A Letter from the Editors

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I. Introduction

The purpose of this opinion piece is to set the context for the call for papers for this special issue of the Physical Communications Journal on Cognitive Radio for LTE Advanced and Beyond.

The field of cognitive radio has grown significantly in the past number of years. It is arguable that *most* scenarios under investigation represent the cognitive radio as a secondary user that dynamically accesses available spectrum in an unlicensed manner when that spectrum is unoccupied by a primary user. While this approach has led to great advances in the field and much has been learned, it has resulted in a tight coupling of cognitive radio with dynamic spectrum access and unlicensed use of spectrum. We believe that this has contributed to the term cognitive radio being interpreted in an overly narrow fashion in the wider community. Hence the purpose of this special issue is to explore the potential of cognitive radio in the context of future generations of LTE communication systems in an attempt to cast the net a bit wider. With this in mind we speculate about *LTE Advanced and beyond*, speculate about the role for cognitive radio and invite authors to respond with relevant research material.

We ask therefore that authors submitting to this special issue of Physical Communications, to situate their work within the discussion that follows. We will reproduce a version of what is in this document in the special issue. We seek submissions that explore cognitive radio for LTE Advanced and beyond. We encourage authors to submit new work or to recast existing work in novel ways that are applicable to this space. And indeed we encourage submissions that contradict the opinions expressed here.

Note we do not reference specific pieces of work so as not to bias the special issue in any one direction. Hence the papers referenced in this commentary are survey papers.

II. A Brief Reminder & Some Other Thoughts

LTE stands for long term evolution. It is also sometimes referred to as 4G to indicate that it is the successor to current 3G systems. LTE comprises an all-IP architecture unlike the mixed circuit and packet switched cellular network solutions of today. LTE aims to provide high data rates and low latency and it promises support for VOIP and real-time applications. The radio access technology in LTE is orthogonal frequency division multiple access (OFDMA) in the downlink and single carrier frequency division multiple access (SC-FDMA) in the uplink. LTE supports scalable carrier bandwidths (from 1.4 MHz to 20 MHz) and supports both frequency division duplexing (FDD) and time division duplexing (TDD) systems. Multiple antenna technologies are catered for. Multiple antenna technologies, including transmit diversity, beamforming, spatial multiplexing, and multi-user MIMO, play a crucial role to attain the performance, data rates and cell capacity offered by LTE.

Though LTE is just beginning to materialise, next generations of LTE are already well under way. LTE Advanced or LTE+ are the terms used when referring to the next version of LTE. LTE Advanced refers specifically to Release 10 of the LTE standard. LTE Advanced is in fact a 3GPP candidate technology for IMT-Advanced.[1] IMT-Advanced is the term used by ITU for radio-access technologies beyond IMT-2000.

LTE Advanced offers more of everything. It offers greater bandwidths by supporting what is known as carrier aggregation. Carrier aggregation is the process of combining different chunks of spectrum to increase effective

[1] In reality LTE Advanced goes beyond IMT-Advanced in that it promises greater bandwidths- (100 MHz rather than 40 MHz) greater peak spectral efficiency - (30 bps/Hz (DL) / 15 bps/Hz (UL) as distinct from 15 bps/Hz (DL) / 6.75 bps/Hz (UL))and greater system efficiencies etc.

system bandwidth. It offers more MIMO. MIMO will be advanced to include more layers and to allow multiple entities to cooperate. It offers greater coverage/capacity through supporting the coexistence of low and high powered access nodes often referred or in the terminology of LTE Advanced through supporting heterogeneous networks (HetNets). It offers greater range through supporting relay facilities.

While LTE Advanced will introduce these features (i.e. carrier aggregation, advanced MIMO, HetNet and relay support etc.) they will not all be fully exploited in Release 10. For example carrier aggregation can be inter- or intra-band and both flavours will not be supported on all links initially. Hence in the first instance *beyond LTE advanced* might include the fully fleshing out of the features introduced in Release 10. Having said that there is much to be decided and the time is right for considering what more may feature in *beyond LTE Advanced*.

