk preferences in the user transmission decision making approaches that traditional models fail to capture.

A key differentiating contribution of this article is that it offers the appropriate science and technology to conceptualize and design for the realistic deep inter-dependencies among behaviors, interactions and decisions, within the era of resource management. The proposed paradigm identifies critical operation points, where jointly user satisfaction is achieved and several benefits are obtained from both the user perspective and the system perspective. This comes in contrast to the majority of existing approaches, that stress the system to maximize an objective function, while guaranteeing some minimum QoS constraints. In particular, we investigate how satisfaction equilibrium, uncertainty, risk aversion and gain seeking behaviors, transform the traditional models employed by optimization approaches and the obtained solutions thereof, in realistic resource-constrained wireless communication environments, toward meeting the key objective of energy and spectrum efficiency. Proof of concept use cases and numerical results are presented demonstrating the benefits that can be obtained by the proposed operation paradigm shift. Finally, some open research issues are also highlighted.

Satisfy Instead of Maximize

There are two motivating factors behind the consideration of QoS satisfaction, rather than targeting QoS maximization. The first one stems from the observation that several types of services are either simply interested in achieving a minimum QoS level, or equivalently the users are insensitive to small QoS changes [5, 6]. Accordingly, users would be reluctant to consume additional resources, while achieving higher spectrum efficiency [7]. For example, reducing signal transmission power can not only lessen interference among wireless devices, but at the same time lead to energy savings and extend the battery life of wireless devices. Therefore, the second driving factor targets the objective of energy consumption reduction and intelligent bandwidth exploitation [8], both of which are of critical importance in wireless resource-constrained environments.

Energy Efficient Operation Points for Wireless Networks

The introduction of microeconomic theories in wireless data networks was established in order to properly model the resource allocation process, toward achieving energy efficiency. Initially, the efforts focused on the per user maximization of the energy efficiency utility function. Nonetheless, in [9] the authors demonstrated that the unique Nash Equilibrium (NE) which can be obtained in such a game is poor from a social welfare point of view. In order to ameliorate the selfishness of the users in the context of such games, several research works (e.g., [9]) introduced pricing schemes in users' utilities. Whereas more socially acceptable outcomes were achieved, the pricing functions still remain completely arbitrary and case dependent. Though both linear and convex schemes were tested, none of them converges in an objectively acceptable outcome for the whole system and in a holistic manner. In this article, we introduce a novel paradigm where the aforementioned inefficiencies are treated by changing the whole mechanism, instead of manipulating the form of the utility function that users opt to maximize.

Satisfaction Equilibrium Based Operation Points

The notion of the satisfaction of a user is already implicitly hidden in the energy efficiency utilities that have been widely used in the literature. In fact, in the overwhelming body of the adopted utilities, the numerator is typically expressed through some form of a sigmoidal function with

