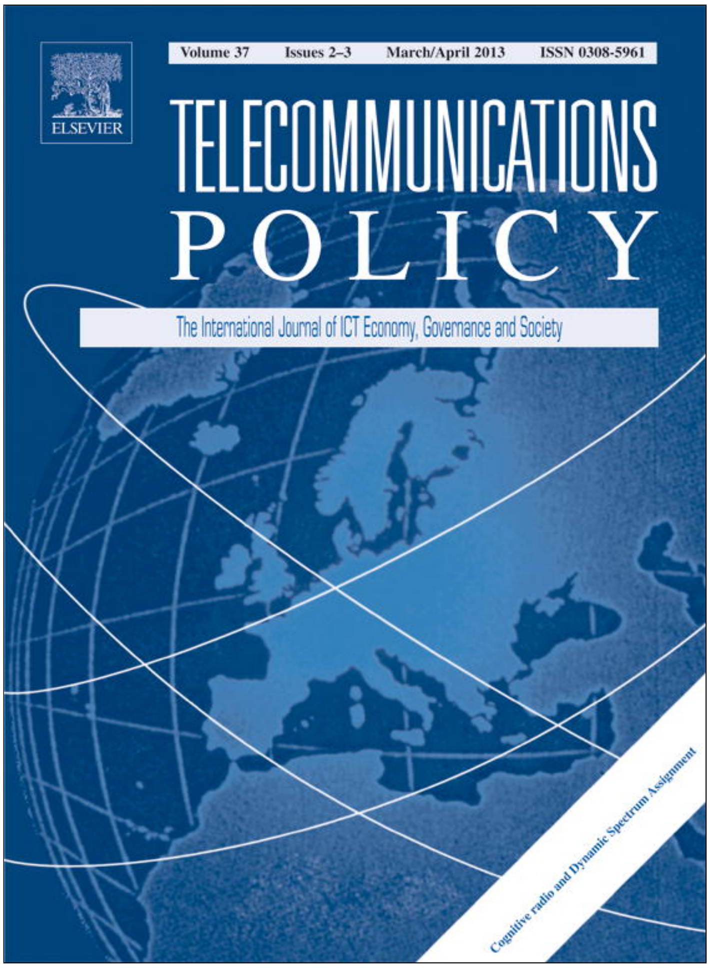
Volume 37
Issues 2–3
March/April 2013
ISSN 0308-5961
ELSEVIER
TELECOMMUNICATIONS
POLICY
The International Journal of ICT Economy, Governance and Society
Cognitive radio and Dynamic Spectrum Assignment

Telecommunications Policy 37 (2013) 108–115

Contents lists available at SciVerse ScienceDirect

Telecommunications Policy

URL: www.elsevier.com/locate/telpol

Stalling innovation of Cognitive Radio: The case for a dedicated frequency band

Arturas Medeisis [a,*], Leo Fulvio Minervini [b]

[a] Telecommunications Engineering Department, Vilnius Gediminas Technical University, Naugarduko 41, LT-03227 Vilnius, Lithuania
[b] Department of Law and Economics, Università di Macerata, Via Angeloni 3, 60035 Jesi, Italy

ARTICLE INFO

Available online 22 November 2012

Keywords:
Cognitive Radio
Cognitive Radio regulation
Wireless telecommunications market
Radio spectrum

ABSTRACT

After more than a decade of frantic R&D efforts, Cognitive Radio (CR) technology continues to fail to pass the first developmental milestone of a working prototype, suggesting that the CR innovation process may be stalling. This paper analyzes possible reasons for this situation from the perspective of innovation management and economics. The CR innovation process has developed in a complex environment shaped by a combination of technology-push and market-pull forces. This paper shows that this process is being stifled by two barriers emerging from the current reliance of CR technology on opportunistic dynamic spectrum access as the sole means for entry into the wireless market. The technology-push is affected by the barrier of technological complexities linked to the requirement to protect highly sensitive incumbent systems. The market-pull forces are being negated by market lock-in and a strong status quo of well-established wireless players. This paper argues that overcoming these barriers and revitalizing the practical development of CR could be possible with the aid of light-touch governmental intervention. This could take the form of designating a dedicated CR band, which would benefit CR through less strict spectrum access requirements. A vibrant cognitive environment could flourish in this type of band, supporting CR innovation.

1. Introduction

It has been more than a decade since the concept of Cognitive Radio (CR) was coined by Mitola (2000). It quickly became the most fashionable topic in the field of wireless research, with explosive growth in the numbers of conferences and publications dedicated to this subject. Regardless of the hype and frantic research activity, however, the advancement of CR to the market seems to proceed too slowly, as evidenced by R&D efforts that remain largely limited to academic environments and the continued lack of appropriate radio frequency (RF) front-end offerings (Pawelczak, Nolan, Doyle, Oh, & Cabric, 2011). This paper analyzes possible reasons for this sluggish progress from the perspective of innovation management and economics, with the aim of recommending suitable policies to boost further and more fertile developments of CR technology.