We see the world beyond LTE Advanced as being a world of self-planning, self-monitoring and self-regulating networks and significantly reduced emphasis on any manual intervention. These are the kinds of capabilities that can really leverage and exploit the types of features that are emerging in the LTE standard. In addition we see opportunities for new models of ownership of resources as combinations and bundles of spectrum, equipment, processing, storage and energy resources get allocated and re-allocated in line with emerging needs and trends. The levels of awareness (e.g. about the environment, user preferences, network conditions etc.) that will be needed, the kinds of support for dynamic decision-making that will be necessary, the degrees of reconfigurability that will be called for and the potential for deploying learning all point towards cognitive radio technologies.

In addition, in our opinion much of what is beyond LTE Advanced will be linked to the creation of a complete service and technology neutral world. The use of any block of spectrum is governed by a set of technical restrictions that are in place to ensure that different communication systems can co-exist. Traditionally the restrictions have been formulated on the basis of knowing which technologies are operating in which bands - i.e. knowing what types of technologies are spectral neighbours and defining rules that are tightly coupled to these technologies. In a service and technology neutral world technical conditions for use will have to be formulated in a way that does not link those restrictions to specific technologies. We see the developments in LTE speeding up the need for this approach. The demand for LTE spectrum is already growing. And relevant spectrum is becoming available at different times and in different locations around the world rather than in a coordinated manner. Hence LTE systems will increasingly use differing bands and increasingly become neighbours of very different systems (even more so in the case of non-contiguous blocks of LTE spectrum). Technology and service neutral usage rights which promote *harmonization of usage approaches* (rather than what we currently have which is a harmonisation of use) for the LTE systems themselves as well as for other spectral blocks makes sense. And in our opinion cognitive radio also has a role to play in this wider context.

III. The Potential for Cognitive Radio

To ground the discussion of how cognitive radio can contribute to LTE Advanced and beyond, we now return to the features that are earmarked already for LTE Advanced. Hence in the remainder of this document we look at carrier aggregation, advanced MIMO techniques, support for HetNets and relaying and briefly explore the potential for cognitive radio. Cognitive radio has the potential to both provide solutions to overcome challenges or to improve the efficiency/effectiveness of existing techniques.

A. Cognitive Radio & Carrier Aggregation

Carrier aggregation is the process of combining different chunks of spectrum to increase effective system bandwidth. Carrier aggregation facilitates the IMT-Advanced objective of achieving 100MHz bandwidths between basetstations (eNBs in LTE speak) and mobile uses (UEs in LTE speak) by accommodating the dispersed nature of the availability of spectrum either dedicated to, or open to, IMT-Advanced systems around the globe. LTE Advanced supports carrier aggregation between both contiguous and non-contiguous carriers within a band. Non contiguous carrier aggregation involves combining chunks of spectrum that are not neighbouring each other. Offering much more potential, aggregation can also occur between carriers in different bands, e.g. perhaps a carrier at 800MHz and a carrier at 1800Mhz could be aggregated in the spectrum was available. The carriers, an individual carrier being called a component carrier, may be of different bandwidths to offer the greatest flexibility to the mobile network operators. Aggregated carriers do not have to be the same size. Supporting component carrier bandwidths ranging from 1.4MHz to 20MHz, with a maximum aggregation of 5 component carriers, an individual LTE Advanced system can potentially aggregate up to 100MHz over a range of bands.

The task of carrier aggregation is a task that is very at home in the cognitive radio world. The manipulation of OFDM waveforms to fill an available bandwidth, the shaping of the out-of-band emissions so as not to detrimentally affect spectrally neighbour systems are all techniques that seem relevant. In the following paragraphs we highlight a few other challenges that might suit a cognitive approach.

