ISM-Advanced: Improved Access Rules for Unlicensed Spectrum

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***Abstract*—Access to unlicensed spectrum has thus far been based on simplistic rules, such as a transmission power limitation, requirement for tolerance of interference, and a relaxed out-of-band transmission mask. Such rules originate from the rudimentary applications originally envisaged for such spectrum, which don't consider the current technical capabilities of radio devices. This paper introduces the concept of "ISM-Advanced", which incorporates Cognitive Radio capabilities into the rules for unlicensed spectrum access in ISM bands. It is argued and shown that the introduction of such capabilities can significantly improve the efficiency of spectrum usage, as well as the quality of service that is experienced by spectrum users. Moreover, constraints such as on transmission power can be relaxed under the proposed scheme, and the stability in performance of unlicensed spectrum can be improved. Among many other benefits, these characteristics facilitate use of unlicensed spectrum by quality–of–service-conscious telecommunication service entities such as cellular (LTE) operators, likely in aggregation with and supplementing their licensed spectrum.**

In view of the increased use and allocations being seen of unlicensed spectrum, it is suggested that the policies and technical rules that govern dynamic spectrum access in ISM bands be reviewed bringing them up to a level matching technical capabilities of modern radio equipment using Cognitive Radio technology.

Keywords—Radio spectrum access rules, ISM bands, Wi-Fi, Short Range Devices, Cognitive Radio

I. INTRODUCTION

This paper introduces the "ISM-Advanced" (ISM-A) concept. ISM-A proposes novel spectrum access rules for unlicensed frequency bands, based on Cognitive Radio (CR) capabilities. Importantly, ISM-A may lead to the elimination of some of the most onerous operational restrictions for access to ISM bands, most notably leading to a divergence from the requirement for a rigid Effective Isotropically Radiated Power (EIRP) limit.

The primary reference case study for application of our proposed concept may be found in ISM bands such as the 2.4 GHz. The early moves by regulators to allow general access to this band [1] by innovative wireless consumer systems led to a worldwide flourishing of wireless ecosystems, with Wi-Fi (IEEE 802.11) technology being the most notable example. Much hope is pinned on further growth of Wi-Fi and other similar technologies in this and other bands [2]; however, there are significant challenges. First of all, Wi-Fi itself is spectrally inefficient and suffers from highly erratic quality of service in congested environments. The ISM bands are treated as a free-for-all; consequently they are prone to the "tragedy of the unmanaged commons" [3], with their utility being constrained by uncontrolled overexploitation and a lack of coordination among radios.

Even though we depart from the conventional roots of ISM bands, the proposed spectrum access regulatory framework should be suitable for any other unlicensed bands, particularly newly designated ones[1]. For instance, the wireless industry is constantly pushing for designation of new bands and spectrum access opportunities for various applications jointly described as Short Range Devices (SRD). The recent European effort to re-allocate the band 870-876/915-921 MHz to SRDs illustrated the predicted future of SRD deployment densities from 5 to 50,000 per sq.km with transmit power ranging from 10 mW to 4 W and maximum Duty Cycle (DC) from 0.1% to 25% [4]. This shows that industry requires the freedom to deploy radio systems in shared unlicensed spectrum scenarios with increasingly higher powers, serving applications such as car-to-car communications (EIRP up to 500 mW), machine-to-machine smart metering (EIRP up to 1 W), and RFID applications (EIRP up to 4 W) [4].

It should be noted that wireless technology had not been standing still, and many of devices being deployed today have various technical features to allow agility and more efficient exploitation of unlicensed bands. Examples of such techniques include Frequency Hopping, Automatic Power Control, and Dynamic Frequency Selection, to name but a few. All these could be seen as precursors of CR-like operation, noting that various other developments are strongly supporting CR and related capabilities such as TV White Spaces. Indeed, the time

[1] This would be especially critical for newly-assigned bands in higher frequency ranges, where increased EIRP would help to compensate for reduction of link distances due to increasing path losses while containing the interference potential.

is ripe to make a qualitative leap and structure the rules of access to ISM and other unlicensed bands with cognition in mind. This would allow more efficient and more robust use of those invaluable commons.

The rest of this paper is structured as follows. The second section delineates the technical problems to be resolved by the new paradigm for access to unlicensed spectrum and also compares them with the state-of-the-art CR features that may be employed in the short-to-medium future. Departing from that analysis, third section outlines the proposed concept of ISM-A, including discussion of a possible innovative power control algorithm that would allow letting go of hard EIRP limit. This is backed by an initial feasibility analysis and simulations. Fourth section discusses key applications that might benefit of improved spectrum access rules. The final, fifth section summarizes the paper and outlines directions for further work.

II. PROBLEM FORMULATION AND ANALYSIS

A. Background

Today the co-existence in ISM bands, such as 2.4 GHz used for Wi-Fi and many other SRDs, relies heavily on setting a low ceiling for EIRP (in Europe limited to 100 mW for Wi-Fi in 2.4 GHz) and low DC (i.e. less than 0.1…1%) as main mitigation factors to contain interference on the local level. Both of these methods constitute severe inhibitors that dramatically limit the communication range (or link quality) and effective throughput of wireless applications in the ISM and other unlicensed bands. Such a paradigm for constructing unlicensed spectrum access rules is now decades old, therefore this paper aims to consider whether the prospect of using modern CR capabilities may allow proposing a novel way of sharing unlicensed bands with more efficiency and less limitations for deployment of innovative systems with higher bandwidth and service quality.

The original spectrum regulations that led to the development of Wi-Fi and gave it its novel socio-economic/wireless niche and unprecedented growth also result in its poor reliability and hinder its use. The emissions mask of Wi-Fi devices, channelization plan and media access approach are, for the most part, left unaddressed by regulations although some standardisation of these issues might be beneficial to improve efficient utilisation of spectrum, as is the case in many other (licensed) bands[2]. Those same regulations leading to the development of wireless systems that must unresponsively tolerate all interference, have created a situation where the spectrum and devices' utility is constrained by uncontrolled and unpredictable interference. These limitations make it questionable whether Wi-Fi, as it is presently constructed, will be able to evolve and meet the demands of small cell heterogeneous adaptive networks that are now being touted for the next generation wireless applications. Commensurate with this is the concern that the public bands, despite their growing encumbrances of highly suitable spectrum, will satisfy the expanding socio-economic expectations of a society increasingly dependent on wireless (the above quoted EC study on broadband traffic offloading [2]).

Technical or regulatory changes to Wi-Fi and the ISM bands are complicated by the necessity to maintain backward compatibility with the huge number of legacy Wi-Fi based technologies that are deployed globally. Consequently, if the Wi-Fi standard's bodies work to conform to new spectrum regulations, they will likely need to follow an evolutionary path that supports the core attributes of Wi-Fi, principally at its PHY layer, but allows modifications to its MAC attributes, augmenting them in a manner that allows implementation of functions common to intelligent networks. The challenge to new spectrum regulations and policy supporting introduction of CR technologies in ISM band evolution is that it must remain technologically neutral and not force future Wi-Fi evolutions or other wireless applications toward a specific technique. New regulations need to stimulate the standards process in a way that engages researchers in as wide a technical discussion as possible without skewing the choice of CR networking solutions or limiting options.

It may be posited that the low EIRP and DC limits represent an embodiment of barriers to innovation in the ISM and other unlicensed bands. If they might be overcome, then by itself the more liberal spectrum access paradigm for unlicensed band will unleash a wave of new uses of the band and will allow testing and validating the main premises of CR technology. Along the way, the new concept and the occasion of reviewing the overall regulatory package governing the use of subject band, would also allow addressing and resolving some of the other above described critical problems that are plaguing the efficiency of using Wi-Fi and ISM bands in general, such as:

- Optimization of PHY/MAC layers, by further improving and augmenting the CSMA/CA mechanism that has limitations due to an absence of any enforceable coordination features (e.g. the PCF method envisaged in Wi-Fi yet rarely used in reality);
- Poor Out-Of-Band (OOB) emissions limits, which limit spectrum reuse and coexistence;
- Quality of Service experienced by the user; due to uncontrolled congestion and interference;
- Energy efficiency of transceivers, due to excessive and redundant control and management signalling with a view on reducing the battery drain of portable devices.

