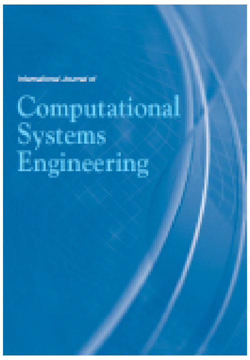

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The future of spectrum management - conciliating spectrum allocation, spectral efficiency and spectrum monetisation

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The future of spectrum management – conciliating spectrum allocation, spectral efficiency and spectrum monetisation

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Abstract: Current spectrum management paradigms are reaching their limits; communication systems such as 5G are key drivers for the world economy, but regulation authorities are facing challenges to identify suitable spectrum allocation for wide area deployment. On the other hand, in a given location and at a given time, the actual level of usage of allocated spectrum is often low. Thus, it seems inefficient to squeeze key economic drivers into small portions of available spectral resources while other parts of the spectrum may remain underused. As a result, a shift in spectrum management policy is inevitable. This paper describes various candidate directions, combining novel approaches such as spectrum sharing with dynamic rules exploiting variable spectral efficiency configurations of existing technologies. These proposals dramatically increase the overall exploitation of the limited resource of spectrum.

Keywords: spectrum; monetisation; public policy enforcement.

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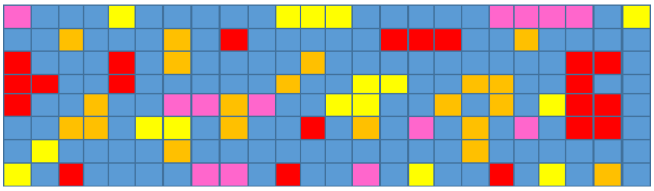
1 Introduction

Traditional spectrum management is currently reaching its limits. It has indeed been common to allocate a certain block of bandwidth to specific applications and services which finally lead to a considerable fragmentation of the scarce spectral resources as it is illustrated by Figure 1.

Although the related allocations have been decided upon and implemented with great care, the actual usage level of a specific spectral band is often low for a given point in time and a given geographic location. To give just one example, fixed link services are typically deployed in specific geographic locations with high gain antennas being directed to a specific recipient. Outside of these locations, related spectral resources remain unused. Finally, only very limited spectral resources remain available for key economic drivers such as 5th Generation communication systems (5G) while large parts of the spectrum are often scarcely used at a given location and a given period of time.

In Europe, there is an opportunity arising to propose changes to the related spectrum allocation regimes. Europe's radio spectrum policy is indeed relying upon a multi-annual program entitled the *Radio Spectrum Policy Programme (RSPP)*. Currently, the EC intends to specify a new such RSPP for the 2025–2030 period which will be first prepared by the European Radio Spectrum Policy Group (RSPG) through an *opinion* and then provided to the European Parliament and the European Council for approval. In this context, RSPG is requested to *reflect about concrete actions to improve spectrum efficiency by using technological innovations (in particular, artificial intelligence), notably exploiting such innovations, inter alia, in the context of (dynamic) spectrum sharing and cross-border cooperation*. This intention clearly deviates from the classical spectrum allocation paradigm and opens the door to far more efficient spectrum management strategies.

Figure 1 Spectrum allocation competition between operators and/or customers (see online version for colours)



While a number of spectrum sharing strategies exist in the literature, as they are discussed in Section 2 of the present article, Section 3 will investigate further disruptive solutions including new spectrum auctioning models and approaches, conditional ownership models (*use it or lose it*), advanced sharing for distinct services, etc. Also, an innovative disruptive and novel approach is proposed introducing dynamic adaptation of spectral efficiency (balancing system complexity and thus power consumption versus available spectral resources) in combination with spectrum sharing mechanisms. Corresponding solutions will be designed such that they meet the requirements for efficient data exchange relying on ultrahigh throughput applications such as video downloading, personal videoconference, autonomous vehicle development, cloud, etc. At the same time, we will address additional conflicting requirements, including those related to ecological considerations and the global fight against global warming.

Corresponding discussions are highly relevant to today's 5G and beyond 5G system discussions; still, their importance will only increase as they extend the classical cellular applications to vertical stakeholder needs, such as automotive communications, industrial automation based on wireless technology, etc. and as we move towards a future 6th generation (6G) framework.