1) Advanced Carrier Aggregation Scenarios: Though carrier aggregation will be supported by the basic LTE Advanced specifications, the actual implementations will be strongly constrained. There will only be a limited number of aggregation scenarios considered. Cognitive radio can play a strong role in pushing the limits. For example more complex scenarios involving inter-band aggregation will call for many advances. Inter-band aggregation poses challenges if the component carriers operate on widely different bands; carriers using differing antennas, operating on very different bands will exhibit vastly different PHY characteristics. When mobile end users are considered, the varying effects of Doppler frequency shift on each carrier at low and high frequencies must also be accounted for. These characteristics are unlikely to be homogeneous for a given network operator, let alone for competing LTE system operators. There are the physical challenges of designing radios that suit such widely different modes of operations or designing systems with appropriate multiple RF frontends. Some of the associated challenges are already challenges of the cognitive radio world in which radios are destined for multiple usage scenarios. There are dynamic resource management problem - i.e. how to make best use of spectral resources with different attributes in different conditions.

Dynamic resource management is part and parcel of cognitive radio. If we turn to the knobs and meters terminology often used to describe a cognitive radio, LTE Advanced and beyond scenarios can be seen as introducing an increased number of knobs that can be set in a complex resource allocation problem. In addition different available LTE bands will have different neighbours. Hence inter-operator adjacent channel interference will be a more challenging prospect that it has been heretofore. Unlike current UMTS/GSM networks which are all planned according to similar macro/micro cell topologies in well-planned frequency assignments, future deployment scenarios may see basestations for distant frequency bands independently located, resulting in many more points where one component carrier experiences hole-punching in its coverage as a result of adjacent channel interference from another operator's carriers. Therefore there may be a need to accommodate dynamic adjacent channel interference mitigation and employ more sophisticated spectrum sculpting techniques, both in the co-channel and adjacent channel domains. It may even be the case that while LTE is an OFDM-based technology more advanced multi-carrier waveforms may be needed.

Consequently, the complexities and opportunities that arise as a result advanced carrier aggregation will require that more sophisticated PHY and MAC resource management techniques be developed. It is an open question as to how the PHY and MAC will manage an aggregated bandwidth, components of which may be in diverse bands. Currently, it is suggested that blocks of transmitted data could be aggregated either at the PHY or at the MAC. In the first case, aggregated component carriers are treated as a single PHY interface controlled by a single MAC; as such the control of each carrier component must be synchronised so that the multiple carriers appear as one to the MAC. This approach poses challenges if the component carriers operate on widely different bands; as noted above, carriers using differing antennas, operating on very different bands will exhibit vastly different PHY characteristics. When mobile UEs are considered, the varying effects of Doppler frequency shift on each carrier at low and high frequencies must also be accounted for. The other option, a MAC aggregation scheme, would allow an LTE Advanced system to treat each component carrier, or a subset of carrier components, as individual PHYs, each with their own controlling MAC. In this approach each component carrier is individually configured, i.e. the power, modulation, coding and antenna configuration for each carrier is set for each separate carrier PHY, and an individual MAC HARQ handles each PHY. This approach has the advantage of enabling more flexible control of data transmission on both the UL and DL, but at the expense of introducing extra control channels.

B. Cognitive Radio & MIMO

In LTE and LTE Advanced networks, application of MIMO technologies plays an essential role to meet the requirements for bit-error performance, peak data rates, number of users per cell, and cell-edge user throughput [3], [4], [5], [6]. Both single-user (SU) and multi-user (MU) MIMO techniques are applicable in LTE and LTE Advanced. Key MIMO downlink (DL) techniques and overall MIMO capabilities in the downlink and uplink (UL) are listed in Tables I and II [6], respectively. In LTE, downlink single-user MIMO techniques incorporate transmit

TABLE I
KEY MIMO DOWNLINK TECHNIQUES IN LTE AND LTE ADVANCED [6]