Ideally, any solution governing the use of ISM bands should be aimed at autonomously deployed centrally uncoordinated devices, which would be more in line with spontaneous nature of commons band. However, when justified for improving overall efficiency (and thus avoiding the "tragedy of commons"), it may be reasonable to assume that some form of coordination between devices might be sometimes necessary. This means that one of the challenges that need to be addressed by the proposed concept is striking the balance between technology neutrality and some form of necessary coordination, if and when necessary.

B. The Wi-Fi legacy and path to ISM-Advanced

Some of the most pronounced performance limitations with IEEE 802.11 (Wi-Fi) WLAN devices is due to their OOB

[2] Although care should be taken in order to not make regulations too prescriptive, so as to limit the technological innovation. However the issue of technological neutrality in spectrum regulation is now well understood and applied in most recent regulatory decisions.

emission spectrum. The poor suppression of RF energy outside of the OFDM modulation bandwidth (17 MHz) results in poor adjacent channel interference rejection ratios (ACIR). Consequently, co-located Wi-Fi networks operating on adjacent channels see combined performance degradation that decreases only when there is increased physical separation between networks [5]-[7]. Wi-Fi congestion problems in one channel can affect adjacent channels, especially when inter-terminal distances are reduced. Such problems give rise to poor spectrum efficiency and spectrum re-use, and contribute to the poor performance often noted within the ISM/RLAN bands.

Part of this problem can be attributed to the current globally implemented regulations for unlicensed use of ISM/RLAN bands, which do not provide channelization plans nor stipulate in-band emission and reception requirements on devices using the bands, other than transmitted power. This lightly-regulated approach was taken when the unlicensed spectrum was underused and the number of devices was low, and low ACIR criteria were acceptable and kept at easily achieved levels; consequently ACIR as low as -1 dB for 64 QAM OFDM (54 Mbps) Wi-Fi is acceptable [8]. In comparison, recently developed industry standards for equivalent QAM modulation for licensed spectrum, such as the LTE-EUTRA, have ACIR ratios in the order of 30-44 dB and specify much sharper filtering characteristics [9], [10].

To overcome some of the Wi-Fi bandwidth limitations due to ACIR, the IEEE 802.11 standards process implemented channel bonding which effectively increases the OFDM modulation bandwidth of the Wi-Fi signal. IEEE 802.11n and 802.11ac, for example, have modulation bandwidths of 40 to 160 MHz in the 2.4 and 5.8 GHz bands. Though in theory channel bonding (combined with MIMO) significantly increases spectrum efficiency and utilization, practical deployments seem to indicate otherwise. It is noted that channel bonded Wi-Fi devices are severely impacted by interference from other Wi-Fi devices operating on a co- and adjacent channel basis; resulting in a performance anomaly where the higher rate modulation schemes become degraded by lower rate schemes [11]-[13]. To overcome this problem, requires knowledge about both desired and interfering link transmission power and distance, their channel separation, their physical rates, and use of techniques based on power control, explicit link scheduling, and resolution of hidden and exposed terminals, a problem which increases significantly with ACI and overlapping and adjacent channels [14], [15]. One significant conclusion in [15] is that the lack of orthogonal channels (in the ISM and RLAN bands) severely limits any solutions that would be based on the IEEE 802.11 Physical layer MAC protocol.

As regards channel access modes, the IEEE 802.11 standard encompasses two MAC mechanisms namely: DCF (Distributed Coordination Function) and PCF (Point Coordination Function). The DCF mechanism is the one that has been mostly deployed in all the Wi-Fi compatible devices because it is the only mechanism certified by the Wi-Fi alliance. DCF relies on the CSMA/CA mechanism which is preferred by the manufacturers due to its fully decentralized nature. However, this mechanism exhibits poor performance in highly interfered environment. Therefore, a priori, unlimited EIRP should be the last thing to do in this context. However, as we will see in the following, PCF could be the right answer for this case.

PCF is a polling mechanism. In this mechanism a coordinator initiates what is referred to as a "contention free period (CFP)" (to be distinguished from the contention period when DCF mechanism is used). The coordinator is generally an Access Point (AP). During the CFP, no collision occurs between the users served by the same AP which saves all the wasted time spent by the devices during a collision or the recover from a collision. The coordinator polls in a round robin manner all the users to send the data they buffered. Originally, PCF was intended mostly for delay sensitive traffic. A fixed period of successive CFP followed by a contention phase for background traffic is scheduled. Interestingly this approach did not attract too much attention from manufacturers and has not been extensively implemented. Some of the reasons can be due to the polling overhead [16] or the requirement that a station that has nothing to send must anyway send a null frame.

Nevertheless, the increasing amount of deployed Wi-Fi networks operating with a small number of non-overlapping channels (3) generates such a high interference environment that the using of PCF has been recently re-considered. Therefore the use of PCF should be considered as one possibility to efficiently exploit ISM spectrum. It worth to mention that even in the ad hoc mode of Wi-Fi where no AP Is deployed and which requires a distributed mechanism such as DCF, it is still possible to use PCF. Some recent works have been done to adapt PCF to a distributed environment without AP where the point coordinator is chosen among all the participants and become the master of the cluster [17].

Among the dominant challenges that differentiate wireless from wired transmission are the hidden and exposed node problems. If the use of improved RTS-CTS or other MAC layer techniques succeeds in solving most of the hidden node scenario instances, the exposed node issue remains in most of the cases unsolved (some proposed solutions require strong assumptions such as node synchronization to solve the issue or require change in the MAC protocol).

In the exposed node scenario, a node is prevented from undertaking a concurrent transmission because it senses the activity of another node, even though the concurrent transmission could have been successful, due to the fact that their respective receivers are far enough from the interfering transmitter. Due to its decentralized nature, the CSMA/CA mechanism does not allow the identification of whose concurrent transmission could take place, resulting in a decrease in the overall system capacity. The use of CR techniques such as geo-location data bases that contain information as to which station transmits at what time could not only avoid this problem but even leverage the opportunities of possible multiple concurrent transmissions.

Despite its drawbacks Wi-Fi embodies many attributes in its physical and link layer packet operation that are useful for ISM-A applications. Wi-Fi packet reception is highly tolerant of noise and link gain fluctuations allowing packets to be demodulated at low signal to noise ratios. Reception is also tolerant of frequency offset and receiver oscillator error. This supports Wi-Fi’s asynchronous burst modulation operation and allows interfering and desired packets to be received and examined for their source and destination addresses, received signal level, channel of transmission, size, length, inter-arrival time, and modulation rate, amongst other metrics. Consequently a Wi-Fi radio inherently has the ability to create a mapping of its radio interference environment and manipulate such information as a data base that can be conceivably exchanged with other terminals or stored in a manner that would allow data mining. Mapping can include geo-location coordinates to enhance its usefulness. In addition to these interference-information extraction capabilities, Wi-Fi devices often possess powerful (mostly proprietary) channel sensing capabilities that support carrier sensing in the CSMA/CA protocol. Such enhanced sensing is found in Wi-Fi radios that support coexistence with primary spectrum users, such as 5 GHz radar systems. In essence, many of the existing attributes commonly embodied within Wi-Fi will support radio cognition if they are made available to higher layer coexistence/collaboration processes. A number of proprietary versions of Wi-Fi [18]-[20] already have embedded cognitive functions, thus enhancing Wi-Fi availability by undertaking dynamic frequency access, radiation direction selection, and dynamic interference power control. However, as promising as the potentially new CR attributes of Wi-Fi are the greatest obstacle to Wi-Fi performance and IEEE 802.11 evolution remains with the CSMA/CA protocol. The simple elegance of the protocol cannot be denied, but this same simplicity forces the Media Access Control system to become encumbered with excessive inter-device signalling, mostly constituting beacons, association/de-association, authentication and probe management messages related to maintaining link integrity and security, and which occupy the bulk of Wi-Fi channel occupancy [21], [22]. A significant amount of bandwidth is also used to support the retransmission which grows exponentially with congestion [23], [24]. Over the time that the Wi-Fi standard has been in place, many attempts have been made to manipulate the CSMA/CA protocol in a variety of ways, such as adjusting contention window sizes [25]; embedding adaptive threshold channel sensing [26], [27], or instituting changes to the IEEE 802.11 standard such as the inclusion of RTS/CTS [8]. However, the benefits of these changes, such as RTS/CTS, remains questionable [28], [29], whilst proprietary changes to the protocols (outside the IEEE 802.11 standard), can further deteriorate performance [30]. Performance gains are highly dependent on the radio environment or loading conditions where measurements were undertaken. Real world testing of Wi-Fi networks [31] reveals that networks working in congested interference environments can sustain considerable throughput degradation. A typical example is shown in Fig. 1, which shows the maximum total throughput achieved by a Wi-Fi (IEEE 802.11g) hotspotnetwork consisting of 3 client terminals and an AP operating within line of sight of each other, within an urban city environment (downtown Ottawa, Canada) where several hundred interfering Wi-Fi have been detected [21] on the most congested Wi-Fi channels (channel 6).