Presently, a plethora of definitions of CR exists. The authors adopt the holistic definition of CR as a radiocommunications device or a network of such devices that possesses full awareness of its operational context: the real-time situation with radio environment, the communication requirements of its user, the applicable regulatory policies and the device's own capabilities. CR uses this information to make autonomous decisions on how to configure itself for the communications task

* Corresponding author. Tel.: +370 5 274 47 73; fax: +370 5 274 47 70.
E-mail addresses: arturas.medeisis@vgtu.lt, amedeisis@gmail.com (A. Medeisis), minervini@unimc.it (L.F. Minervini).

0308-5961/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.telpol.2012.07.001

at hand (Doyle, 2009). Hence, in the context of this paper, CR represents a significant evolutionary step from traditional radiocommunication systems. The autonomous, cognitive re-configuration of CR opens up opportunities for new business models in the wireless communications marketplace built on the novel utility profiles of CR.[1]

As an innovative technology, CR must progress through several developmental milestones. The first of these is the delivery of a working prototype (Suarez, 2004).[2] However, it appears that after more than a decade of extensive R&D efforts, CR still largely fails to pass the maturity test of producing a solid working prototype. Hence, industry watchers have sounded warning bells (Pawelczak et al., 2011).

It may be surmised that some systemic deficiencies exist, the reverse salient barriers (Hughes, 1987) in the composition and functioning of an eco-system of CR innovation that restrain the impetus of CR development. In their technical essence, both of the fundamental components of CR – the re-configurable radio hardware and the processors to run it with the help of software – are well-known modern technologies. Thus, in terms of technology, the challenge of CR boils down to designing suitable software algorithms to convert reconfigurable radios into proper CR. Why, after more than a decade as one of the most popular research topics in wireless R&D, does CR technology remain an elaborate concept rather than existing as a working prototype and establishing itself as an innovation that might bring tangible (commercial) benefits?

To address this question, this study focuses on the technology-push and demand-pull processes (Nemet, 2009) as applied to CR and discusses the barriers that may be stalling CR innovation. The rest of this paper is structured as follows. The following section considers the evolutionary role of CR innovation and analyzes its forces and dynamics to identify reverse salient barriers. The third section discusses the findings and proposes interventional policy measures, such as the designation of a dedicated CR band, which may enliven the technological innovation of CR and hasten its market introduction. The final section offers some concluding observations and ideas for future developments.

2. CR innovation and business development

2.1. Evolutionary role and forces of CR innovation

Given the stalling progression of CR to the market, it may be of interest to consider why this issue is important in already highly competitive wireless markets. Therefore, this begins from the tenets of evolutionary economics. Metcalfe (1994) postulated that any sustainable economic development is intrinsically linked to the dynamic interplay between the processes of variety (providing the necessary breadth of innovative options to the market) and selection (the market opting for a preferred alternative among competing solutions).

In the context of modern wireless markets, it can be argued that CR represents an important new option that contributes to a variety of competing technological solutions. Accordingly, the aforementioned stalling of CR innovation could point to the existence of market failure conditions and may call for policy intervention.

The evolutionary perspective leads us to consider two complementary yet distinct strategic forces shaping the dynamics of innovation and impacting the transfer of technology from the research laboratories to the market. The first of these forces can be described as the technology-push, which explains technology transfer as motivated by means. In this process, the sheer technological superiority of the innovation compared with traditional technologies dictates its broad acceptance by an industry. A second contributing force is characterized as a demand-pull or market-pull, the intensity of a market proposition and a commercial promise of a new technology (Nemet, 2009). It may be hypothesized that the halting dynamics of CR innovation may be connected to deficiencies in the workings of one or both of these forces.

2.2. Faults of the CR technology-push

The main impetus of the classical technology-push is built on the premise of the technological soundness and superiority of new innovative solutions compared with existing state-of-the-art technologies. This usually requires a clearly formulated technological concept and an initial working prototype that can pass the elaborate testing of the market and convince stakeholders of the emergence of a new, dominant technological design (Suarez, 2004; Teece, 1986). Thus, the fact that there still does not exist an unambiguous definition of CR, let alone a working prototype, suggests that something may be obstructing the technology-push of CR. As discussed in this section, incumbent systems and standards are likely to pose a substantial barrier to the technology-push of CR.

