Spectrum Overlay through Aggregation of Heterogeneous Dispersed Bands

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***Abstract*—Carrier Aggregation has been included in 4G systems such as 3GPP LTE-Advanced to allow the utilization of larger (up to 100MHz) and fragmented spectrum. Aggregation is happening at the MAC layer and each carrier is using the same PHY layer. Further, given the nature of LTE, each of these carriers must use a licensed frequency band. In the SOLDER project we will go further by aggregating heterogeneous radio access technologies with potentially different spectrum access schemes such as unlicensed or light-licensed. This is an important step towards fulfilling the requirements of spectrum hungry 5G systems. This paper presents the scenarios, vision and possible technical solutions envisioned in the SOLDER project.**

***Index Terms*—Spectrum Aggregation; LTE-Advanced; 4G/5G; Heterogeneous Radio Access; Heterogeneous Networks;**

I. Introduction

4G mobile communication systems achieve high data rates, which could be compared with those provided by landline communications. Several key technologies played a significant role towards this end. A new element to this success is the carrier aggregation (CA) technology, which has been introduced in 3GPP LTE-Advanced. In particular, CA can dynamically utilize multiple contiguous or non-contiguous carriers. This technique will satisfy larger bandwidth demands of emerging services while maintaining higher spectrum utilization factors.

Future network deployments will be heterogeneous—in many different ways. First of all we will see an increasingly deployment of small cells on top of existing macrocells, leading to more difficult interference scenario. Such a multi-tier network is the classical heterogeneous network (HetNet) in the 3GPP sense. Further, cellular networks will increasingly make use of other radio access technologies (RAT) such as WiFi access in addition to the existing LTE access, leading to a network of heterogeneous RATs (h-RAT). Last but not least, spectrum access will also be heterogeneous because in addition to the licensed bands, unlicensed or license-exempt bands will be used.

The main objective of the SOLDER project is to develop methods for the aggregation of such heterogeneous bands (HetBands) enhancing thereby the overall composite capacity and quality of service at the user equipment (UE). In this paper we first review the state of the art of different aggregation technologies and spectrum access techniques and then present the main vision of the SOLDER project. We then list some of the challenges that we will tackle in this project.

Table I
LTE aggregation bands (Source:Sequans)

Region	Operator	Bands
USA	AT&T	B2, B4, B13, B17
	Verizon	B2, B4, B13
	Sprint	B25, B41
ASIA	SKT	B1, B3, B5
	KT	B1, B3, B8
	LGU+	B1, B5, B7
	CMCC	B39, B40, B41
	KDDI	B1, B18, B26
	Softbank	B1, B8, B11
	NTT	B1, B19, B21
Europe	All operators	B3, B7, B20

II. Aggregation Technologies—State of the Art

A. Carrier Aggregation in 3GPP LTE-Advanced

LTE-Advanced Rel-10 allows the aggregation of up to five component carriers (CC) both on the downlink (DL) and the uplink (UL). The bandwidth occupied by each CC may be 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz or 20 MHz, which results in an aggregated bandwidth of up to 100MHz. Carriers can either be in the same band (intra-band CA) or in different bands (inter-band CA).

Table I lists some examples of operators in the world having shown the willingness to open a CA network, and the corresponding frequencies. When more than two frequencies bands are mentioned in the table, the operator may like to use CA with 3 carriers or CA with two carriers on any subset of its frequencies.

Some bands offer large bandwidth and are therefore suitable for intra-band CA. For instance, in the FDD spectrum, B4 is 45MHz wide and could offer two channels at 20MHz.

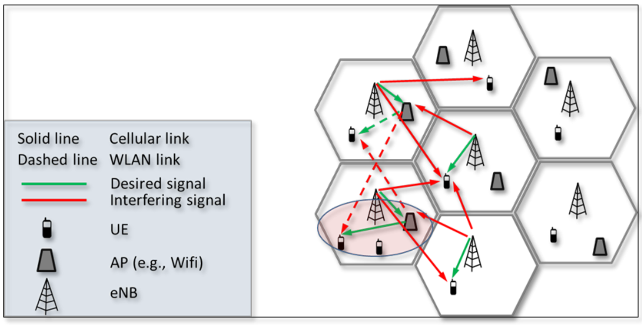

Figure 1. A multi-cell h-RAT network

Similarly, in the TDD spectrum, bands 40, 41 are more than 100MHz wide, and thus perfectly adapted to intra-band CA.

Rel-10 CA has been designed for co-located cells, while Rel-11 CA also supports multiple uplink Timing Advances (TA) and other enhancements to support non-collocated cells (inter-site CA). One of the key scenarios is the extensive use of Remote Radio Heads (RRHs) connected via fibre to a central baseband unit [1]. Rel-12 is also expected to introduce aggregation of both TDD and FDD carriers [2].