The throughput of the network is shown to be highly dependent on its operational radius, regardless of the fact that the signal strength at all locations (-45 to -62 dBm) of the terminals was maintained at levels that would have sustained the maximum achievable (measured) throughput of ~28 Mbps (whilst operating in the 54 Mbps IEEE 802.11g modulation rate). The network was loaded using TCP/IP input streams containing variable packet lengths (64-1514 Bytes). The congested channels (channel 6 with > 200 interferers) faired considerably worse than lesser congested channels (channel 9 with < 50 interferers). What the experiment shows is that the throughput capacity of a Wi-Fi network is more dependent on the congestion and interference that it sustains than by the signal strength it operates under [32], [33].

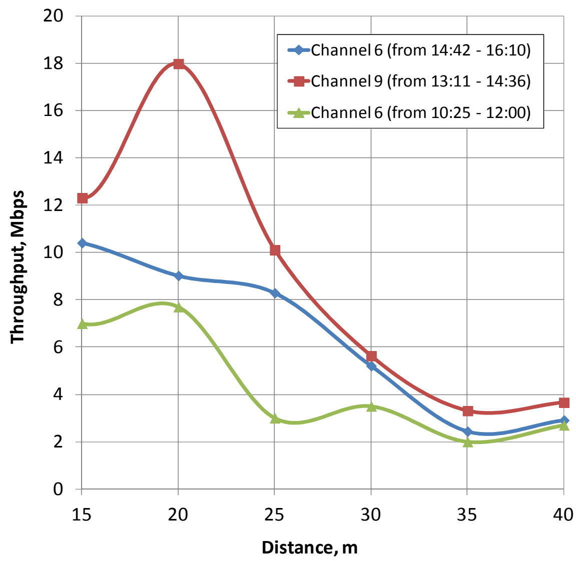

Fig. 1. Throughput of a four-node Wi-Fi IEEE802.11g network as a function of network radius (congested outdoor environment, all terminals at line of sight and RSSI always >-70 dm)

One ISM-A approach to dealing with the high overhead of signalling messages [21], [22] could involve shifting some messaging to the wireline infrastructure to mediate interactions amongst wireless devices. The majority of Wi-Fi routers acting as APs are IP addressable. Collaboration between collocated routers or interfering routers could be more reliably handled by interchanges over robust wireline IP connections than over the air. The paradigm of the IP addressable data base, common to the TVWS constructs for cognitive radio, could see replication in the ISM bands as well. The rich packet ID content of the interfering Wi-Fi packet could facilitate the creation of data bases that would be associated with a specific geographic location; covered by a group of collaborating small cells, for instance.

A move toward an ISM-A regime for Wi-Fi would need to maintain a backwards compatibility the global population of Wi-Fi devices. Cognitive Wi-Fi devices would be indiscernible from generic Wi-Fi radio and they could operate amongst themselves with better spectral efficiency and provide a better quality of service and security to their user population. The ability to operate Wi-Fi in a TDD/TDMA mode would improve its spectrum efficiency markedly [34], [35] and cannot be discounted as a possible future option. TDD has successfully been used with Wi-Fi to overcome hidden terminal problems [36], [37] and the some variants of the standard (such as IEEE 802.11e) have TDD-like access with support media intensive applications.

TDD/TDMA is supported by the WiMAX, IEEE 802.22 and the 3GPP EUTRA /LTE standards, all of which have the facility to implement such cognitive capabilities as interference coordination and spectrum sharing in collaborative networks [38]. Much groundwork in this has been undertaken in the development LTE femtocells and self-organizing networks [39]. Networks based on these standards also demonstrate high spectrum efficiencies and could arguably be implemented in the ISM bands to provide shared spectrum and coexistence amongst co-channel users. One major obstacle to doing this comes from the dominance of the CSMA/CA standard, which with its pseudo random bursty operation would make it impossible for the TDMA and channelization scheduling of LTE to operate. Such coexistence was sought at one time between the TDD-centric IEEE 802.16 systems (WiMAX) and IEEE 802.11a (and 802.11y at 3.65 GHz) systems; without a practical resolution [40] to the problems at hand. Nevertheless in the interest of technical neutrality in finding ISM-A solutions, the application of the spectrally efficient TDD/TDMA based standards should be considered. Conceivably, such systems could see application by changing regulations and dedicating some part of ISM bands (such as the RLAN bands at 5 GHz) to TDD/TDMA systems. It would be up to the standards bodies then to modify their technical standards to support coexistence and the diversified services characteristic of the unlicensed spectrum use of the ISM band. The ability of standards to reinvent themselves is well known, especially if there is the incentive of getting access to new spectrum. Good examples are the IEEE 802.11af standard or the LTE; both of which have adapted themselves to 700 MHz operation and coexistence with TV White Space devices.

C. *The latest Wi-Fi advancements*

The latest thinking of Wi-Fi industry may be visible in 802.11ac as the most recent standard in the IEEE 802.11 family. This standard is being developed with the aim of reaching Gigabit throughputs in the 5 GHz frequency band. As mentioned in previous subsections, the 802.11ac may have some inherent drawbacks due to wide 160 MHz channels, such as increased interference. But it introduced some important improvements to the RTS/CTS mechanism [41], together with improved signal detection threshold [42]. Therefore 802.11ac should be able to share spectrum much more efficiently than its predecessor 802.11n because detection of networks on non-primary channels is significantly better with 802.11ac hardware. The Channel Switch Wrapper element extends the existing channel-switch announcements by enabling a channel switch announcement frame to not only guide devices to a new channel, but also state the channel bandwidth.

Usually most of the time network won't use the full available bandwidth, so 802.11ac has the capability to clean out the needed channels if they aren't occupied at the moment. However it is a static algorithm that decides on assigning channel bandwidth, which means that at times the assigned channel bandwidth will remain at maximum, regardless of falling link throughput. Originally the 802.11n used a rather rigid version of bandwidth management; meaning that if one of the channels was marked as being occupied, the back-off mechanism would be triggered. 802.11ac improved this by enabling device to send data on the primary channel even though the secondary is occupied at the moment.

It may be concluded that 802.11ac bandwidth management clearly improves the spectrum use efficiency, however it may be suggested that its further evolution towards dynamic channel bandwidth selection based on real-time throughput requirements would enable to share spectrum even more efficiently, especially in high density hot spots with multiple APs.

D. *State-of-the-art of dynamic spectrum access in ISM bands*

The pressing nature of the above discussed problems is evidenced by the fact, that industry had been actively testing various proprietary solutions for improving the efficiency of Wi-Fi operations in the ISM band. Most of these recent technological developments show clear trend towards the CR paradigm, albeit falling short of complete realisation without a supportive regulatory framework. This subsection will review some examples of recent proprietary solutions that try tackling the challenge of dynamic access in the context of ISM band operation.

The most typical road followed by many manufacturers of Wi-Fi APs is imbuing them with certain autonomous sensing that in turn provides input for dynamic frequency selection (DFS mechanism). Typical examples of such approach include Cisco Aironet, Infinet, and Ruckus' products.