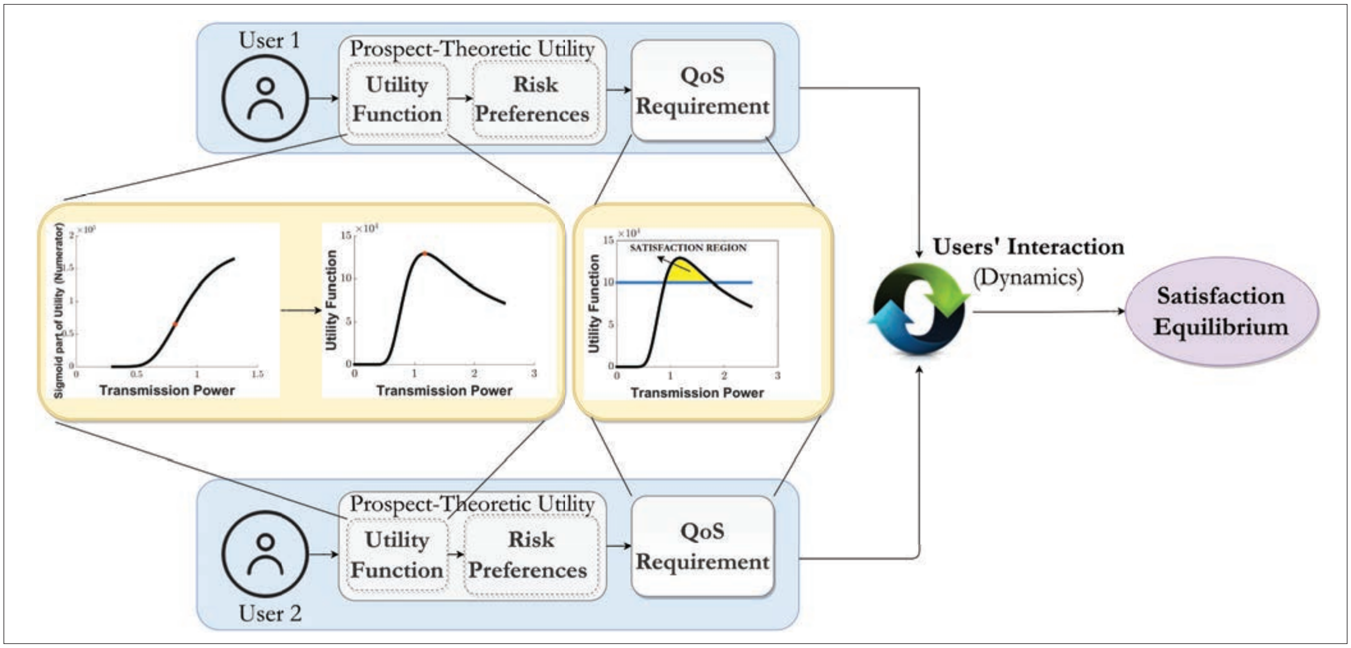

FIGURE 2. Overall framework operation overview.

respect to its transmission power. In a nutshell, this translates to the observation that there is a region that a particular user is not satisfied at all and a small perturbation leaves it unaffected, a region around the inflection point at which the profit of the user is strictly increasing (with different slopes), and finally a region that we can assume that a user is satisfied and a small perturbation leaves it unaffected. Notice that there are regions where if a user increases its transmission power, its utility will stay virtually unaffected, while the interference in the system will increase dramatically (Fig. 2). The final energy efficiency utility is obtained when this quantity is divided by the transmission power, to produce a more efficient outcome. In this manner, the maximum of this function would be realized in principle at some point closer to the beginning of the "satisfaction region," preventing the user from excessive power waste.

For any given user, though satisfied in terms of meeting a predefined QoS threshold, any change to moving closer to the aforementioned maximization point would most likely trigger the increase of another user's transmission power, thus resulting in a further increase of the interference, and so on. Founded on this argument, one can claim that there should be a strategy profile in which everyone is satisfied, while the unique NE would be both individually and socially worse. Those profiles are the ones that are of high research and practical importance, in order to achieve both energy efficiency and efficient spectrum utilization.

Designing for Satisfaction Equilibrium

Some recent research works (e.g., [5]) introduced the framework of games in satisfaction form with direct applications in resource management in wireless networks, introducing the notion of Satisfaction Equilibrium (SE). Altering this way the mechanism of the game, instead of solely the formulation of the utility, formally approves the usage of the QoS constraints while also respecting the non-cooperative nature of the process. The adoption of non-cooperative games are promoted here instead of the cooperative ones, not only due to the fact that the users tend to illustrate antagonistic and selfish behavior in real networks, but also due to several issues that limit the applicability of the latter approaches. Indicatively, we mention the increased levels of information exchange among the users in the case of cooperative games, which in turn leads to increased energy and bandwidth consumption, along with the associated privacy concerns of the users.

The proposed novel approach can therefore lead to more efficient solutions for the whole system as well as for each user individually. In particular, such an approach drives its user toward meeting its QoS prerequisites without wasting the valuable resources of the system at all. One additional advantage of such an approach is its user-centric nature. Last but not least, there exist cases in which the NE leads the users to transmit with their maximum transmission power (e.g., [9]), as the energy efficiency objective function at some point of the interference degenerates to an increasing function without a bounded maximum.

The Inefficiency of Simply Maximizing Energy Efficiency: A Proof of Concept

Maximizing the energy efficiency utility could lead to a random outcome for the system, while in several cases the resulting solution could be completely inefficient. It is possible for the corresponding convergence point not only to be irrational, but more importantly to waste the system's resources without someone else being able to harness them. Specifically, in the maximization problem, a user may obtain a fair score in terms of energy efficiency, either by simply exceeding its QoS prerequisites, or alternatively by transmitting with a low transmission power, without nevertheless meeting its QoS prerequisites. The framework of games in satisfaction form proposes a sleek solution to this problem, by not providing incentives for a user to increase its profit, if satisfied.