Section 4 will propose models related to the monetisation of spectrum, which will be applied to some of the proposed new approaches and frameworks. One of the angles to be considered relates to spectrum auctions as a source of revenue for the government budget. The current way of asking for a one-time flat fee may indeed prove inefficient and more adequate models are being further discussed through the usage of spectrum slicing (Section 5). Section 6 finally gives conclusions and indicates next steps.

2 State-of-the-art

Traditional spectrum allocation policy largely relies on the allocation of dedicated licensed spectrum to specific technologies and licensees. Additionally, a limited part of the spectral resources are reserved internationally for industrial, scientific and medical (ISM) purposes – including unlicensed systems such as Wi-Fi and similar. Recognising the evident lack of spectrum for key economic drivers, such as 5G systems, regulation administrations have recently added principles of "spectrum sharing" to the set of tools available to policy makers. The objective is indeed to exploit underused portions of the spectrum.

Szydelko et al. (2012) provide a new framework for spectrum sharing in cellular networks. This framework is based on the Vikrey, Clarke and Groves (VCG) mechanism which relies on multi-unit auctions in the context of radio resource allocation. The VCG is well known in algorithmic game theory and maximises the social value while ensuring incentive compatibility (i.e., participants do not gain by bidding different than their true valuations). The paper details the instantaneous auction mechanism and provides very useful results in the allocation of resources. However, it does not tackle differences of coverage, network generation or consumer usage. Matinmikko et al. (2014) provide a large review of spectrum sharing models in Europe and the USA which are composed of three categories. First, licensed shared access (LSA) consists for an operator in monetising its spectrum bandwidth with new users and ensure them a certain quality of service (with low interference). Second, collective use of spectrum (CUS) relies on sharing spectrum among an unlimited number of independent users. Some radio constraints could be introduced to reduce interference between users. Lastly, three-tier hierarchy model are described with the example of the President's Council of Advisors on Science and Technology (PCAST). This architecture relies on primary incumbent licensee (spectrum regulators), secondary licensee (service providers) and a tertiary user (taking advantage of spectrum opportunities). The authors also provide a comparison of these spectrum sharing models and conclude that their adoption depends on their simplicity, applicability and reliability. They also indicate that their implementation will be limited to some national bandwidths in a first step. Kalliovaara et al. (2018) propose a solution based on the LSA concept to improve spectrum usage and guarantee Quality of Service for resources shared by spectrum incumbents. The proposal is dedicated to existing sub-6 GHz frequency bands where the incumbents do not ensure an efficient usage of their spectral resources. Although the article is worthwhile, the authors underline that the protocol requires improved sensing techniques to be more efficient. Moreover, they indicate that the interest towards short-term and geographically limited spectrum access should be investigated. Sohul et al. (2015) take advantage of the initiatives of the Federal Communications Commission in the USA to propose a spectrum access system implementation. The authors detail an architecture which enables to share spectrum dynamically. The proposal interleaves between the incumbent operator and tier services in charge of spectrum access as well as interference management. The conclusion of this paper underlines the importance of gathering governments, industry and academia to tackle this problem and provide value around the spectrum sharing functionality.

Beyond the development and introduction of technological solutions for spectrum sharing, related spectrum monetisation is a key challenge to be considered. Singh et al. (2015) propose a model to coordinate spectrum sharing among multiple operators. The proposal relies on an internal virtual currency but does not implement monetary transactions. This is a mutual renting overview. The authors describe a set of negotiation rules to ensure fair competition and illustrate spectrum sharing through a concrete example of four rooms and two operators. They implement different cooperation algorithms: one-shot game, one-shot plus repeated game, long-term cooperation and demonstrate that cooperation improves spectrum usage. Whereas the proposal are really interesting, the increase of spectrum usage is limited in the context of intense inter-operator interference.

The issue of spectrum scarcity for key novel technologies has furthermore been addressed in multiple publications. Bhattarai et al. (2016) advocate that there is a shift towards spectrum management. This evolution comes from the drastic increase in data exchange while spectrum availability decreases. The authors identify many topics to improve spectrum sharing: spectrum management, metrics publication, interference management, security insurance, etc. They also underline that each subject should associate academics, phone constructors, spectrum regulators, network providers and customers within multiple countries (the USA, China, Canada, France, New Zealand, etc.). While this review is really valuable for any researcher it does not provide a proposal on the orientations to pursue. Wang et al. (2015a) advocate that wireless communications will inevitably suffer spectrum scarcity. This idea is suggested by the fact that spectrum is a limited resource whose cost of usage increases with the frequency (higher frequencies reduce the cope of radio coverage). Thus, the authors propose a truthful auction mechanism which consists in granting incumbents' idle spectrum to licensee access points from different operators to develop operators business. The algorithm proposed offers better radio usage as well as an increase of Incumbent revenue and licensee satisfaction. Although these results are relevant, they do not tackle the problem of multiple technology usage.