Cisco *CleanAIR* technology uses patented method of inspecting the spectrum, since standard 802.11 chipsets do not provide enough "spectrum intelligence" information. Cisco's Prime Network Control System is designed to aggregate information from multiple APs in order to build multi-faceted picture of radio environment, as illustrated in Fig. 2.

One of the key elements in such approach is the spectrum analysis hardware engine, which is integrated in a Wi-Fi chipset. This embedded core performs basic spectrum sensing, augmented with computationally-intensive high resolution FFT and pulse-detection operations. Thus obtained initial raw information is passed on to a software application, where more detailed calculations are performed for fingerprint analysis. Notably, the spectrum analysis computations are carried out by an additional dedicated processor core, so as not to impact the primary wireless transceiver's functioning. This dedicated core known as DSP Vector Accelerator, or simply DavE, performs such operations as filtering, decimation, rotation, sync-word detection and modulation detection. Finally the obtained results are pushed to the higher level where the identification of sources of interference takes place. Each interferer is assigned a pseudo-MAC, so that when multiple devices participate in sensing and detect the same interference source, it can be identified and geo-located based on triangulation method. The

Fig. 2. Monitoring various spectrum parameters in the Cisco CleanAIR Prime Network Control System [43]

main advantage of such parallel system is that spectrum monitoring is performed constantly, which allows transceiver to take immediate action in re-configuring its spectrum access mode based on radio environment changes.

Similar approach is followed by Infinet with their *iDFS* feature [44]. It uses a dedicated secondary radio to scan the environment which feeds the data to DFS functioning. The collected data includes signal levels and amount of traffic on each channel, which allows performing grading of channels according their interference potential.

Yet another example of DFS implementation may be found in Ruckus' *ChannelFly* approach [45]. Its specific feature is the use of smart antenna array, which collects radio environmental data from different directions. Importantly, the channel selection is carried out based on capacity averages across all channels. An optimal channel is selected based on the historical data. The ChannelFly mechanism is integrated into each radio and allows constant monitoring of radio environment, with collected data used to establish a trending history of the capacity and interference on every channel. Whenever the device detects degradation of performance on current channel, it instantly switches to the next optimal on the list.

There also exist more elaborate multi-functional platforms, such as the CRC *CORAL* [46], which can work as centrally managed and fully re-programmable network of Wi-Fi APs, see Fig. 3. The radio environment data is collected by network nodes, which can perform continued monitoring without interrupting data transmissions.

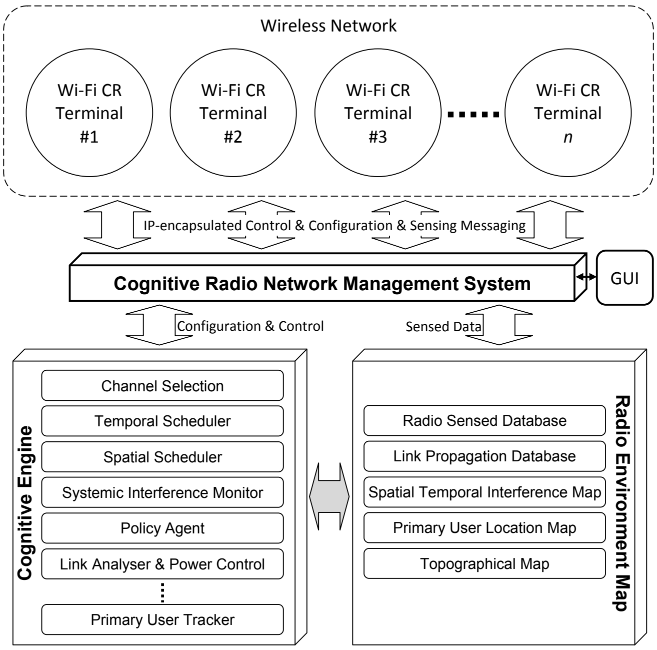

Fig 3. Structure of CRC CORAL system (adapted from [46])

The heart of CORAL is Cognitive Radio Network Management System (CRNMS), which performs all the necessary evaluation of received data both from network nodes as well as end-users. CRNMS includes such features as controlling network nodes by changing operating mode: slave/master, operating frequency, transmit power, data rate, and packet transmission schedules. The spectrum monitoring data is accumulated within Radio Environment Analysis Map (REAM) database, which allows analysing it from multiple angles in order to take a decision on most optimal spectrum access configuration.

The above examples demonstrate that industry is trying to address the inefficiencies of current ISM use and that technology that is being developed is fully capable of taking full advantage of CR modes of operation, including both local and distributed environmental sensing, extensive analysis of real-time and historic data, and instant re-configuration of radio access parameters to address the optimisation challenge.

Therefore there seem to be no obvious reasons why the regulation governing the access to ISM (and other unlicensed bands) could not be updated so that the rules correspond to current technological capabilities of modern consumer devices.

III. Building blocks of the ISM-Advanced Concept

As was discussed in the previous section, the considerations for modernising spectrum access framework for ISM bands such as 2.4 GHz band may be directed along two broad avenues:

- Revisiting the rules on general organisation of the band (i.e. channelling options), spectrum emissions (i.e. OOB limits) of devices and channel access rules (MAC);
- Instituting provisions for using CR technologies as the means for improving quality of service to users while maximising spectrum use efficiency.

Accordingly, the rest of this section will review some fundamental principles that might be considered in instituting the ISM-A regulatory framework.

A. General organisation of the band and channel access modes

As regards the first identified direction, the prime objective would be to consider stipulating more stringent OOB emission requirements, which would support the move toward channel orthogonality. Such a stipulation could be proposed with fixed channel plan, preferably one based on the de-facto 20 MHz bandwidth occupied by the vast majority of legacy Wi-Fi systems. Such a plan could propose to use the current Wi-Fi channels of 1, 5, 9 and 13, and would allow 4 orthogonal channels to fit within the 2.4-2.4835 GHz ISM band.

A related issue would be to consider a dynamic channel bandwidth allocation, based on fluctuating traffic requirements. Today most of the Wi-Fi devices operate with fixed channel bandwidth, even though most of the APs have capability to work with both 20MHz and 40MHz channels (since 802.11n stipulates such default capability in mixed mode). Therefore an adaptive channel bandwidth based on real-time throughput requirement would be an improvement in order to increase the spectrum capacity for multiple devices [41], [47]. This is supported by findings [42] proving that even though 40MHz channel bandwidth may provide the peak throughput value, the 20MHz channel bandwidth is better suited to real world environment where signal level might not be high.

The adaptive channel bandwidth selection mechanism would need evaluating such link parameters as Signal to Interference and Noise Ratio (SINR), antenna mode (SISO, MIMO modes), current RF modulation and the required throughput. If throughput requirements from the served client are not high, then AP would issue request-to-send using smallest possible channel bandwidth that is sufficient to achieve the required throughput. With such approach, the APs would always roll back to the minimum channel bandwidth without degrading link performance, or in fact possibly even improving it, thanks to higher power density (and less interference) in the narrower channels.

A group of devices with distributed sensing and adaptive channel bandwidth mechanism would be able to share the spectrum most efficiently based on their throughput requirements, thanks to the availability of better mapping of the environment. Whenever channel bandwidth adaptation would no longer provide the sufficient throughput, then the DFS mechanism would be able to kick in by choosing more optimal channel.

Another aspect is that while 802.11ac took bandwidth management to a new level with improved RTS/CTS mechanism, the airtime occupation levels are still a main issue due to dominance of management packets, which are sent between devices. By modifying the MAC layer and decreasing the amount of management packets which are sent between devices, it's possible to dedicate more airtime for traffic packets.

B. Use of CR technologies

As regards the provisions for using of CR technologies, the previous discussion showed that the DFS mechanism is already being progressively implemented by the industry and therefore does not require any additional regulatory intervention in order to promote it further. Therefore it is proposed to focus the additional consideration of potential benefits of CR on the question of EIRP limit that often significantly restricts the range and/or link quality of wireless access devices. It is reasonable to ponder whether "intelligent" devices really need to be told as to what maximum power they should adhere to. We posit that with appropriately designed rules, the CR-enabled devices should be perfectly capable of choosing most appropriate transmit power while seeking the optimum compromise between link range/quality, ambient interference level, and its own energy consumption.