The aforementioned observation can be derived from and demonstrated by Fig. 3. In particular, let us consider a traditional power control game, in which the players represent the users of the network, the strategy space represents the possible transmission power levels, and each user possesses a utility function that reflects its earnings. With the objective of maximizing energy efficiency, the NE of the non-cooperative game is unique and corresponds to a unique power allocation. Nonetheless, this resource allocation usually occurs without taking into account the QoS requirement (in the specific example under demonstration the Shannon capacity threshold) of each user, and therefore can lead to either an inefficient or inadequate solution. In particular, Figs. 3a and 3b represent such a game with two and three users, respectively. The marked point in the graph represents the power vector that corresponds to the unique NE of each game while the colored region represents all the SEs of the corresponding game in its satisfaction form. For demonstration purposes only and without loss of generality, we assumed that the users declared QoS thresholds that are 95 percent of those that the NE assigned to them. Each point's color depends on the total transmission power spent, where the light and dark color represents high and low cost solutions, respectively.

It is clearly shown that although the users of the network targeted Shannon capacity utilities very close to the one that the NE would assign to them, the system can indeed reach solutions that are significantly more efficient, both system-wise and component-wise. The energy efficiency maximization point (i.e., NE) is also a SE, as each user meets its supposed QoS threshold. Nevertheless, for the aforementioned QoS prerequisites (or lower), this point is a completely arbitrary and inefficient SE. That said, it appears that the power vector that corresponds to the NE of the game is component-wise greater than the majority of the SEs, resulting in a point in the graph with a very light color. On the other hand, as shown in Figs. 3a and 3b, there are several other SEs that are less energy consuming for all users, while the users still remain satisfied [6].

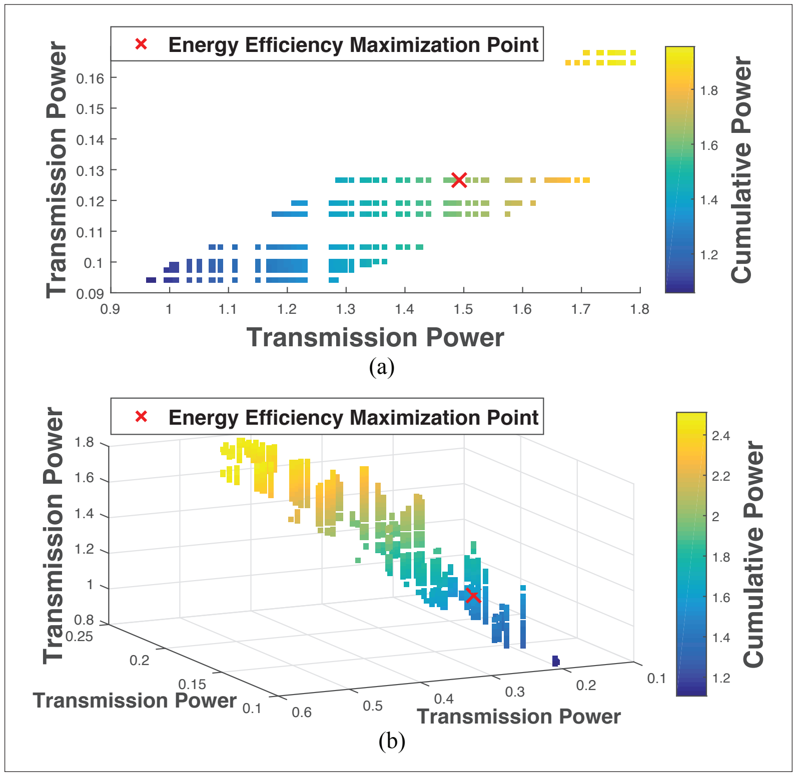

FIGURE 3. Satisfaction Equilibria and Nash Equilibrium in Power Control Game: a) 2-user game; b) 3-user game.

Risk Taking in Resource Allocation

In principle, increased spectrum efficiency may be achieved by the real-time adjustment of radio resources, realized and supported by the adoption of dynamic spectrum access in 5G wireless networks, as well as the co-existence of licensed and unlicensed bands. This introduces a new landscape and paradigm concerning the availability and management of spectrum, under a co-existing licensed–unlicensed spectrum scheme. In the following, we complement the pragmatic framework of games in satisfaction form, with suitable models capable of capturing users' risk preferences in accessing the system resources, and thus properly formulating their realistic behavior. Both approaches, acting complementary to each other, aim at reforming the resource management mechanism, in order to acknowledge and capture the user perspective in an intrinsic manner, toward achieving the properties of efficiency and satisfaction. A high level overview of the overall introduced framework is presented in Fig. 2, including a graphical example of the shape of the considered utility functions and the corresponding satisfaction region.