In the case of CR technology, it can be suggested that the technology-push may be steered along two paths. The first path is an incremental process of innovation by incumbent operators and vendors that might gradually propel CR

[1] Mitola (2000) predicted several CR utility profiles, most notably opportunistic dynamic access to the radio spectrum (i.e., sharing a radio spectrum band that would be otherwise unavailable due to its exclusive allocation to some incumbent system), more efficient use of networking resources through dynamic re-configuration, and the delivery of user-aware services.

[2] Suarez (2004) focuses on the dominance battle between alternative competing technologies (e.g., IBM's PC vs. Apple's MAC). This seems to parallel the case of CR, which is perceived as an alternative technological design philosophy that attempts to compete with modern well-established wireless technological architectures.

technology to the degree of technological excellence necessary to win the position of successful industrial design and effect the paradigmatic switch toward the new technology by means of industry consensus (Teece, 1986). The second path is through a standardization process in which CR proponents (especially those without current stakes in the wireless industry) push CR technology to the position of a recognized industry standard by means of formal standardization processes that involve formal Standards Development Organizations (SDO), such as IEEE or ETSI (Delaere & Ballon, 2008).

Regarding the first option, the process of incremental innovation is occurring, as evidenced by attention to CR technology from existing wireless players. However, the traditional operators may be tempted to act with great caution to avoid disturbing the status quo (as discussed in the following section). Therefore, it is likely that these operators would proceed in carefully measured steps to ensure that any realized technological gains are harnessed as part of the toolbox of existing wireless service offerings[3] or through a carefully screened set of CR use cases that may be of interest to the incumbents (Fitch, Nekovee, Kawade, Briggs, & Mackenzie, 2011).

In contrast, the formal standardization process might be an effective avenue of technology-push toward gaining market recognition of the disruptive aspects of CR. However, this process is lengthy, perilous and, at times, confusing. Recent research by Delaere and Ballon (2008) in the field of CR standardization shows the multi-layered complexity of standardization in the telecommunications field. This complexity can be characterized not only by the multi-dimensionality of stakeholder groups and covered issues (from addressing pure technology to seeking political consensus) but also by its overall complexity and lack of certainty. The situation is further complicated when multiple concurrent standardization trajectories are initiated by various groups of technology proponents and in various SDO (which tends to spread the lobbying efforts too thinly and further mire the process in complexity). These competing standards and recommendations may, in turn, lead to the fragmentation of the markets (Fitch et al., 2011).

This situation may be observed clearly in the case of CR. Standardization efforts were initiated in several SDOs, such as the IEEE Standards Committee DySPAN (former SCC41), IEEE 802, ETSI Technical Committee RRS, ITU-R and others. Of these, the IEEE SC DySPAN takes the most holistic approach. However, even there (or especially there because of the attempted wholeness of consideration), the standardization process is excruciatingly slow because it needs to reconcile technological advancement with business and policy considerations (Granelli et al., 2010). If one considers the most challenging issues listed by Granelli et al. (2010), then it can be observed that only one out of five (system design and networking) represents a genuine technological challenge, whereas the other four (regulation and testing, security and two types of malicious operational transgressions) are rooted in various aspects of operational policies to ensure the protection of incumbent services. Furthermore, the long list of implementation challenges compiled by Fitch et al. (2011) shows a heavy bias toward non-technical issues, including ambiguities of the standardization process.

Finally, seeking analogies in the literature on innovation management, the hindrances discussed above may be linked to the impact of excessive bureaucracy and risk barriers (Assink, 2006). In the case of CR, these two obstacles are elevated from a company level to an industry-wide level and are enshrined in several layers of ex ante regulatory policies, including the harmonized allocation/pre-partitioning of the radio frequency spectrum for specific uses where particular technical standards have established themselves as strong incumbents.

2.3. Faults of the CR market-pull

The market-pull of an innovative technology may be described as a gravitational force generated by market players that appreciate the commercialization prospects of the new technology. The question of a credible business case is of paramount importance when attempting to understand the gravitas of the market-pull. In the case of CR, however, the situation may be complicated by the fact that current wireless markets are effectively locked in to the existing players and their dominant technologies and services (Arthur, 1989).

A few early examples of CR technology road-mapping exercises (Casey, 2009; Chapin & Lehr, 2007) highlight the potential for business propositions of CR in a specific application: the opportunistic exploitation of the spectrum used by some incumbent services through a Dynamic Spectrum Access (DSA) mechanism. DSA enables nearly instant access to radio spectrum usage gaps and is able to transcend complex and cumbersome traditional administrative spectrum allocation procedures. This is undoubtedly appealing to the many companies wishing to enter the fray of high-profile and profitable wireless businesses.