Trying to model this optimisation task, we may turn to Game Theory (GT) which was shown to be a fitting companion to describe the device interaction within the domain of CR. A plethora of algorithms and protocols for optimizing channel and power allocation have been proposed [48]-[50]. All of these algorithms have in common the use of concepts and tools from two very innovative and fertile fields of CR and GT.

CR interactions are strategic interactions (in the sense defined by GT): one player's payoff depends on the other players' actions. The main particularities of ISM/RLAN operation come from the fact that the band is unlicensed, incurring uncoordinated deployment, high-density, open access, opportunistic behaviour, and, at some point, spectrum congestion. It is a dynamic environment, difficult to analyse and for which it is difficult to provide sound resource management schemes. Standard analytical models no longer cope with the increasing complexity and dynamics of nowadays communications systems. GT provides the framework in which the paradigm shift to more flexible and efficient resource sharing may eventually materialize.

Within this framework, the key problem is to design distributed resource allocation rules that lead to a Nash equilibrium that is efficient and possibly fair [48], [50]. These rules would be self-enforcing and therefore not requiring external intervention to verify compliance [50].

Note that we consider the framework of non-cooperative games, meaning that the decisions are taken autonomously by the CRs (no coalition is made for decision making purposes). Yet, non-cooperative does not mean non-collaborative; a certain amount of communication among the devices may be assumed (there are games for which this may not be necessary; ideally, if the sensing and context awareness are perfect, signalling would be minimal). From the GT perspective, what players know, in a non-cooperative game, is the game: i.e., the players, the payoff function, the set of available strategies, but they do not know in advance what actions the other players will take. GT analysis helps predict the outcome of complex interactions between CRs.

In the below analyzed power allocation game, direct communication between players is not necessary; coordination effect is obtained by adjusting the strategies of each CR as a function of the changes in the environment (i.e. function of the other players' actions).

Let us assume the resource allocation is determined as the outcome of a game; a distributed, interference-aware, power allocation game. Given a wireless network of N transmit-receive pairs (Tx_i-Rx_i), where a "pair" is referred to as a "player", let's subject it to a GT analysis where the objective is to find stable points of power allocation for each player such that the players' global utility is maximum while the cumulated power levels are kept to a minimum.

More formally, given a set of N players (or N CR Tx-Rx pairs) $N = \{1, 2, \ldots, N\}$ and their corresponding power allocation profile $P = \{p_1, p_2, \ldots, p_N\}$, the utility function of each player (Tx-Rx pair) is given by:

$$u_i = log\left(1 + \frac{h_{ii}p_i}{n_0 + \sum_{j\neq i} h_{ji}p_j}\right), \quad (1)$$

where:

p_i, p_j are the transmit powers of players i and j,
h_{ii} is the direct gain,
h_{ji} is the channel gain between transmitter j and receiver i,
n_0 is the noise power.

User i's observed SINR at the receiver side is:

$$r_i = \frac{h_{ii}p_i}{\sum_{j\neq i} h_{ji}p_j + n_0}. \quad (2)$$

The objective is to maximize the global utility function, $max \sum_i u_i$, while minimizing the globally allocated power $min \sum_i p_i$, where $p_i \in [0, P_i^{max}]$.

The convergence and stability condition may be given as [51]:

$$\left|\frac{h_{ji}}{h_{ii}}\right| < \frac{1}{N}, i = 1, \ldots, N. \quad (3)$$

This condition is a decisive factor when choosing the topology on which the power allocation game is implemented. If it is not fulfilled for all players, there will be no strategy profile that will satisfy the players.

In the theoretical case, considering (4) below, equilibrium is reached in the game when $p_i(t-1) = p_i(t)$ for all players at once,

$$b_i(p_{-i}) = \frac{1}{c_i} - \frac{\sum_{j\neq i} h_{ji}p_j + n_0}{h_{ii}} = \frac{1}{c_i} - \frac{I + n_0}{h_{ii}}, \qquad (4)$$

where:

$b_i(p_{-i})$ represents the best response of CR i given the current state of the game (the power profile for all other CRs is denoted by p_{-i}),
c_i represents CR i's energy cost,
hij are the channel gains,
pj is the transmitted power for all the other CRs, and,
n_0 is the noise.

It should be noted that the choice of the c_i parameter is critical as it sets the ultimate convergence level in the above equation. This parameter, the energy cost, is the limiting factor precluding the player to raise its power indefinitely. Its values below 1 would mean that the energy cost is little; such as e.g. may be assumed in the case of mains powered APs. On the other hand, the battery driven portable devices represent a good example of high energy costs (above 1), as excessive use of increased transmit power would lead to fast depletion of the battery.

Note that (4) will thus represent the best response for any of the players (equivalent to the Nash equilibrium condition). However in practice, where p_i can take only discrete values, an experimental, robust stopping criterion is needed in order to determine reaching of the equilibrium. A criterion may be given by comparing the difference between the last k best responses with a threshold power used to compensate for the environment dynamics, P_{th}, and k is determined experimentally as

$$|b_{i-k}(p_{-i}) - b_i(p_{-i})| < P_{th}. \qquad (5)$$

Based on the above, the following power control protocol may be proposed for most efficient utilisation of spectrum band in the envisaged ISM-A spectrum access scenario:

- Step 1: CRs initialize their transmit powers p_i^0, p_{-i}^0;
- Step 2: If CR i updates its power, it will alert the neighbouring CRs that a power change has been made. This sharing of current state may be achieved also by sensing;
- Step 3: If CR i detects a change in neighbouring CRs' powers, it updates its power according to

$$b_i(p_{-i}) = \frac{1}{c_i} - \frac{\sum_{j\neq i} h_{ji}p_j + n_0}{h_{ii}}, \qquad (6)$$

  and alerts the neighbours of its own change (or they notice it by sensing).
- Step 4: CR i checks if the Nash equilibrium condition is satisfied;
- Step 5: If the Nash equilibrium is reached, the game is stopped. The CRs maintain NE as this is a situation they have no incentive to unilaterally deviate from – it may be seen as a self-enforcing rule [50].

Simulation of the power allocation game was conducted using the above described algorithm modelled by developing a bespoke software programme [52]. Parameters used for simulation were as follows: n_0 = 10-12, c_i = 1 for all users, h_{ij} were calculated using ITU indoor propagation model P.1238 [53], number of users varied between 2 and 20 and the main result was expressed as a function of total system capacity (i.e. sum of capacities of all individual links) on number of users in the system. Transmitters, each corresponding to one user, were distributed randomly with uniform density in a 100x100m square and each was assigned a corresponding receiver, placed within a 40x40 m square around that transmitter. Each simulation was repeated 5000 times (using different randomly generated user positions) and average total capacity was derived.

The results of these simulations are presented in Fig. 4.

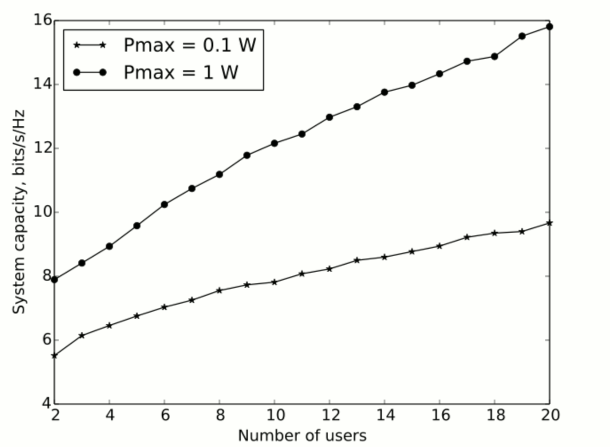

Fig. 4. Total system capacity as function of number of users in a 100x100m area. Simulation results of a distributed interference-aware power control game with the 100mW limit removed, source code available at [52]

It can be clearly seen from these results that in this scenario removing the 100 mW limit and allowing users to operate up to 1 W EIRP does have positive consequences on the overall capacity of the links sustained in a given bandwidth. This is especially striking noting the rather small scale of the simulated scenario of just 100x100 m, where the higher power would not be normally considered necessary based on purely link distance necessities. This shows that allowing higher power would lead the devices to use the additional power margin in order to increase the SINR and thus improve the quality of the link. At the same time it is shown, that given the clear rules, the system would converge and no excessive over-exploitation of power would occur.