In particular, considering the shared nature and access policies of the licensed and the unlicensed spectrum, the theory of the Tragedy of the Commons [10] arises as an appropriate framework to model mobile users' preferences to avoid unlicensed spectrum over-exploitation. Under this paradigm, the licensed spectrum is considered as a *safe resource*, where the users can invest their personal resources on it, enjoying a constant return on their investment and knowing a priori the level of satisfaction that they will experience. In contrast, the unlicensed spectrum is considered as a Common Pool of Resources (CPR). The latter, being free-of-charge openly accessed by the users, has the potential to provide superior benefit to them; however, its rate of return is decreasing in the total users' investments. More critical is the phenomenon of the failure of the unlicensed spectrum due to its over-exploitation, where the latter can eventually end in negative returns to the users.

The theory used so far for resource management in communication networks has not managed to properly address the fact that users in real life do not behave as neutral expected utility maximizers, but they tend to exhibit risk seeking or loss aversion behavior under uncertainty. To deal with this challenge, we exploit Prospect Theory (PT) [4] to integrate risk preferences in the users' utility functions, which represent their perceived satisfaction. Although the research status of PT

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for resource management in wireless networks is still at an early stage, works have already used this theory in evaluating user or operator decisions in cases where risk induces serious challenges to the network's performance [11, 12]. Specifically, the users determine and evaluate their experienced utility from investing their personal resources to the licensed and the unlicensed spectrum, based on the corresponding derived gains or losses, with respect to a reference point $\mathbf{z}_0$ (*reference dependence property*). This reference point is considered as the zero point (i.e., ground truth) of users' satisfaction.

In contrast to Expected Utility Theory (EUT), where all the users are assumed as risk neutral with respect to their choices, Prospect Theory embodies individuals' behavioral patterns, which demonstrate systematic deviations from the EUT. In particular, in our study, the individuals assess uncertain outcomes under a loss aversion attitude, thus their experienced utility is formed as a probabilistic utility function. Under the dynamic spectrum management environment of available choices with uncertain payoff (e.g., unlicensed spectrum), the users tend to overweight low probability events and underweight high probability ones. This leads them toward shaping a prospect-theoretic utility function, which is concave and steeper convex for positive and negative outcomes, respectively [4].

Risk Based Spectrum Management

Following the aforementioned discussion, user prospect-theoretic probabilistic utility functions are formulated and devised, while considering the different user investment options in the available resources.

The general form of the prospect-theoretic utility function is given as follows.

$$u(\mathbf{z}) = \begin{cases} (\mathbf{z}-\mathbf{z}_0)^{\alpha_i}, \mathbf{z} \geq \mathbf{z}_0 \\ -k_i(\mathbf{z}_0-\mathbf{z})^{\beta_i}, \mathbf{z} < \mathbf{z}_0 \end{cases}$$

The user' actual utility is denoted by $\mathbf{z} \in \mathbb{R}^n$, $n \in \aleph$, where $\aleph$ is the users' set and their prospect-theoretic satisfaction is evaluated with respect to the *reference point* $\mathbf{z}_0 \in \mathbb{R}^n$. To capture users' *loss aversion* characteristics, the parameter k_i, $k_i \in \mathbb{R}$ is introduced, which represents the idea that the loss curve is usually steeper than the gain curve, thus quantifying user's i sensitivity to losses as compared to gains. The user characteristic of *diminishing sensitivity* is quantified by the concave part (first branch of Eq. 1) of the prospect-theoretic utility function in gains and the corresponding convex part (second branch of Eq. 1) in losses. Additionally, the personalized tuning of the parameters α_i, $\beta_i \in \mathbb{R}$ can determine the extent of the non-linearity in the utility curves, illustrating the user' relative sensitivity to gains and losses of small magnitude compared to those of large magnitude.