Key MIMO downlink techniques	**LTE**	**LTE Advanced**
SU-MIMO - Open-loop transmit diversity	SFBC, SFBC+FSTD	Inherited from LTE
SU-MIMO - Open-loop spatial multiplexing	Multiple codewords with large delay CDD	Inherited from LTE
SU-MIMO - Closed-loop spatial multiplexing	Codebook-based precoding, UE specific RS based beamforming	Advanced beamforming and precoding (under development)
MU-MIMO	Closed-loop MU-MIMO	Closed-loop MU-MIMO (under development)

TABLE II
MIMO CAPABILITIES IN LTE AND LTE ADVANCED [6]

MIMO Capabilities		**LTE**		**LTE Advanced**
		Release 8	**Release 9**	**Release 10**
DL	SU-MIMO	Up to 4 streams	Up to 4 streams	Up to 8 streams
	MU-MIMO	Up to 2 users (unitary precoding)	Up to 4 users (nonunitary precoding)	Under development
UL	SU-MIMO	1 stream	1 stream	Up to 4 streams
	MU-MIMO	Up to 8 users	Up to 8 users	Under development

diversity, spatial multiplexing, and beamforming which is considered as a special case of spatial multiplexing. LTE Advanced is backward compatible with these features and also supports the closed-loop spatial multiplexing of more streams per end user as well as more advanced beamforming. For the uplink, spatial multiplexing of 4 streams is also applicable in LTE Advanced, whereas only a single stream per UE is allowed in LTE. In addition to downlink/uplink multi-user MIMO features in LTE, more sophisticated downlink/uplink multi-user MIMO techniques will be supported by LTE Advanced. CoMP is another candidate technique in LTE Advanced, which is based on a multi-cell MIMO strategy and aims to improve the average cell throughput and the cell-edge user throughput.

Although these techniques are based on a well-established theoretical background, there are many issues while going from theory to practice, in both implementation and system levels. In addition to RF hardware issues, it is important to take into account the increase in computational complexity due to extra signal processing load and the need for efficiency while using MIMO resources. We suggest cognitive radio techniques can be deployed to address the issues that arise and the following paragraphs contain some examples of where cognitive radio might help.

1) Efficient Scheduling: Because of the backward compatibility requirement, an LTE Advanced base station will schedule radio resources to both LTE and LTE Advanced users, which have different downlink and uplink SU-MIMO and MU-MIMO capabilities. In this heterogeneous environment, introducing clever scheduling algorithms to select the users, MIMO techniques, and the data rates for each user will improve the utilization of available resource blocks and antennas for both downlink and uplink. Application scenarios become even more interesting if the carrier aggregation in LTE Advanced and low path loss in UHF frequencies are also taken into account. Cognitive decision making, which takes into account the dynamic activity of LTE and LTE Advanced users with different MIMO capabilities and the quality of MIMO communication links, will result in more effective user selection and better allocation of radio resources. Due to real-time processing limitations, suboptimal but low-complexity scheduling algorithms also have potential promise.

2) Reconfigurable radio chain: It is possible to have a set of signal processing algorithms with different computational complexity, where more complex ones are used when really needed. For example, uplink MU-MIMO transmissions require the use of more advanced algorithms at the base station receiver, to separate UE signals. Based on the received signal quality and the number of users, base station can make a decision to either replace the algorithm in use or modify the parameters of the existing algorithm (for instance, number of iterations in a turbo receiver can be dynamically reconfigured). This will result in better use of the computational resources and improve the energy efficiency. The use of flexible system architectures already introduced for cognitive radio will be beneficial for efficient MIMO signal processing in LTE and LTE Advanced.

3) Facilitating CoMP transmissions: In the downlink, CoMP implies [7] (A) coordinated scheduling and/or beamforming, where one of the base stations is selected to transmit the data to a single UE and the scheduling decisions are coordinated by multiple cells to control interference and (B) Joint processing/transmission (CoMP-JP), which is the coherent or non-coherent data transmission to a single UE simultaneously from multiple base stations, to improve the received signal quality and/or cancel interference to the other UEs. For the uplink, CoMP implies the UE signal reception by multiple base stations and applying relevant signal processing at the receiver side.