The same scenario and the proposed algorithm were also tested in a practical ad hoc experiment in an indoor environment with several closely collocated Wi-Fi radios using the same channel in 2.4 GHz ISM band. The achievable maximum channel throughput was monitored using *pktgen* tool (UDP stream). The results of this practical test (Fig. 5), show that by applying the proposed power control algorithm with the maximum power limit increased to 30 dBm resulted in ~30% increase of aggregated channel throughput.

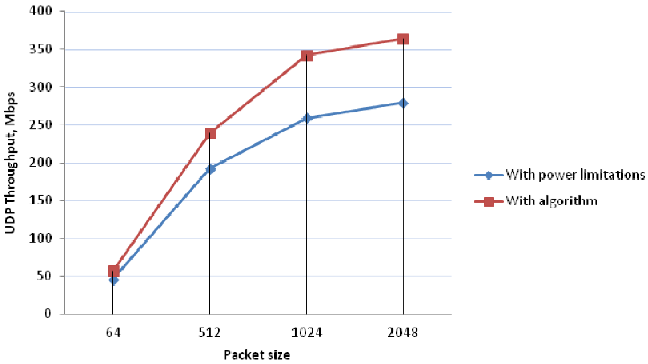

Fig. 5. Total throughput in a given Wi-Fi channel, as a sum of throughputs of all devices using that channel

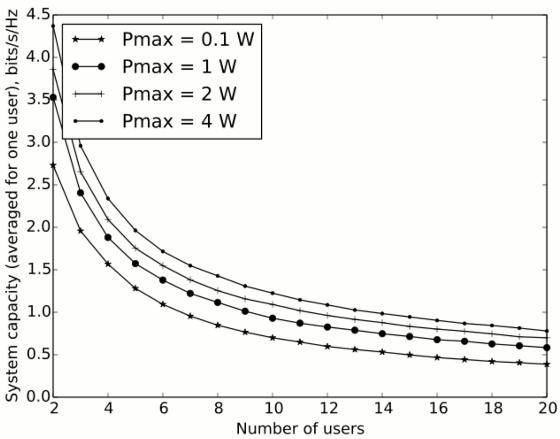

Fig. 6. Average link capacity in the simulated system as function of total number of users

On the other hand, theoretical simulations also showed that the issue of fairness in power allocation is highly relevant in today's Wi-Fi networks and would remain challenging if the power limit is lifted. This is illustrated by the results of simulations presented in Fig. 6 that shows an average capacity per user, which deteriorates proportionally with the growth of number of supported users in the band. It may be observed from Fig. 6 that the individual links would suffer of spectrum congestion regardless of the power limit. It is especially illustrative that the 100 mW EIRP limit is not really a solution to address that problem. Yet even in very congested situations having the higher power limits would allow achieving higher link capacities. Furthermore, having the devices with CR-capabilities might allow addressing the fairness more "intelligently", i.e. by appropriate adjustments to power allocation and MAC algorithms. The details of such improvements would be considered in future work.

Another possible avenue for increasing EIRP would be through the principle of "spatial containment" which may be achieved by setting the limit on transmitter output power (which indeed could be quite low) and instead requiring that any additional EIRP increase would be obtained through antenna gain, i.e. the use of more directional antennas. This would correspond well with the logic of containing any excessive interference within increasingly restricted geo-spatial beam.

In order to test this hypothesis, we carried out an analysis using SEAMCAT software tool [54]. The SEAMCAT performs Monte-Carlo simulations that allow programming various distributions of any radio link parameter. The scenario defined wanted and interfering links . Both types of links were set to work at up to 1 km distance, at random positions without any correlation.

Four antenna types were used in simulations: the current reference case was modelled by using omnidirectional antenna, whereas alternative options were modelled by assuming three types of 10 dBi directional antennas of different quality (F/B ratios). All devices (interfering and wanted) were equipped with the same antennas types and had the same EIRPs during the analysed scenario. The results of these simulations, expressed as probability of interference[3], are reported in the following Table 1.

The results show significant reduction of interference potential when an ISM/RLAN system achieves higher EIRP by using directional antennas, as opposed to omnidirectional antennas. Due to short distances between interfering and wanted links other propagation models used in calculations give similar results to the Free Space Loss model, however more detailed calculation of propagation (e.g. with Digital terrain Elevation Maps) would be expected to show further decreased probability of interference.

TABLE I. PROBABILITY OF HARMFUL INTERFERENCE FOR RLAN 5.8 GHZ LINK CALCULATED USING SEAMCAT SIMULATION TOOL

Path loss model	Probability of interference			
	Current (Note 1)	**Case A (Note 2)**	**Case B (Note 3)**	**Case C (Note 4)**
Free Space Loss	86.0%	44.2%	26.5%	15.8%
Longley-Rice [55]	81%	43.4%	26.1%	15.7%

Note 1: EIRP 30 dBm, omnidirectional antenna 0 dBi gain
Note 2: EIRP 40 dBm, directional antenna Type 1 (10 dBi gain, 66 degree of -3dB side lobe, Front-to-Back ratio -16 dB)
Note 3: EIRP 40 dBm, directional antenna Type 2 (10 dBi gain, 57 degree of -3 dB side lobe, Front-to-Back ratio -20 dB)
Note 4: EIRP 40 dBm, directional antenna Type 3 (10 dBi gain, 57 degree of -3 dB side lobe, Front-to-Back ratio -30 dB)

As an overall conclusion, it is clear that the results of simulations show that allowing increased EIRP with directional antennas can in fact decrease interference problems, including interference to legacy incumbent users of the same band. Higher gain antenna terminals would also have greater sensitivity, hence would be able to detect and coexist with lower power devices. Higher directivity/EIRP systems are used in ISM bands in many countries outside Europe and there are

[3] In SEAMCAT simulation, harmful interference event is triggered when the unwanted signal level exceeds the prescribed SINR of the wanted signal on victim link in given time instance (simulation snapshot).

no indications that they are more disruptive than EIRP-limited devices.

IV. Possible applications to benefit from ISM-Advanced framework

A. *Ad-hoc and Mesh Networking and New Paradigms for Infrastructure Mode Operation*

ISM-A would improve prospects of using Wi-Fi for ad-hoc and mesh applications. A higher EIRP will allow larger coverage areas for such networks, making them attractive for rural deployments where only a portion of the homes may have wired broadband backhaul and the capability of acting as APs or gateways. The ability for ISM-A ad-hoc devices to identify and communicate with each other and exchange location, interference, and network information would support spectrum re-use and coexistence and allow self-healing and auto-configurable relay networks to be implemented, especially if multi-band ISM-A devices are developed (i.e., having the ability to simultaneously use 2.4 and 5GHz spectrum). The higher OOB emission suppression proposed for ISM-A would support co-location of adjacent channel Wi-Fi devices on towers and buildings and would simplify the channel assignment in ISM-A terminals since they would only need to adapt around co-channel interference. The compilation and exchange of a data between databases containing channel utilization, EIRP, radiation direction, and location information could drive wireless network planning applications such as ray tracing and propagation prediction algorithms and support spectrum planning and assignment, whether done autonomously by an intelligent network or by means of human intervention. Such capabilities would be of interest to long range wireless system service providers, giving them a level of local ISM band spectrum control unattainable with current systems. Such needs stem from the recent and growing interest in Wi-Fi ad-hoc operation; a need that is so great that the Wi-Fi alliance has dedicated a specific certification called “Wi-Fi Direct” [56] for products that support these kinds of applications.