The users may exploit the degree of simultaneous use of licensed and/or unlicensed spectrum, determining their actions based on their QoS prerequisites, as well as by assessing the probability of unlicensed spectrum failure. This probability depends on the total investment of all the users to the unlicensed spectrum, and determines the probabilistic occurrence of each branch in Eq. 1 and sets the prospect-theoretic probabilistic utility functions thereof. We consider the risks induced by the unlicensed spectrum over-exploitation, where excessive aggregate investment may lead to complete collapse of the unlicensed band, as the users may enjoy unlimited access to the available spectrum. The optimal resource allocation problem, in terms of individual optimal personal resource investment to the licensed and unlicensed bands, can be confronted as a non-cooperative game among the users [13], who are aware of their personal strategy sets and their probabilistic prospect-theoretic utility function (Eq. 1). The outcome of the resource management non-cooperative game, that is, NE points, will converge to stable operational points for the overall system, while the user' personal investments (i.e., transmission power distribution) to the licensed and/or unlicensed bands are determined, and thus, the spectrum utilization is obtained.

Dynamic Spectrum Management: Proof of Concept

Spectrum Opportunistic Sharing

Under 5G driven user-centric operating models, the users can direct the nature of their transmission via the licensed and unlicensed bands according to their QoS requirements or the type of service they require (i.e., elastic or inelastic). Both band sources are modeled under the same transmission access technology, that is the Non-Orthogonal Multiple Access (NOMA) transmission technique. Licensed spectrum is strictly monitored by the service provider, while the absence of any regulatory authority in the unlicensed spectrum does not restrict over-investment from users, who compete with each other to exploit the corresponding spectrum. If the available spectrum does not suffice to meet the overall demand, this will drive the unlicensed band to certain failure with none of the users being able to transmit. In contrast, the users who selected to either transmit explicitly on the licensed band or split their transmission power between the licensed and unlicensed bands, will recover a part of their original investment through the licensed transmission.

For demonstration purposes, we consider a NOMA wireless network of radius R = 2.5 km, with N = 20 users randomly located within its range, assuming a 20 percent-80 percent spectrum split between the licensed and unlicensed bands, as a realistic reflection of the provisions available in the market. The users select to transmit via one or both bands by indicating the percentage x_i of their transmission power allocated to the unlicensed spectrum (CPR resource), whereas the remaining part is reserved for the licensed spectrum (safe resource). Under the NOMA paradigm, the Successive Interference Cancellation (SIC) technique is applied with users decoding only the signals of other users with inferior channel gains, contributing to intracell interference mitigation.

Figure 4a depicts the system's performance under increasing levels of the mean sensitivity parameter a_i. It is observed that the investment to the unlicensed band increases with the rise of a_i leading to a subsequent increase in the attainable average rate in the unlicensed band. On the other hand, licensed rate remains mostly stable despite the falling percentage of power invested in the safe band and the reduced competition, due to the fact that some users prefer to exclusively transmit via the unlicensed band. When the sensitivity parameter reaches a critical value, user investment to the unlicensed spectrum exceeds the band's capacity and the unlicensed band fails from over-exploitation. In this case, only the users investing, even partially, within the licensed band are able to operate.

Prospect Theory vs Expected Utility Theory

In this section, we provide a comparative study of the spectrum utilization, under the PT and EUT operation. It is noted that EUT is a reflection of classical economics, where consequantialism [14] determines user decision making based solely on the weighted outcome of actions. Thus, EUT fails to depict risk aversion when a situation of loss occurs with high probability, as user judgment is based on wealth accumulation estimates, with EUT models being often violated.

Figure 4b depicts exactly how differentiating risk aversion perceptions and subjectivity of user decisions captured by the more pragmatic approach of Prospect Theory, can considerably affect decision making strategies with inevitable impact on network's performance. Specifically, we examine users' transmission powers in the unlicensed band under varying values of the loss aversion parameter k_i, and compare them to the corresponding value obtained under the assumption of an EUT-based model. When loss aversion parameter k_i received high values, users adopt in general a more conservative stance toward competing for the unlicensed spectrum. This indicates lower transmission powers which induce reduced interference, also facilitated by the application of the NOMA SIC technique. On the other hand, EUT and more risk seeking approaches under PT (lower values of risk aversion parameter) deliver a more aggressive behavior of users in claiming the available spectrum. Consequently, they substantially increase the probability of unlicensed band failure, affecting the network's energy efficiency, user satisfaction and service delivery. It is finally noted that under the proposed framework, the satisfaction of the users is guaranteed in the sense that their expected utility exceeds their QoS prerequisites. Under high congestion and due to system physical constraints, there may be users that could end up with actual utilities lower than the threshold.