B. Aggregation of Heterogeneous Radio Access Technologies

Besides the HetNet concept, the cooperation of different radio access technologies has attracted particular interest as an efficient method to increase the capacity of the network. Among them the capacity offloading to non-cellular radio technologies, especially to 802.11-based wireless local area networks (WLANs) (i.e., WiFi) is considered as a cost-efficient, easy to deploy solution [3]–[11]. In [3], a downlink of a multi-cell wireless network, where the macro-cells are underlaid with a number of WLAN APs, which are not connected to a wired backhaul, is depicted. Because of the frequency reuse pattern among the macrocells, the UE and the APs in each macrocell are subject to co-channel interference due to a number of nodes. It is also noted that, in line with such offloading and also supporting aggregation of links between WiFi and LTE, and potentially other services, numerous efforts have been undertaken to combine WiFi and LTE and other capabilities, particularly through integrated WiFi Access Points with Femto-cells [12]–[15]. Building more WiFi hotspots is significantly more cost efficient than network upgrades or small cells deployments. Furthermore, taking into account the huge number of WiFi access points (APs) already installed at home or at work, it becomes evident that a very dense network is already deployed. It is interesting to note that the IEEE 802.11 standard includes a convergence with 3GPP standards through the Extensible Authentication Protocol Subscriber Identity Module (EAP-SIM) protocol for authentication and key agreement protocol enabler for utilizing the WLAN APs for offloading cellular data in practice [16]–[18]. A tighter integration between LTE and WiFi is planned for Rel-12 [19]. Also, 3GPP is also looking into the use of LTE in unlicensed spectrum (also sometimes referred to LTE-U) [20].

III. Spectrum Sharing Schemes—State of the Art

Spectrum sharing has undergone significant progress in recent years. Traditionally, spectrum has been accessed primarily through one of two models: "command-and-control" licensing whereby the regulator is a central authority responsible for allowance of spectrum accesses and allocation of associated licenses, and license-exempt access (typically in "unlicensed" bands), whereby devices are allowed to access the spectrum without a license so long as they adhere (and are certified as adhering) to certain basic technical rules, such as a maximum transmit power, duty cycle limitation, spectrum mask conformance, etc.

SOLDER aims to aggregate spectrum/carrier opportunities not only in licensed bands, but also to take advantage of unlicensed spectrum and other forms of "heterogeneous" spectrum opportunities and system/link types. Hence an in-depth understanding of spectrum access and sharing rules and regulations is extremely helpful to modeling SOLDER work going forward. In particular, the spectrum access and usage world is undergoing immense change right at this moment, and SOLDER has to take into account the different access types and rules that will result from such change in its resource aggregation.

A. Licensed Spectrum Sharing

"Licensed" spectrum sharing applies when licensed spectrum user may choose to release spectrum that is not being locally or temporally used to another entity, e.g., in return for some financial gain. Technically, this form of spectrum sharing is already achievable, however, the mechanisms of administering such a process manually are relatively cumbersome and slow, unable to react in time to the rapid change in traffic demand and provide appropriate spectrum availability through sharing to cover such demand. Various initiatives are at hand to improve spectrum sharing through licensed schemes, a key example of which is Licensed Shared Access (see, e.g., [21], among many other examples). This attempts to define the elements and automated procedures involved in such spectrum sharing, whereby both the incumbent spectrum user and the "LSA licensee" (opportunistic spectrum user) are given licenses with assumed "access rights", and a better guarantee of QoS (also for the opportunistic spectrum user), whereby the secondary user must vacate the spectrum as soon as it is required by the incumbent user. Elements that are defined to support such a scheme include means for the underlying agreement between the incumbent spectrum user and the licensee, and a geolocation-based database to support the process (e.g., conveying information on allowed locations for such opportunistic access to the LSA licensee), among others [21]. Such schemes are augmented by a greater flexibility in licensing through the concept of Pluralistic Licensing, for example [22], introducing the choice of licenses each with different assumed opportunistic spectrum access rules to the primary spectrum user up-front.