However, even the great promise of DSA has failed to generate the necessary commitment and investments sufficient to overcome the challenges of CR innovation. When attempting to understand the reasons for the lack of attention by the big companies to DSA prospects, insight may be provided by recent academic research. For instance, a study conducted by Nguyen, Zhou, Berry, Honig, and Vohra (2011) models the economic impact of opening a new DSA-accessed spectrum for wireless Internet service providers. It finds that the equilibrium profits for incumbent service providers with licensed spectrum may decrease as a result of the introduction of new unlicensed spectrum access, whereas the equilibrium profits for service providers that enter the unlicensed spectrum will be zero. This outcome paints a rather bleak picture that may be described as a loss–loss situation. Moreover, if the amount of available unlicensed spectrum bandwidth is below a certain threshold, then the overall social welfare of the provided services may actually decrease.[4]

[3] Such as software-defined base station designs offered to wireless operators; for example, see Vanu Inc. (http://www.vanu.com/).

[4] Compare with the well-known concept of the tragedy of commons.

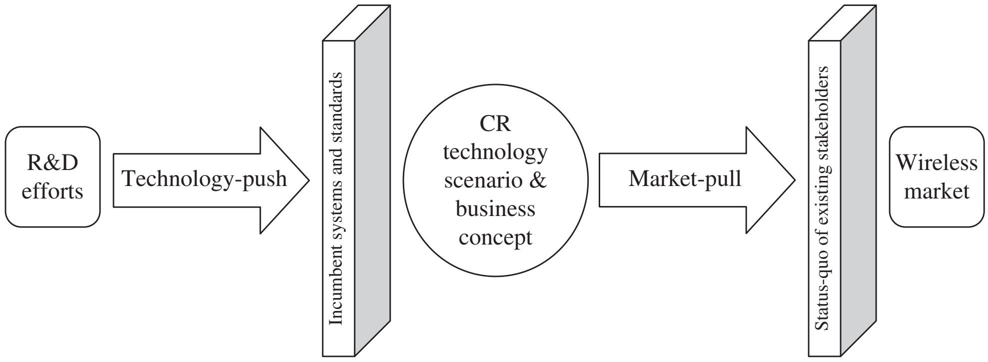

Fig. 1. Proposed interpretation of CR innovation path from R&D to diffusion, with identified barriers.

The above example suggests that, even considering the most clearly articulated business promise of CR as a means of opportunistic spectrum access, it is difficult to gain solid ground and to drive the market-pull process in the current spectrum management regime. Especially in the case of DSA, the incumbent ownership of the targeted spectrum remains the main obstacle for the development of CR technologies. Thus, the traditional operators speak of being forced to allow sharing (Fitch et al., 2011). Because the existing wireless players already have a stake in the current spectrum allocations, they must be wary of jeopardizing the status quo with radio spectrum (and wireless market) access.

These circumstances can be observed as reverse salient barriers that increase CR innovation costs and reduce incentives for its development. This asphyxiation of fledgling CR business ideas is akin to what innovation theoreticians describe as the technological lock-in, the adoption barrier or the stifling of the status quo (Assink, 2006).

2.4. *Summarizing the state-of-the-art of the CR innovation process*

Based on the discussions in the previous sub-sections, the CR innovation process may be represented along a single axis of technological transfer from R&D labs to the wireless marketplace (see Fig. 1). In this respect, it is important to note that the effectiveness of technology-push and market-pull processes is cross-dependent (Nemet, 2009). That is, market players hoping to realize the business potential and the gravitas of market-pull strongly prefer the clearest possible technological scenarios.

By considering this process, the identified barriers affecting the respective technology transfer forces may be observed as providing a compounded negative effect on the development of CR innovation. To analyze the manifestation of these barriers, a case study is offered for one recently promoted DSA-based wireless application, the so-called White Space Devices (WSD). These devices aim to exploit the white spaces, or gaps of virtually unused spectrum, that are present in any transmission plan of terrestrial TV broadcasting.

In the case of WSD, the overly restrictive requirements to protect the incumbents, resulting in extremely onerous DSA spectrum access rules, have stifled the standardization process (technology-push). This has impaired the formation of the overall technological and business concept. Presently, the business case of WSD (market-pull) remains weak (i.e., Who will pay for free WiFi-like access?). This is well described by a provocative phrase from William Web, who questioned whether WSD might be a solution in search of a problem.[5]

Originally proposed in the US, the authorization regime for WSD[6] first envisaged semi-autonomous CR devices that would be able to choose their operating frequency based on their own observation of spectrum occupancy (spectrum-sensing function) and by consulting the central database of TV and other transmissions (geolocation database). However, the original proposal sparked lengthy debates and field experiments regarding how to ensure full protection of TV broadcasting (and other incumbent users). As a result, the notion of autonomous WSD operation through spectrum-sensing was largely discredited, and the WSD rules ultimately approved by the FCC allowed WSD operation on the sole condition of being tethered to a geolocation database. The same regulatory approach is currently being replicated by European regulators.