Dual Access Technology Option: Satisfaction and Efficiency

Hybrid variations of NOMA have received increasing attention in the research community [2], with proposals including multi-carrier NOMA or combinations of multiple OFDMA subcarriers with NOMA, as a means of managing complexity and intracell interference mitigation. OFDMA eliminates interference by allowing users to transmit via distinct portions of the spectrum by partitioning it into different resource blocks. At the same time, the emergence of smart devices with dual transmission access capabilities is a reality. In view of this, licensed and unlicensed spectrum sharing techniques can also become available under different access technologies. An interesting paradigm would involve users dynamically adjusting their transmission between a) the interference free but limited in terms of throughput OFDMA within the licensed band only, and b) NOMA, where the entire spectrum can be exploited; however it has to be shared with the rest of the users, as illustrated in Fig. 5 [15]. Within the context of the aforementioned approach, OFDMA-based transmission is treated as the safe resource and NOMA-based transmission plays the role of CPR.

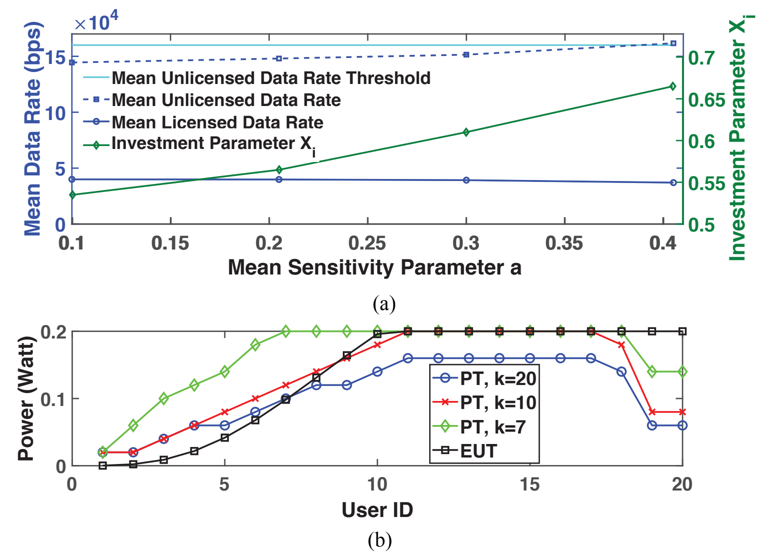

FIGURE 4. Dynamic Spectrum Management: a) rate and investment over licensed/unlicensed bands; b) PT vs. EUT performance — Power per User ID for increasing loss aversion parameter k_i, (k_i = 20 (high-), k_i = 10 (mid-), and k_i = 7 (low-aversion behavior)).

Accordingly, there are numerous types of equilibrium operation points that the framework based on the concept of games in satisfaction form could impose, depending on the nature of the users and the system, thus enhancing the prospect-theoretic based resource allocation. In the following we exemplify two basic cases where we highlight how a user should orchestrate his/her transmission in the available options, and accordingly distinguish two application-specific SE points.

Use Case 1 — Safe Satisfaction Equilibrium (SSE): Let us assume that the users of the system require guaranteed QoS provisioning, toward completing a task with certainty and within given constraints, for example, inelastic data offloading applications such as video applications or online gaming. Owing to the limited (or complete lack of) interference in the OFDMA transmission, it is expected that the users with such a prerequisite would opt to invest as much as possible to the safe resource, while being satisfied. This translates

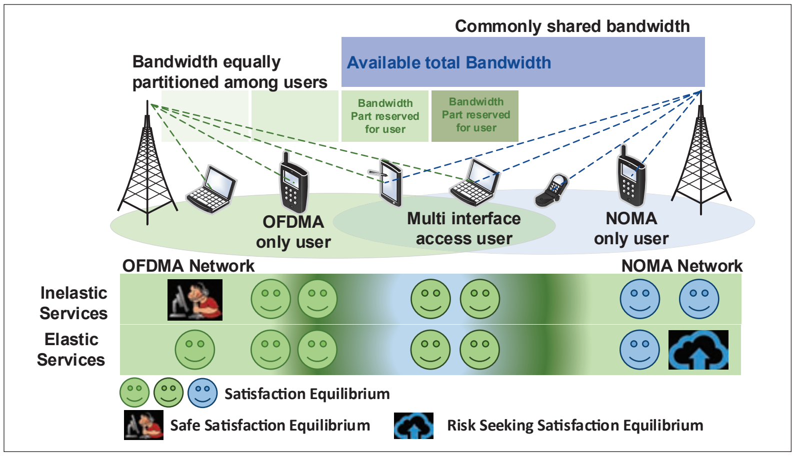

FIGURE 5. Conceptual dual access network with OFDMA and NOMA technologies.