ISM-A framework would also improve Wi-Fi’s Infrastructure Mode of operation and support small cell deployment. Current commodity Wi-Fi devices have no knowledge of their interference range nor do they coordinate spectrum use over common geographic spaces, such as apartment buildings and shopping malls. By using wireline TCP/IP backhaul resources to which ISM-A Infrastructure Mode routers would have access, cross-OSI layer control and coordination between devices would be supported. Consequently clusters of ISM-A Wi-Fi devices could implement the adaptive/collaborative features detailed above for ad-hoc networks but in a much faster and more reliable manner. Information exchanges between MIMO ISM-A devices could include sharing channel state information amongst multiple users to improve orthogonalisation and interference alignment between devices, in addition to supporting channel selection, TDD/TDMA, and antenna directional control.

B. *Cellular network spectrum aggregation and cellular traffic off-loading*

Facing a continued increase in the traffic originating from smartphones and other portable devices, cellular operators are looking to alternative means to supplement their capacity and distribute traffic load. Solutions might take forms such as: (i) cellular networks’ links/capacity being combined with unlicensed spectrum through aggregation, or (ii) full data traffic (i.e., entire flows or entire data networking capability for some devices) being offloaded to links in unlicensed spectrum such as achieved through Wi-Fi standards.

Regarding the capability of aggregation of licensed spectrum with unlicensed spectrum, key movers in the cellular communications industry are advocating this, especially in recent months [57], [58]. The enhanced performance and stability of unlicensed spectrum through our proposal (e.g., ISM-A devices mitigating mutual interference effects while achieving higher total data throughput by reaching GT-enabled operational equilibrium states) greatly enhances the viability of the use of unlicensed spectrum in aggregation with licensed spectrum access.

A supplementary solution to the above, and indeed one that has been first to materialise in practice due to the ready availability of solutions, is the offloading of traffic from cellular networks to Wi-Fi hotspots or open access APs [59]. The proposed rules for ISM-A would facilitate such offloading by ensuring more reliable communication with higher effective throughputs, without creating excessive interference and over-use of the ISM band. Additionally, new public Wi-Fi services such as BT Wi-Fi© which are providing crowd-sourced wireless data connectivity in competition to cellular, could also take advantage of the intelligent networking advances proposed by ISM-A, conceivably supporting an increasing multiplicity of competing ISM band service providers using shared unlicensed spectrum.

V. Summary and future work

This paper posits that a new set of rules, termed here “ISM-Advanced”, would lead to an evolutionary improvement to Wi-Fi and expand the use of ISM bands to spectrum efficient and intelligent radio technologies.

Allowing higher EIRP levels is one of such improvements. It is shown that with intelligent radio systems and/or the use of directive antenna systems, higher EIRP scenarios can operate in a stable and controlled manner and will not exacerbate the current ISM interference environment. There is already a number of intelligent but proprietary ISM band radio technologies in operation that control interference by use of dynamic channel selection and power control, TDD/TDMA, and antenna directivity control, however their operation and evolution is hindered by absence of forward looking regulation. Unless regulations address the long standing technical deficiencies, it will be difficult to implement the advanced systems that will improve spectrum utilization and efficiency in the public bands.

On the practical side, Wi-Fi chipsets are made in such large numbers that the changes we propose should not add significantly to the cost of the wireless routers. For instance, there was no noticeable cost change for Wi-Fi devices to move from the IEEE 802.11g to the IEEE 802.11n standard. Moving to ISM-A-enabled chips would see changes no greater in magnitude than with other evolutionary changes to the IEEE standards.

Regarding future work, perhaps the most important questions we have to ask about any new ISM/unlicensed band technologies involves an examination of the stability, fairness, and wireless capacity requirements as a trade-off between user density and interference to other users of the band. This will be further analysed in our forthcoming work, aiming to show that minor adjustments to the GT algorithm could significantly improve the fairness of radio spectrum access.

It should be also noted that the proposed ISM-A concept is expected to work well also in the transitional scenarios with presence of legacy users and having only (growing) part of the nodes in the area as CR-enabled. The first step of the game is to assess the environment, i.e. to know how many players are around, what strategies they exhibit (EIRP, channel bandwidth). In that sense, legacy Wi-Fi and other ISM band users, sensed by the CR players, may be considered players with fixed strategies or the range of their strategies would be given or known. Then the CR players can accordingly compute their strategies as the best response to environment. This aspect of co-existence with legacy users of ISM bands may be addressed further with simulation of mixed nodes scenarios and real life experimenting.

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REFERENCES

[1] "Authorization of Spread Spectrum Systems Under Parts 15 and 90 of the FCC Rules and Regulations". Federal Communications Commission, USA, June 18, 1985.

[2] "*Study on Impact of traffic off-loading and related technological trends on the demand for wireless broadband spectrum*", Report for the European Commission, 2013.

[3] Hardin, Garrett. "The tragedy of the unmanaged commons." *Evolutionary perspectives on environmental problems* (2007): 105-107.

[4] *Co-existence studies for proposed SRD and RFID applications in the frequency band 870-876 MHz and 915-921 MHz*. CEPT ECC Report 200, September 2013.

[5] Nachtigall, J.;Zubow, A; Redlich,J-P "The Impact of Adjacent Channel Interference in Multi-Radio System using IEEE 802.11" International Wireless Communications and Mobile Computing Conference IWCMC 6-8 Aug 2008.

[6] Doering,M; Budzisz,L; Wilkomm,D; Wolisz, "About the practicality of using partially overlapping channels in IEEEE 802.11b/g networks" Proc. of IEEE International Conference on Communications (ICC), pp. 3703–3707, June, 2013.

[7] Hills, A " Large Scale Wireless LAN Design" IEEE Communications Magazine November 2001, Page 98-103.

[8] Institute of Electrical and Electronic Engineering (IEEE) Standard: Part 11, Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: High-Speed Physical Layer in the 5 GHz Band IEEE 802.11a. 1999.

[9] ETSI TS 136 101 V10.3.0 (2011-06) Technical Specification " Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE)radio transmissin and Reception(3GPP TS 36.101 V 10.3.0 Release 10. Section 7.5 Adjacent Channel Selectivity.

[10] Ng,M.H;Lin S.D; Li,J.;Tatesh,S. " Coexistence Studies for 3 GPP LTE with Other Mobile Systems" Communications Magazine Vol 47, Issue 4, April 2009, pp. 60-65.

[11] Shrivastava,V;Rayanchu.s;Yoon,J;Banerjee,S. "802.11n Under the Microscope" IMC 2008 Proceedings of the 8th ACM SIGCOMM conference on Internet Measurement Pages 105-110 Oct 20-22, 2008.

[12] Texas Instrument White Paper SPLY0033- Sept 2003 "WLAN channel bonding: Causing Greater Problems Than It Solves" Sep 2003.

[13] Fiehe,S;Riihijarvi,J;Mahonen,P "Experimental Study on Performance of IEEE 802.11n and Impact of Interferers on the 2.4 GHz ISM Band" IWCMC '10, June 28- July 2, 2010.

[14] Deek,L;Garcia-Villegas,E;Belding,E;Lee,SJ;Almeroth,K; "The Impact of Channel Bonding on 802.11n Network Management" CoNEXT'11 Proceedings of the Seventh Conference on emerging Networking Experiments and Technologies, Article No.11 6-9 Dec 2011.

[15] Zubow,A;Sombrutzki,R "Reinvestigating Channel Orthogonality- Adjacent Channel Interference in 802.11N Networks" Humbolt University Technical Report SAR-TR-2011-14 Sept 2011.

[16] Kuan-Hung Chou; Woei Lin, "Performance Analysis of Packet Aggregation for IEEE 802.11 PCF MAC-Based Wireless Networks," *Wireless Communications, IEEE Transactions on*, vol.12, no.4, pp.1441-1447, April 2013.

[17] J. Alonso-Zárate, C. Crespo, Ch. Skianis, L. Alonso, Ch. Verikoukis, Distributed point coordination function for IEEE 802.11 wireless ad hoc networks, *Ad Hoc Networks*, Volume 10, Issue 3, May 2012, pp. 536-551.

[18] " Dynamic Channel Selection and IEEE 802.11h Transmit Power Control" Cisco IOS Software Releases 12.4.