Further work targets the specific field of spectrum monetisation through appropriate auctioning approaches. Wang et al. (2015b) advocate provide a new auction based framework to increase data rates in 5G networks. The mechanism relies on the spatial reusability of spectrum and on a mixed graph to manage the interference level between base stations of different operators. The results obtained through simulations outline the importance of the radius ratio for different sizes of interference-free area. Moreover, the economic properties of individual rationality and truthfulness are not modified by the auction algorithm proposed. Again, this work could be extended to the context of bandwidths from different technologies and with various characteristics. Wang et al. (2017) propose a size-negotiable auction mechanism (SNAM), whose novelty relies on the bidder proposal to use a spectrum chunk per unit space and a set of associated coverage ranges. The negotiation manager ensures that winners do not interfere with each other while maximising the auction's total revenue. The mechanism proposed highly increases the spatial efficiency, and thus the total revenue.

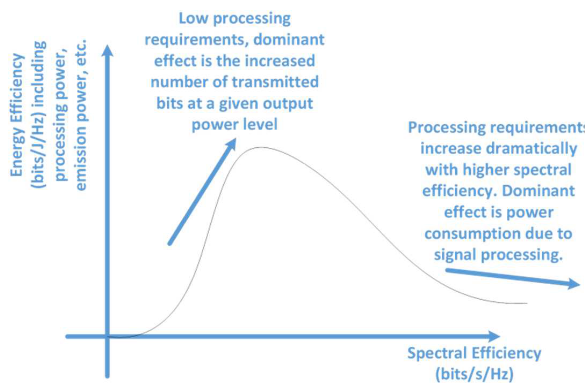
3 New spectrum allocation and management framework proposals

3.1 A novel spectrum management approach: combination of spectrum sharing and dynamic adaptation of spectral efficiency

As discussed in Section 2, spectrum sharing is a novel tool in the tool-set available to regulation administrations and policy makers. Locally and/or temporally underused spectrum can be reallocated to systems in urgent need of spectral resources.

In the present paper, the authors propose to combine spectrum sharing with a *dynamic adaptation of the spectral efficiency* of a given communication system. Typically, modern communication systems, including 5G technology, apply design options which allow highly spectral efficient operation in order to achieve a maximum usage of the scare spectral resource. The increase in spectral efficiency, however, often comes with a hefty price. Ultra-linear radio-frequency front-end designs, high resolution analogue-to-digital converters (ADCs), complex signal processing, etc. take their toll in terms of power consumption and energy efficiency. We thus propose to adapt the locally and/or temporally applicable level of spectral efficiency to the availability of spectral resources in applicable, typically neighbouring, frequency bands as illustrated in Figure 2.

Figure 2 Dynamic adaptation of spectral efficiency (see online version for colours)



The trade-off between spectrum efficiency and energy efficiency is well-known since the spectral efficiency was mathematically detailed by Verdu in 2002. Then, multiple publications outlined the exponential consumption of high density constellations such as Zhou et al. (2014) (especially Figures 3 to 6) and Sboui et al. in 2019. This strengthens the interest towards using simple coding when spectrum is low utilised (for instance in rural areas).