Cognitive functionality can be advantageous in the self-coordination of neighbouring base stations to employ CoMP transmissions. For instance, in case of small cell networks, neighbouring base stations can exploit unoccupied UHF frequencies (which have good propagation characteristics), to establish robust wireless links with each other and share control information. This approach can ease the need for a high-speed backhaul, especially to apply coherent CoMP-JS. Establishing and maintaining a robust wireless backhaul in any frequency band is very much in the scope of cognitive radio research.

4) Learning from traffic and user behaviour: Base station can learn from time-varying traffic and user properties, and part of the antennas and relevant RF hardware can be turned off in certain times of the day when they are not needed. In this way, energy efficiency can be improved. Learning, as a core idea in cognitive radio and one of the main steps of the cognitive cycle, can be applied over a certain period of time to identify the potential patterns related to the use of MIMO resources. Then this information can be exploited to improve efficiency, as mentioned above.

C. Cognitive Radio & HetNets & Relay Support

The term heterogeneous wireless networks has, until recently, evoked the idea of coexistence between distinct but complementary wireless technologies, such as a smart phone seamlessly transitioning between WiFi and 3G coverage. In LTE, the term heterogeneous networks, or HetNets, refers to the coexistence between access nodes with different RF characteristics and coverage area, potentially operating over the same set of frequency bands and using the same technology. This means that macro and pico-cells using dedicated lines for backhaul and open to all subscribers may coexist with femtocells deployed by individuals, the latter employing home-use broadband access technologies for the backhaul and having more restricted association policies. Providers can also deploy relay nodes to support multi-hop communications and extend the coverage area.

HetNets are meant to address the expected explosion in demand for high data rate services and consequent need for substantially higher spectral efficiency. They also present new challenges that seem tailor-made for the capabilities of cognitive radios. We next highlight a few of those opportunities and associated challenges.

1) Intercell interference coordination: Home-evolved node B (H(e)NB) devices will result in higher quality of experience for users through improved indoor coverage. Providers may also adopt pricing policies that offer a discount in subscription charges for those users willing to open their femtocells for public access. However, the unplanned deployment of femtocells by end users will result in complex interference scenarios that cannot be addressed by traditional frequency planning that cellular operators are used to. They will require frequency agility, complex power control, and dynamic channel selection. The use of cognitive radio technology in H(e)NBs will allow these femtocells to perform the adaptations required and to negotiate with macro cells the allocation of downlink and uplink air interface resources among bearers to meet quality of service goals. A solution to the intercell interference coordination issue can build on recent work on spectrum sharing, and a shift from interference avoidance to interference tolerance may make the coexistence among cells of difference sizes more effective.

2) Adaptation by mobile devices participating in a HetNet: We envision that, in a HetNet scenario, the mobile device will also be a cognitive radio, capable of making complex association decisions and taking advantage of available relays. Our view is that the cognitive radio is a device that can make smart decisions based on their observations of network conditions, not restricted to spectrum decisions and coexistence between primary and secondary users. It is known that if the decision of which base station to associate with is made primarily according to received signal strength, this will limit the effectiveness of small cell deployment s - mobiles would associate overwhelmingly with high power macro-cell base stations [9]. The decision of whether to associate with a macro-, pico-, or femto-cell may depend on current mobility patterns, current applications active, current load on the server base station, backhaul bandwidth, and others. Mobile devices can take advantage of machine learning techniques to predict the state of the environment and navigate a complex decision parameter space.

3) Dynamic spectrum access and relay links: The current relay architecture for LTE version 10 envisions different types of relays, according to whether they generate their own control messages, have their own cell IDs, and share the same bands for access and control links [Loa10]. An access link initiates or terminates at a subscriber station, while a relay link is established between a relay and a base station or between two relays. Relay and access links can operate over the same band or in different bands. We can envision the possibility of a relay link sharing spectrum as a secondary user (say, using TV white spaces), while access links are kept on licensed spectrum already held by operators. Frequency planning for access and relay links and the possible role of dynamic spectrum access have been largely unexplored in the literature.