	Prob. of Collapse (%)		Mean Investment		
#Users	N	SSE	NE	SSE	Mean Utility
5	3.96	0.48×10^{-1}	0.20	0.22×10^{-1}	3.44
10	6.17	0.20×10^{-2}	0.25	0.50×10^{-2}	2.69
15	7.57	0.19×10^{-3}	0.28	0.10×10^{-2}	2.20
20	8.49	0.29×10^{-6}	0.29	5.42×10^{-4}	1.86
25	9.06	0.86×10^{-7}	0.30	2.94×10^{-4}	1.59
30	9.28	0.52×10^{-7}	0.30	2.29×10^{-4}	1.36

TABLE 1. Comparative results

to a strategy profile where all users simultaneously choose the least x_i required to achieve the above objective (let us refer to this state as Safe Satisfaction Equilibrium (SSE)). It is noted here that following only the prospect-theoretic concept (without adopting SSE), the user could expect to still achieve similar overall utility, but in a probabilistic manner. The latter means that though the expected utility could be satisfactory, in reality it is by far more likely that the user will end up with a utility smaller than the expected one, especially in the case that the NOMA collapse probability gets high enough. In this fashion, both the interference and the fragility of the unlicensed spectrum expressed through the probability of collapse in the NOMA system would be drastically decreased resulting in high probability in satisfied users.

Use Case 2 — Risk Seeking Satisfaction Equilibrium (RSSE): Alternatively, there are situations where users prefer to invest more in the CPR in order to augment their possible welfare in a more opportunistic manner, for example, applications more adaptable to network conditions such as elastic data offloading. In that manner, the users ought to decrease the percentage of the power transmitted through the safe option (i.e., OFDMA) and each user opts for the maximum x_i that can satisfy it, given the strategies of the others. In that way, the users taking into account the uncertainty and fragility of the unlicensed band, while acting in a more risk seeking manner, exploit more the NOMA-based transmission option which can be significantly more profitable, in case it does not collapse. Accordingly, we refer to this state as Risk Seeking Satisfaction Equilibrium (RSSE).

The aforementioned discussion is graphically captured in the bottom part of Fig. 5. Though multiple satisfaction equilibrium points may exist, the nature of the users' requested application guide them to select their strategy profiles so as to either converge to the safe satisfaction equilibrium in the case of inelastic services, or converge to a risk seeking satisfaction equilibrium in the case of elastic services.

In Table 1, we provide a quantitative comparison between the results achieved by a conventional resource management solution targeting NE, and the proposed SE based approach. For demonstration purposes we consider a scenario according the the Use Case 1 above, while for fairness in the comparison we assume that in each experiment the users in the SSE set their threshold equal to the corresponding mean utility achieved by the NE-based solution. We clearly observe that as the number of users increases, the probability of collapse increases at the NE, while significantly decreasing at the SSE. In other words, as the NE-based achieved mean utility decreases with the increase of the number of users, the QoS aware users can reach the SSE much easier. In conclusion, it is shown that a traditional NE-based approach underestimates the capabilities of the system, as the users can reach the same thresholds with significantly lower investments.

Conclusions and Future Research Directions

In this article an efficient and pragmatic risk-aware resource sharing and management framework was discussed, toward facilitating user QoS satisfaction, in the upcoming deployment of 5G wireless networks, while considering the resource fragility due to over-exploitation from users.

In order to exploit the full potential of this paradigm shift in realistic scenarios, there remain many interesting open issues to tackle. Some of them are highlighted below:

- To deal with the inherent difficulties that wireless networks face in reality, including the incompleteness of available information regarding the game structure, dynamicity of the network environment and uncertainty on the observations of the users, the incorporation of learning-based approaches is required.
- For realization and mainly practical purposes, the adaptation of the energy efficient, flexible and realistic solutions introduced in the proposed paradigm, while considering discrete and finite strategy spaces, is of high research and practical importance.
- Special attention should be devoted to ensuring fairness among the users in terms of accessing the available shared resources toward their satisfaction, while appropriate operation rules should be designed and enforced, to identify and control aggressive, greedy user (mis)behaviors.

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