Figure 3 Interest towards continuous spectrum monetisation (see online version for colours)

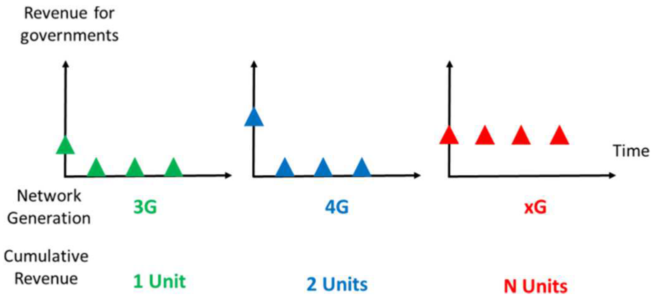


Figure 4 Parameters used for the spectrum monetisation model

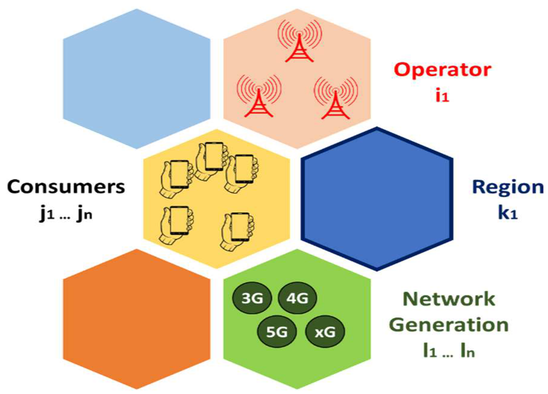
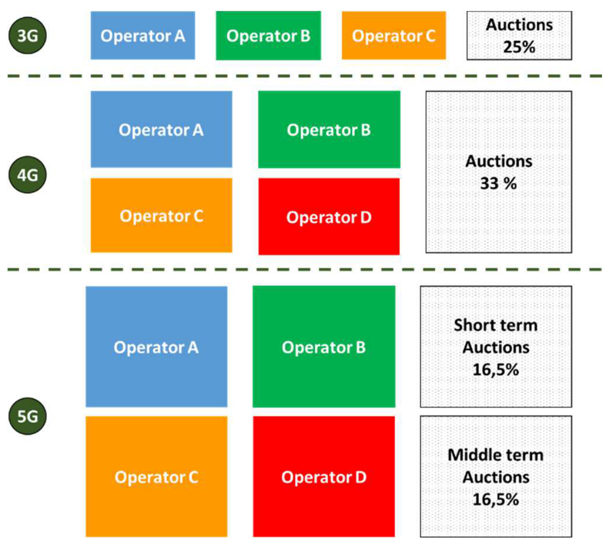


Figure 5 Illustration of spectrum slicing (see online version for colours)



State-of-the-art communication systems allow an adaptation of the spectral efficiency through suitable parameterisation. Commonly available approaches include the following selection of suitable trade-off between complexity and spectral efficiency. Strategies are based on an adaptation of:

- modulation order (e.g., BPSK, QPSK and QA)
- number of spatial streams
- channel coding methods (e.g., turbo codes, convolutional codes, etc.), etc.

The application of existing spectrum sharing strategies to dynamic adaptation of spectral efficiency is discussed in Subsection 3.2.

3.2 Novel combination of dynamic adaptation of spectral efficiency to state-of-the-art spectrum allocation framework proposals

The above discussed mechanism of dynamic adaptation of spectral efficiency is proposed to be combined with spectrum sharing approaches: in case that sufficient shared spectrum is available, the overall energy efficiency may be increased by reducing spectral efficiency requirements; in the opposite case, when only limited spectral capacity is available, target throughput may still be achieved employing higher levels of spectral efficiency at the expense of increased power consumption. Candidate spectrum sharing approaches are summarised in the sequel:

- LSA was introduced by ETSI TS 103 235 V1.1.1 in 2015 as a simple and low-complexity approach to spectrum sharing. Incumbents provide information into a repository on spectrum availability to secondary systems. A controller is coordinating the access to the spectral resources to secondary systems.
- Subsequently, ETSI introduced evolved LSA (eLSA) in 2020 (ETSI TS 103 652-2 V1.1.1, 2020) in order to accommodate for the needs of local and private networks as they may be operated in the context of industrial manufacturing, cultural events, etc.
- In parallel to ETSI's efforts, the Citizen Broadband Radio System (CBRS) approach was defined in the USA (Kułacz et al., 2019). CBRS was specifically designed for the context of non-cooperative primary systems which require active detection through suitable sensing networks.

All of the upper approach allow for secondary usage of spectral resources which, as mentioned above, is proposed to be combined with a dynamic adaptation of the spectral efficiency and thus power efficiency of the overall system.