The technology-push processes of WSD evolution can be observed in the standardization field, where they resulted in the production of a recent IEEE 802.22 standard (IEEE, 2011). However, it took seven full years to develop this standard, which offers only a glimpse of one narrowly defined application, a forerunner of true CR technologies. Regarding the market-pull forces, the industry promoting WSD development has observed large companies, such as Google, Microsoft and Dell, joining forces within the Wireless Innovation Alliance. It seems safe to think that such companies should be capable of assuming leadership positions and becoming champions of the technological battle, as evidenced by the development of an industry-backed IEEE 802.22 standard (also known as Super WiFi). However, most of these companies'

[5] See W. Webb in Telecoms.com at http://www.telecoms.com/22952/the-thought-that-counts/.

[6] The original FCC consultation on the possibility of utilizing TV White Spaces was begun in May 2004 and lasted until the positive FCC decision in November 2008. The final technical rules took another two years to finalize and were released only in September 2010.

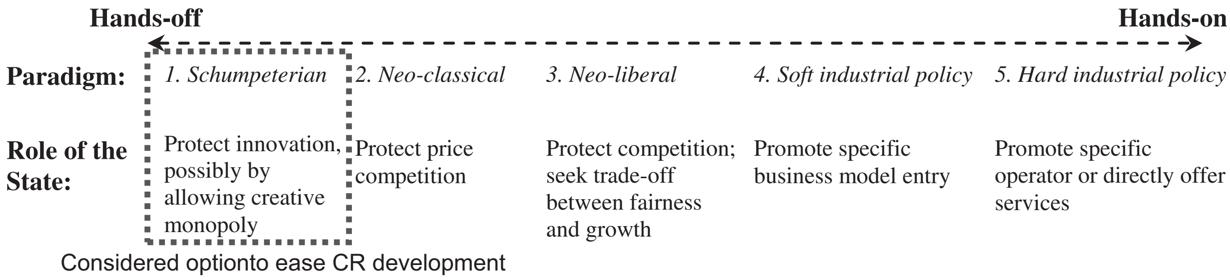

Fig. 2. Options of regulatory intervention to ease CR development (adapted from De Streel, 2008).

involvement focused on lending political clout to the petition for the new rules[7] and observatory participation in a few selected pre-CR technology pilot projects.[8]

3. Discussion of the future development of CR

The previous analysis described a situation in which the innovative development of CR faces an uphill technological battle toward market recognition. The main factors that appear to lock CR development into the R&D phase are the onerous regulatory requirements for the protection of incumbent technologies, which are further compounded by the wary attitude of existing stakeholders. This situation may lead to a standstill, described as a chicken-and-egg dilemma in which vendors wait for large operators to announce support for CR technology as an indication of sufficient volume potential, whereas the operators are reluctant to support new technology unless it is standardized and embraced by the manufacturers as a pre-requisite of acceptable pricing for mass-market devices (Fomin, Medeisis, & Vitkute-Adzgauskiene, 2012).

This situation is suggestive of (market and government) failures to provide the necessary testing ground for the trial-and-error dynamics required for efficient evolutionary processes (Metcalfe, 1994). Thus, the next issue to consider could be the type of regulatory intervention that might be considered appropriate to facilitate the innovative process of CR.

De Streel (2008) stipulates that regulatory intervention in the field of telecommunications policies can take several forms with varying interventional degrees. Although he distinguished four types of approaches, in comparing his proposals with the discussion by Atkinson (2011), The authors suggest that it may be useful to recognize five types, as illustrated in Fig. 2.

The above-mentioned inclination to use an evolutionary approach as a guiding framework speaks in favor of choosing the Schumpeterian paradigm,[9] also fittingly called innovation economics (Atkinson, 2011).

The Schumpeterian philosophy postulates that economic growth is spurred by innovative markets, products and manufacturing processes (Schumpeter, 1942). As the first to observe a profitable opportunity for the use of a new technology and to innovate, the Schumpeterian entrepreneur enjoys a temporary monopoly that rewards innovation with excess profits. Successful innovators are tracked by followers in the search for profit gains, leading to intensified competition and increased demand for inputs with limited supply.[10] This results in the constant destabilization of market equilibrium and forces new leaps in economic development. In a similarly disruptive way, CR is the potential game changer of the entire wireless industry. However, the barriers in the CR innovation path, which are exacerbated by the lack of easy access to suitable frequency bands, prevent any substantial opportunity for CR to push the market into a new Schumpeterian cycle of destabilization and a subsequent innovation leap. Accordingly, governmental policy to clear that path seems crucial. Policy failure (or, in this case, policy absenteeism) is as important as market failure (Metcalfe, 1994).