[19] Rukus Networks White Paper: "Getting the Best Wi-Fi Performance Possible through Both Beamforming and Adaptive Antennas" 2013 Rukus Networks.

[20] "Configuring Radio Resource Management-Chapter 12" Cisco Wirless LAN Controller Configuration Guide Rls. 7.0OL-21524-1.

[21] Hanna,S; Sydor,J "Distributed sensing of Spectrum Occupancy and Interference in Outdoor 2.4 GHz Wi-Fi networks" Proceedings of the Global Communications Conference 2012, 3-7 Dec 2012.

[22] Van Bloem,J; Schiphorst,R "Measuring the service level in the 2.4 GHz ISM Band" University of Twente, Report SAS2011-017 October 2011.

[23] Nguyen, V.N, N; Guerin-Lassous,I;Moraru,V "Retransmission-Based Available Bandwidth Estimation in IEEE 802.11-based Multihop Wireless Networks" Proceedings of the 14th International Workshop on Modelling Analysis and Simulatin of Wireless andMobile Systems 2011, pp. 377-384.

[24] Zhang,J;Shen,H;Tan,K;Chandr,R;Zhang,y;Zhang,Q"Frame Retransmissions Considered Harmful: Improving Spectrum Efficiency using Micro-Acks" Mobicom 2012, 22-26 August 2012.

[25] Bianchi, G "Performance Analysis of the IEEE 802.11 Distributed Coordination Function" IEEE Journal on Selected Areas in Communications Vol 18 No.3. March 2000.

[26] Haghani,E; Krishnan,M; Zakhor, A "Adaptive Carrier Sensing for Throughput Improvement in IEEE 802.11 Networks" Proceedings of the IEEE Globecom 2010 6-10 Dec 2010, pp. 1-6.

[27] Shen,Q; Fang,X; Huang,R; Li,P; Fang,Y "Improving Throughput by tuning carrier sensing in 802.11 wireless networks" Journal Computer Communications Volume 32 Issue 11, July 2009, pp. 1263-1270.

[28] Bruno,R; Conti,M; Gregori, E "IEEE 802.11 Optimal Performances: RTS/CTS mechanism vs Basic Access" Proceeding of the 13th PIMRC 2002, Sept 2002.

[29] Chatzimisios,P; Boucouvalas, A; Vitsas,V "Effectiveness of RTS/CTS handshake in 802.11a Wireless LANs" IEE 2004 Electronics Letters Online No. 20040510, 12 March 2004.

[30] Tinnirello,I; Giustiniano,D; Scalia,L, Bianchi,G "On the side-effects of proprietary solutions for fading and interference mitigation in IEEE 802.11b/g outdoor links" Computer Networks Volume 53, Issue 2 13 Feb 2009, pp. 141-152.

[31] Jardosh,A; Ramachandran,K; Almeroth,K; Belding-Royer,E "Understanding Congestion in IEEE 802.11b Wireless Networks" Proceedings of the 5th SIGCOMM conference on Internet Measurement IMC 2005.

[32] Kemerlis,V;Stefanis,E;Xylomenos,G;Polyzos,G"Throughput Unfairness in TCP over WiFi" Third Annual Conference on Wireless On-demand Network Systems and Services (2006), 26-31.

[33] Acharya,P;Sharma,A; Belding,E;Almeroth,K;Papagiannaki,K "Congestion-Aware Rate Adaptationin Wireless Networks: A measurement Driven Approach" Proceedings of the 5th Annual SECON'08 Conference, 16-20 June 2008.

[34] Omiyi,P ; Haas,H "Maximising spectral efficiency in 4th generation OFDM/TDMA TDD hybrid cellular mobile/ad-hoc wireless communications" Proceedings of the 59thIEEEVTC 2004, 17-19 May 2004.

[35] Djukic,P; Mohaptra,P "Soft-TDMAC: A software TDMA-based MAC over Commodity 802.11 hardware" Proceedings of Infocom 2009, pp. 1836-1844.

[36] Raman, B; Chebrolu,K " Experiences in using WiFi for Rural Internet in India".

[37] Debmalya, P; Bhaskaran, R "TDMA Scheduling in Long-Distance WiFi Networks" 26th Annual Conference on Computer Communications, IEEE INFOCOM 2009 Mini-Conference, April 2009.

[38] Andrews,M; Capdevielle,V; Feki,A;Gupta,P "Autonomous Spectrum Sharing for Mixed LTE Femto and Macro Cells Deployments" Infocom IEEE Conference on Computer Communications Workshops,2010, 15-19 March 2010.

[39] Lopez-Perez,D; de la Roche,G "Self Organization and Interfernce Avoidance in LTE Femtocells", in "Small Cell Networks", Cambridge Press, 2013, pp. 383-411.

[40] Berlemann,L;Hoymann,C;Hiertz,G;Walke,B "Unlicenced Operatin of IEEE 802.16: Coexistene with 802.11a in Shared Frequency Bands. Proceedings of the 17th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications 2006.

[41] Chandra, R., Mahajan, R., Moscibroda, T., Raghavendra, R., & Bahl, P. A case for adapting channel width in wireless networks. In *ACM SIGCOMM computer communication review* (Vol. 38, No. 4, pp. 135-146). ACM, August 2008.

[42] Gast, Matthew. *802.11 ac: A Survival Guide*. O'Reilly Media, 2013.

[43] Cisco. CleanAir Technology product specifications. Available online.

[44] Why InfiNet? Product description. Available online.

[45] Ruckus. ChannelFly — Predictive Capacity Management for Smarter RF Channel Selection. Available online.

[46] Communications Research Centre of Canada. Cognitive Radio Learning Platform (CORAL). User Manual v1.2.

[47] Pediaditaki, S., Marina, M. K., & Tyrode, D. *Traffic-aware channel width adaptation in long-distance 802.11 mesh networks*. In Proceedings of the 15th ACM international conference on Modeling, analysis and simulation of wireless and mobile systems (pp. 261-270). ACM, October 2012.

[48] B. Wang, Y. Wu, K. J. R. Liu, "Game theory for cognitive radio networks: an overview", *Computer Networks, The Int. J. of Computer and Telecommunications Networking*, vol. 54, no. 14, pp.2537-2561, 2010.

[49] E. V. Belmega, B. Djeumou, and S. Lasaulce, "Power allocation games in interference relay channels: Existence analysis of nash equilibria," *EURASIP Journal on Wireless Communications and Networking*, 2010.

[50] R. Etkin, A. Parekh, D. Tse, "Spectrum sharing for unlicensed bands", *IEEE J. Select. Areas Comm.*, vol. 25, 2007, pp.517-528.

[51] G. Fang et al., "*Distributed Inter-Network Interference Coordination for WBANs*", Proc. IEEE Globecom 2010.

[52] Python language programme used for simulation of power control game. Available online in the document download area at COST Action IC0905 TERRA (COST-TERRA) website.

[53] *Propagation data and prediction methods for the planning of indoor radio communication systems and the radio local area networks in the frequency range 900 MHz to 100 GHz*, ITU-R Recommendation P.1238, ITU, Geneva, 2001.

[54] *Spectrum Engineering Advanced Monte-Carlo Analysis Tool (SEAMCAT)*.

[55] Więcek D., Wypiór D.: New SEAMCAT Propagation Models: Irregular Terrain Model and ITU-R P. 1546-4, *Journal of Telecommunications and Information Technology (JTIT)* - 3/2011, pp. 131-140.

[56] *Wi-Fi Direct*. Available online.

[57] Qualcomm, "1000x More Spectrum Especially for Small Cells," Presentation, Nov. 2013.

[58] Qualcomm, "Extending the Benefits of LTE Advanced to Unlicensed Spectrum," Presentation, Nov. 2013.

[59] S. Dimatteo, P. Hui, B. Han and V. O. K. Li, "*Cellular traffic offloading through Wi-Fi networks*," in Proc. of the IEEE 8th International Conference on Mobile Ad-Hoc and Sensor Systems (MASS), Valencia, Spain, October 17-22, 2011, pp. 192-201.