4) Topology control: The availability of relays enables the creation of complex tree topologies, and we envision the relays and base stations for cells of various sizes collaborating in distributed power control and channel selection to arrive at topologies that meet coverage and interference goals. The current literature on topology control and channel assignment for cognitive networks, so far focusing more on mobile ad-hoc networks than on HetNets, may provide a starting point for an investigation of dynamic topologies through the use of relays and small and large cells. In this special issue, we hope to include work that leverages the capabilities of cognitive radios to realize complex heterogeneous networks envisioned in LTE Advanced. References

IV. Summary Comments

As mentioned at the outset of this letter, the purpose of this opinion piece is to set the context for the call for papers for this special issue of the Physical Communications Journal on *Cognitive Radio for LTE Advanced and Beyond*. Having said that the topics mentioned in this letter just scrape the surface and are not intended to be a complete set of challenges or intended to restrict the submissions to what is addressed here. It is likely that there are other topics within the broad space of *LTE Advanced and Beyond* that are of importance to the cognitive radio field. It is also possible that some of the challenges touched on here are best solved without the use of cognitive technologies. The purpose of the discussion is to seed further discussion, comment and research. And as mentioned already we encourage submissions that contradict the opinions expressed here or that draw attention to key areas that we have neglected in our discussions.

We ask interested authors to take up the discussion through submitting work on research topics that address any of the issues mentioned here or indeed any issues we have ignored. Where appropriate we ask that authors might refer to some of the discussions here in the the introductory sections of their papers. We encourage authors to submit new work or to recast existing work in novel ways that are applicable to this space. This approach is experimental. We await to see how this works.

REFERENCES

[1] Iwamura, M.; Etemad, K.; Mo-Han Fong; Nory, R.; Love, R.; NTT DOCOMO, INC. Carrier aggregation framework in 3GPP LTE-advanced [WiMAX/LTE Update] Communications Magazine, IEEE, August 2010, volume: 48 Issue:8 pp60 - 67.

[2] Loa, K.; Chih-Chiang Wu; Shiann-Tsong Sheu; Yifei Yuan; Chion, M.; Huo, D.; Ling Xu; Institute for Information Industry IMT-advanced relay standards [WiMAX/LTE Update] Communications Magazine, IEEE, August 2010 Volume: 48 Issue:8 , PP40 - 48.

[3] S. Parkvall, E. Dahlman, A. Furuskär, Y. Jading, M. Olsson, S. Wänstedt, and K. Zangi, 'LTE-advanced - evolving LTE towards IMT-advanced,' *in the Proceedings of the 68th IEEE Vehicular Technology Conference (VTC'08)*, pp. 1-5, 2008.

[4] J. Lee, J.-K. Han, and J. Zhang, "MIMO technologies in 3GPP LTE and LTE-advanced," *EURASIP Journal on Wireless Communications and Networking*, vol. 2009 (2009), doi:10.1155/2009/302092.

[5] D. Astély, E. Dahlman, A. Furuskär, Y. Jading, M. Lindström, and S. Parkvall, "LTE: the evolution of mobile broadband," *IEEE Communications Magazine*, vol. 47, pp. 44-51, 2009.

[6] Q. Li, G. Li, W. Lee, M. Lee, D. Mazzarese, B. Clerckx, and Z. Li, "MIMO techniques in WiMAX and LTE:a feature overview," *IEEE Communications Magazine*, vol. 48, pp 86-92, 2010.

[7] R1-083410, "Text proposal for RAN1 TR on LTE-Advanced", NTT DoCoMo.

[8] R1-084015, "TR for 36.814 v0.1.0", NTT DoCoMo.

[9] A. Khandekar, N. Bhushan, J. Tingfang, and V. Vanghi, "LTE-Advanced: Heterogeneous Networks," European Wireless Conference, 2010, pp. 978-982.