However, the utmost care should be applied to avoid making the interventional measures themselves a stifling element. Indeed, similar to any disruptive innovation, the development of CR may be described as an extremely complex process that must be placed in a favorable business and regulatory eco-system to develop with sufficient degrees of freedom (Assink, 2006). For instance, research by de Reuver (2011) offers compelling evidence in the field of mobile service innovation that creativity and innovativeness is severely hampered by too many technical complexities. It is worth remembering that "in disruptive situations, actions must be taken before careful plans are made. Because much less can be known about what markets need or how large they can become, plans must serve a very different purpose. They must be plans for learning rather than plans for implementation" (Christensen, 1997, p. 156). Similarly, Metcalfe (1994) argues that

[7] Google was one of the most proactive campaigners for allowing WSD access by setting up the public initiative Free the Airwaves (no longer featured online). This was fiercely opposed by the broadcasting lobby, which mounted a counter-initiative of its own, referring to white spaces as Interference Zones (see http://www.interferencezones.com/).

[8] A list of ongoing trials is available at http://www.wirelessinnovationalliance.org/.

[9] However, it is worth noting that although Schumpeter considered government policies pesky at times, he saw them as a necessary part of the socio-economic landscape (Heertje, 2006). Thus, the Schumpeterian paradigm is not entirely a hands-off approach. A role for state policy remains important as the creator and guardian of an eco-system for innovation.

[10] From the full Schumpeter perspective, this process is placed in the context of increasing credit availability and macroeconomic spillovers. The evolutionary approach (a modern parallel of Schumpeter's analysis) adds that realized profit is a major determinant of investment spending. Thus, firms that have picked good technologies will invest (and grow) more than others.

when problems cannot be well defined, deductively rational decision processes must be replaced with inductively experimental ones. In addition, incremental innovation is more likely to respond to demand-pulls than technology-pushes, and non-incremental innovation is more responsive to technology-pushes (Dosi, 1988). This situation implies that if CR is to unleash its true disruptive potential as non-incremental innovation, the enabling focus should be on the technology-push process (which is identified as an early active force in the authors' rendition of CR innovation process).

In the case of wireless markets, the typical intervention avenues are nearly always concerned with spectrum policies, which provide the means for directing technological trajectories and alleviating market uncertainties. Coupled with previous observations and reasoning, it appears that policies to ease CR innovation should be directed at opening unconstrained learning grounds by offering a self-managed spectrum band suitable for experimentation with CR technology. As shown above, relying on DSA to gain secondary access to a spectrum already occupied by other users may be a critical and superficial impediment to CR innovation. Recently, the idea of a dedicated CR band has been voiced in European academic forums (COST-TERRA, 2011). The presence of a dedicated band would allow easier experimentation and the emergence of dominant designs, which could facilitate the process of standardization and the technology-push process. At the same time, a dedicated band would significantly limit the exposure of fledgling CR technology to the risks of technological and market uncertainties, strengthening the basis of potentially successful innovation (Grant, 2009, esp. chap. 12). Thus, the dedicated band could help to break the aforementioned chicken-and-egg standstill by providing a learning platform that would facilitate the resolution of inherent uncertainties in the coordination and appropriability of CR technology.

Another important aspect is that the dedicated CR band would reduce the risk that CR testing may cause direct disturbances of existing markets. The separation of testing activities from commercially used bands would mean that any possible impact in terms of operational interference or tangible reductions in the surpluses of existing consumers and incumbents could be avoided. Thus, the dedicated frequency band for CR development appears to represent a suitable avenue for light-touch state intervention, which would be concerned primarily with the removal of identified barriers while preserving the status quo of existing wireless markets. Such a band could be shared by multiple CR operators/users without the burden of protecting the highly sensitive incumbent users that provide public services, such as cellular telephony or broadcasting. The CR band could become a learning platform to provide the necessary freedom for experimentation, unrestricted by the need to abide by the rigorous rules for protection of incumbent systems. This would effectively remove the identified barriers and would allow more practical experience to be gathered in using this technology. Evolutionary forces of variety and selection would be evoked by providing necessary feedback and early dissemination (Fig. 3).

The idea of a dedicated CR band is also attractive to the believers of the build it and they will come philosophy. When discussing (or, rather, attempting to guess) the list of future CR applications that are likely to emerge first, many suggest that once the opportunities for CR deployment become transparent, novel applications will emerge by themselves (Webb, 2010). Such experiences would enliven the technology-push and market-pull forces and provide for better understanding of CR technologies before attempting the highly ambitious prospect of self-propelled entry to the licensed frequency bands of existing market players based solely on opportunistic spectrum access.