3.3 New spectrum management framework proposals

The state-of-the art spectrum sharing approaches above may be further complemented by the mechanisms summarised below in order to further increase the overall benefit to society:

- Proposal c1: Discontinue system specific allocations (cellular, unlicensed, etc.) and apply a system agnostic allocation of spectrum. An interesting idea should be to facilitate the migration from a mobile network generation to a newer and more efficient one to facilitate this mutualisation. This would enable to benefit from larger bandwidths with more efficient technologies.

- Proposal c2: Distribute spectrum of a specific spectral block depending on benefits to the society: in case of disaster, allocate it to first responders; in case of a pandemic, allocate it to wireless broadband to facilitate working from home type of applications.
- Proposal c3: Apply a use-it-or-lose-it strategy. Unused spectrum is indeed a loss to the society. If a spectrum owner is not using a part of its spectrum (locally, for a specific period of time), then it may be made available to other services (e.g., unlicensed access) to serve the needs of society.

Combining proposals a1, a2 and a3 would lead to attribute slots either to every kind of usage by introducing a decentralised priority management:

1 military applications
2 emergency applications
3 mobile subscribers
4 public interest users
5 free users.

This simple algorithm could be implemented progressively within base stations for different bandwidths.

- Proposal c4: Instead of applying a one-time fee, lease spectrum using a system agnostic allocation strategy (from government) for a specific period of time and geographic location.
- Proposal c5: Dynamically reallocate spectral resources depending on the needs of the society (in case of disaster, allocate it to first responders; in case of a terrorist attacks, allocate it to wireless broadband to reduce people working transports, etc.).
- Proposal c6: Introduce spectrum access priorities depending on applications (e.g., working from home should have priority over video streaming, etc.) and user groups (e.g., first responders should have priority over video streaming users, etc.).

Combining proposals b1, b2 and b3 would lead to attribute slots either to adjust pricing in real-time to:

1 improve spectrum efficiency
2 reduce power consumption
3 develop public interest usages
4 facilitate radio coverage (to avoid white areas).

4 Spectrum monetisation

European countries usually rely on auctions to grant the access to spectrum to telecommunications providers such as Orange, British Telecom, Vodafone, T-Mobile, etc.

These auctions enable states to obtain money rapidly in a context of very high level of sovereign debt. However, this strategy presents many drawbacks:

- *States* monetise spectrum only once which an unfavourable financial decision on the long-term.
- *Providers* have to borrow large amounts of money to obtain a slice of spectrum before obtaining money from consumers. They also have to invest massively to setup the appropriate network thereafter.
- *Consumers* are compelled to subscribe to an expensive phone bundle as well as a new phone when a new phone generation begins.
- *Ecology* is penalised as actors tend to maximise their telecommunications usage in order to write off their initial investment.

On the contrary a continuous spectrum monetisation provides greater satisfaction for each actor or domain identified previously. As a matter of fact, this evolution would create a dynamic tax which would only rely on consummation. This could also be an incentive to limit the usage of networks as the costs should be passed on to consumers. A similar transfer was recently achieved for streaming services (Netflix, Spotify, Hulu, etc.) in the USA.[1]

Nevertheless, it is important to notice that such an evolution is slightly more complex but fully achievable. Indeed, France has already setup a tax on the gross profits of large telecommunications operators.[2]

In the following paragraphs, the authors propose a modelisation of the spectrum pricing within a country. First, let define the following variables:

- operators are identified by the variable i
- consumers are identified by the variable j
- regions are identified by the variable k
- network generation are identified by the variable l
- constellation density are designated by the variable m.

Then, let define the following variables:

- Number of kilobytes exchanged within the operator bundle initial price $N_{i,j,k,l}(t)$.
- Cost price for the operator within the bundle with a power efficiency modulation $p_{i,j,k,l,m}(t)$.
- Number of kilobytes exchanged through operator auctions $N'_{i,j,k,l}(t)$.
- Cost price for the operator through auctions with a power efficiency modulation $a_{i,j,k,l,m}(t)$.