Providing dedicated frequency bands for innovative technologies has proven to be a wise choice that established the technological trajectory and provided the necessary regulatory certainty for innovating companies to concentrate their focus and investments (Anker, 2011). Successful examples of aiding innovative ideas by allocating a designated frequency band include the allocation by the FCC of a spectrum for cellular telephony in 1970 that led to the first commercial deployment of a cellular system in 1983 by Bell Labs and the designation of the 2.4 GHz ISM band for spread spectrum technologies in 1985 that paved the way for widespread WiFi systems.

Considering the opportunities for the practical implementation of the dedicated CR band concept, the currently envisaged frequency bands where CR might develop are neither entirely appropriate nor sufficient. The WSD introduction in TV bands would be severely constrained by the need to protect the incumbent services, most importantly the highly sensitive TV broadcasting receivers and widely used wireless microphones. The possibility of using unlicensed bands, such as the 2.4 GHz ISM band used for WiFi operations, also offers limited opportunities due to the overloading of ISM bands and severe transmission power restrictions (100 mW in Europe). It is suggested that a suitable dedicated CR band could be either an identified segment of the 2.4–2.4835 GHz band, where unrestricted power would be allowed for all or some specified classes of CR equipment, or a genuinely new, exclusive allocation, where CR could have a preferable sharing arrangement. Such a band should be found in the spectrum below 3 GHz to allow mobility.

Fig. 3. Proposed arrangement with optimal functioning of CR innovation forces.

Possible candidates for this newly assigned dedicated CR band could be the little-used 1452–1492 MHz band, whose future is currently being reviewed by European regulators, or the portions of TV band 470–862 MHz that are gradually being freed from TV transmissions due to conversion to more efficient digital TV broadcasting. Importantly, any dedicated band should be chosen from among those bands that have a suitable set of radiocommunications services allocated to them in the overarching regulatory statutes of the ITU Radio Regulations. For instance, ITU allocation for Land Mobile and Fixed services in the subject band would appear to be sufficient legal basis for the broadest range of innovative services currently envisaged in the domain of CR applications.

4. Concluding remarks

The process of CR innovation is slowly progressing within a complex environment shaped by the combined workings of technology-push and market-pull forces. However, these forces are being stifled by reverse salient barriers that effectively limit CR development.

The findings of this study support the notion that an effective means of overcoming these extant barriers and revitalizing the innovation process for CR technologies could be for governments to designate dedicated CR band(s) with relaxed regulatory requirements for CR-enabled technologies. These bands could become fertile ground for a flourishing innovative eco-system for this promising new wireless technology.

The designation of a dedicated CR band should consider the technical aspects of reliable system co-existence and policy considerations of suitable regulatory regimes as well as the relevant provisions of ITU Radio Regulations. This complex inter-disciplinary subject should be addressed by further studies.

To conclude, it might be worth recalling an insight by Nemet (2009): "Governments can [...] encourage innovation in two ways: they can implement measures that reduce the private cost of producing innovation, *technology-push*, and they can implement measures that increase the private payoff to successful innovation, *demand-pull*" (Nemet, 2009, p. 702, italics in the original). Providing the CR innovation community with an open and unrestrained testing ground would represent a plausible solution for effectively removing the identified innovation barriers and turning the current loss–loss formula into a potential win–win situation.

Acknowledgments

The concept of a dedicated frequency band for CR has been discussed in the framework of the COST Action IC0905 "TERRA" (www.cost-terra.org/). The authors gratefully acknowledge contributions to this discussion from Oliver Holland, Keith Nolan, Luca De Nardis, Simon Delaere and John Sydor, to name but a few. The authors are also very grateful for comments to the drafts of this paper from Vladislav V. Fomin, anonymous reviewers and the editors of this special issue.

The work of A. Medeisis was supported by the Research Council of Lithuania under grant no. COST-1/2011.

References

Anker, P. (2011). Cognitive radio—The need for coordination: Lessons from the past. In: *Pres. 3rd Meeting of COST Action IC0905 (TERRA)*, Brussels, 20–22 June 2011 〈http://www.cost-terra.org/archive-of-past-meetings〉.

Arthur, B. (1989). Competing technologies, increasing returns, and lock-in by historical events. *Economic Journal*, *99*(March), 116–131.

Assink, M. (2006). Inhibitors of disruptive innovation capability: A conceptual model. *European Journal of Innovation Management*, *9*(2), 215–233.

Atkinson, R. D. (2011). Economic doctrines and network policy. *Telecommunications Policy*, *35*(5), 413–425.

Casey, T. (2009). Analysis of radio spectrum market evolution possibilities. *Communications and Strategies*, *75*(3), 109–130.

Chapin, J. M., & Lehr, W. H. (2007). Cognitive radios for dynamic spectrum access – The path to market success for dynamic spectrum access technology. *IEEE Communications Magazine*, *45*(5), 96–103.

Christensen, C. M. (1997). *The innovator's dilemma: When new technologies cause great firms to fail*. Boston, MA: Harvard Business Press.

COST-TERRA. (2011). Research status update and future work areas. In: *Summary of the third meeting, COST Action IC0905 TERRA on Techno-Economic Regulatory Framework for Radio Spectrum Access for Cognitive Radio/Software Defined Radio* 1–6. Brussels, 20–22 June 2011. Retrieved from: 〈http://www.cost-terra.org/archive-of-past-meetings〉.

de Reuver, M. M. (2011). Governance of mobile service innovation after the walled gardens. *Info*, *13*(1), 43–60.

De Streel, A. (2008). Current and future European regulation of electronic communications: A critical assessment. *Telecommunications Policy*, *32*(11), 722–734.

Delaere, S., & Ballon, P. (2008). Multi-level standardization and business models for cognitive radio: The case of the cognitive pilot channel. In: *Proceedings of the IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN2008)* 1–18. 〈http://ieeexplore.ieee.org/xpl/articleDetails.jsp?tp=&arnumber=4658278〉.

Dosi, G. (1988). Sources, procedures, and microeconomic effects of innovation. *Journal of Economic Literature*, *26*(3), 1120–1171.

Doyle, L. (2009). *Essentials of cognitive radio*. Cambridge, UK: Cambridge University Press.

Fitch, M., Nekovee, M., Kawade, S., Briggs, K., & Mackenzie, R. (2011). Wireless service provision in TV white space with cognitive radio technology: A telecom operator's perspective and experience. *IEEE Communications Magazine*, *49*(3), 64–73.

Fomin, V. V., Medeisis, A., & Vitkute-Adzgauskiene, D. (2012). In search of sustainable business models for cognitive radio evolution. *Technological and Economic Development of Economy*, *18*(2), 230–247.

Granelli, F., Pawelczak, P., Prasad, R. V., Subbalakshmi, K., Chandramouli, R., & Hoffmeyer, J. A. (2010). Standardization and research in cognitive and dynamic spectrum access networks: IEEE SCC41 efforts and other activities. *IEEE Communications Magazine*, *48*(1), 71–79.

Grant, R. M. (2009). *Contemporary strategy analysis* (7th ed.). Oxford, UK: Wiley.

Heertje, A. (2006). *Schumpeter on the economics of innovation and the development of capitalism* (edited by J. Middendorp). Cheltenham, UK: Elgar.

Hughes, T. P. (1987). The evolution of large technological systems. In: W. E. Bijker, T. P. Hughes, & T. J. Pinch (Eds.), *The social construction of technological systems: New directions in the sociology and history of technology 51–82*. Cambridge, MA: MIT Press.

IEEE. (2011). *IEEE 802.22-2011 standard for wireless regional area networks in TV whitespaces completed*, 27 July 2011. Retrieved from: 〈http://www.businesswire.com/news/home/20110726007223/en/IEEE-802.22TM-2011-Standard-Wireless-Regional-Area-Networks〉.

Metcalfe, J. S. (1994). Evolutionary economics and technology policy. *Economic Journal*, *104*(July), 931–944.

Mitola, J. (2000). *Cognitive radio: An integrated agent architecture for software defined radio*. Doctoral dissertation, Royal Institute of Technology (KTH), Stockholm.

Nemet, G. F. (2009). Demand-pull, technology-push, and government-led incentives for non-incremental technical change. *Research Policy*, *38*(5), 700–709.

Nguyen, T., Zhou, H., Berry, R. A., Honig, M. L., & Vohra, R. (2011). The impact of additional unlicensed spectrum on wireless services competition. In: *Proceedings of the IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2011)* 146–155. 〈http://ieeexplore.ieee.org/xpl/articleDetails.jsp?tp=&arnumber=5936201〉.

Pawelczak, P., Nolan, K., Doyle, L., Oh, S. W., & Cabric, D. (2011). Cognitive radio: Ten years of experimentation and development. *IEEE Communications Magazine*, *49*(3), 90–100.

Schumpeter, J. A. (1942). *Capitalism, socialism, and democracy*. London, UK: Harper.

Suarez, F. F. (2004). Battles for technological dominance: An integrative framework. *Research Policy*, *33*(2), 271–286.

Teece, D. J. (1986). Profiting from technological innovation: Implications for integration, collaboration, licensing and public policy. *Research Policy*, *15*(6), 285–305.

Webb, W. (2010). *Being mobile: Future wireless technologies and applications*. Cambridge, UK: Cambridge University Press.