Thus, we can define the instantaneous cumulative cost price of the operator *CCPo*(*t*) of spectrum usage as:

$$CCPo(t) = \sum_i \sum_j \sum_k \sum_l \sum_m \left[N_{i,j,k,l}(t) p_{i,j,k,l,m}(t) + N'_{i,j,k,l}(t) + a_{i,j,k,l,m}(t) \right]$$

We also propose to define how the cost price for an operator within the bundle may be computed:

$$p_{i,j,k,l,m}(t) = p_0 \cdot \alpha_i(t) \cdot \beta_j(t) \cdot \gamma_k(t) \cdot \delta_l(t) \cdot \varepsilon_m(t)$$

where

- p_0 is the initial price of 1 kilobyte
- $\alpha_i(t)$ is a bonus-malus granted to the operator according to the radio coverage and efficiency
- $\beta_j(t)$ is a bonus-malus granted to the consumer to take into account its data usage
- $\gamma_k(t)$ is a bonus-malus granted by the regulator or authorities to develop a given region
- $\delta_l(t)$ is a bonus-malus granted by the regulator or authorities to increase or decrease the usage of a particular generation of mobiles
- $\varepsilon_m(t)$ is a bonus-malus granted by the regulator or authorities to promote the use of power efficiency (i.e., low density constellations).

Obviously an additional amount is added obtained the price paid by the consumer within its bundle, this is the profit margin $m_i(t)$:

$$P_{i,j,k,l,m}(t) = p_{i,j,k,l,m}(t) \cdot m_i(t)$$

To limit the system complexity, the authors also propose a simple modelisation for the price paid with auctions this is the special profit margin $m(t)$:

$$A_{i,j,k,l,m}(t) = p_{i,j,k,l,m}(t) \cdot s_i(t)$$

As a result, the instantaneous cumulative cost paid by a user *CCPu*(*t*) to its network provider is:

$$CPPu(t) = \sum_i \sum_j \sum_k \sum_l \left[N_{i,j,k,l}(t) P_{i,j,k,l,m}(t) + N'_{i,j,k,l}(t) A_{i,j,k,l,m}(t) \right]$$

With the upper approach, a suitable price for access to spectrum is determined which may become dynamically available.

5 Spectrum slicing

Giving the access to a new spectrum bandwidth requires to define a thoughtful strategy. This often relies on auctions where rules are thought and built cautiously as they structure the telecommunications market for multiple years. Rules should provide a trade-off between the necessity to obtain a large amount of money to reduce countries debt, the satisfaction of consumers which should be able to choose between different operators and the sustainability of the underlying economy.

As discussed in Mardsen et al. (2017), the strategy should rely on the following principles:

- *Set affordable reserve prices* in order to encourage competition between existing operators and potentially new ones.
- *Provide a maximal spectrum access* and do not keep spectrum for further auctions in order to offer the best experience to users.
- *Set attainable constraints for an operator* which implies that licenses are granted one or two decades and coverage objectives may be reached at a reasonable cost.
- *Adopt a long-term perspective* and do not only focus on short-term issues. Any pricing policy or constraint should be set for multiple years in order to enable operators to anticipate them.

Thus, we present below an example of spectrum sharing which could fit with the previous objective:

- *The 3rd generation* was granted with a reserve price for three operators and auctions could offer a bandwidth to a new operator or to one of the historic operators. Auctions are limited to 25% of the spectrum and should be awarded in any case.
- *The 4th generation* was granted with a reserve price for four operators and auctions could offer a bandwidth to a new operator or to one of the historic operators. Auctions are limited to 33% of the spectrum and should be awarded in any case.
- *The 5th generation* was granted with a reserve price for four operators. Two types of auctions are introduced for a overall envelope of 33% of the spectrum (half for short-term auctions which may be daily or weekly and half for the middle term that is to say 1 to 3 months).
- *The 6th generation* is not included in the example but could give the opportunity to accelerate the 3rd generation replacement. Indeed, it should be a top priority to reuse base stations excepted transmitters and receivers.

6 Conclusions

In the present paper, a novel approach is presented suggesting a combination spectrum sharing with dynamic adaptation of the spectral efficiency of target communication systems. The overall power efficiency is thus optimally adapted to the locally and/or temporally available spectral resources. Furthermore, a related spectrum monetisation approach is being discussed enabling a practical implementation in the context of spectrum scarcity.

The authors propose to introduce these proposals in the upcoming European Union wireless communication regulations and devices.

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Notes

1 https://www.cnbc.com/2020/02/24/states-are-imposing-anetflix-and-spotify-tax-to-raise-money.html.

2 Details are available at the following URL: https://www.legifrance.gouv.fr/affichCode.do?cidTexte=LEGITEXT000006069577&idSectionTA=LEGISCTA000020355836&dateTexte=&categorieLien=id.