An additional means for licensed spectrum sharing is embodied in the concept of "Light Licensing". There are a

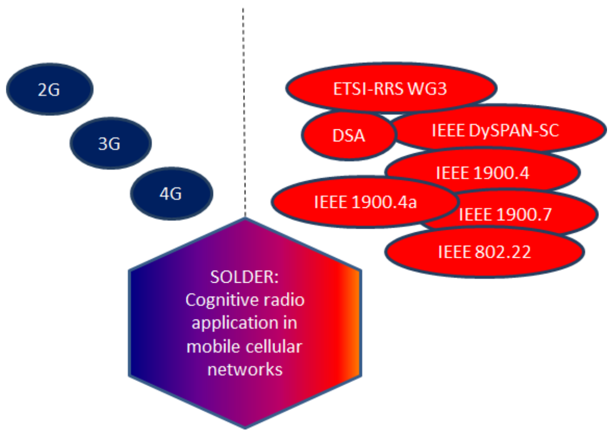

Figure 2. The SOLDER vision

range of approaches to this, but under a common approach a baseline fee is paid by the spectrum user for the ability to use the spectrum per se, and an additional fee is paid on top of that for each radio system (e.g., base station) deployed in the spectrum [23]. Hence, the interference among these systems that are "light licensed" is in a sense automatically regulated through economical means, with those causing more interference paying more for it.

B. *License-Exempt Spectrum Sharing*

License-exempt spectrum sharing might be achieved through a number of means. For example, access rules in unlicensed spectrum bands might be improved to facilitate greater coordination through awareness of local spectrum availability, e.g., by requiring devices to employ "cognitive radio" (e.g., spectrum sensing) mechanisms before accessing the spectrum [23]. Alternatively, additional tiers of spectrum access might be introduced, which could be based on such mechanisms as well as geolocation-supported means. This might encompass also different tiers of access for licensed spectrum users [24].

By far the most prominent means for facilitating spectrum sharing (opportunistic spectrum access) by license-exempt devices is the use of a geolocation database to check availability of spectrum on a local level. In line with this, extensive work is currently ongoing in Europe, particularly driven by Ofcom (UK) (see, e.g., [25], among other references), with rules being encompassed into a European Harmonized Standard [25], allowing such devices to use TV channels in certain locations and with given transmission EIRPs so long as they conform to the requirements specified in the European Harmonized Standard. These requirements include the need for geolocation determination, and (secure) checking with a geolocation database based on conveyed technical characteristics (e.g., a device ID, and associated spectrum mask class of performance, transmission gain characteristics, etc.) which TV channels can be used at which EIRPs. Such a scheme is important in the sense that one the geolocation database concept is established, it could theoretically be used in other bands for which such opportunistic access might be allowed.

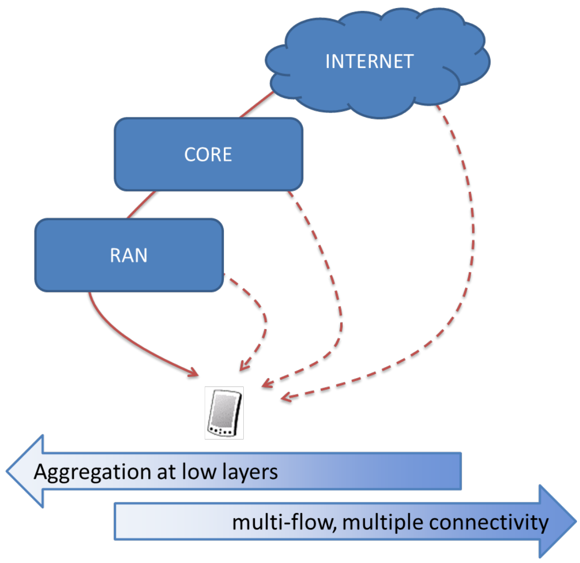

Figure 3. Several options of aggregation

Given its promise and benefits, LTE in TVWS has been a strong area of interest for some industrialists, academic research and experimentation, and some standardization groups (see, e.g., [26], [27]).

SOLDER takes such "white spaces" strongly into account in the spectrum opportunities that it attempts to aggregate. One strong area of work in SOLDER is how such "white space" spectrum usage might be combined with other forms of spectrum access such a licensed access and "conventional" unlicensed access, e.g., in ISM bands.

IV. The SOLDER Vision

The main vision of the SOLDER project is to bring together the best of the two worlds: mobile cellular networks and cognitive radio (see Figure 2).

A. *Objectives*

The main objective of the SOLDER is to provide the aggregation of such HetBands enhancing thereby the overall composite capacity and quality of service at the user equipment (UE). More specifically, the main objectives of the SOLDER project are the following:

1) To design and develop physical layer techniques for efficient CA over HetNets and h-RATs; new transceiver architecture, aggregation algorithms and diversity techniques in non-continuous multi-carrier communications.
2) To provide efficient medium access control over the HetNets and h-RATs with aggregation capabilities through link adaptation and scheduling approaches. To develop radio resource management exploiting the full potential of heterogeneous carriers.
3) To efficiently aggregate HetBands used by 3GPP LTE, WiFi and other systems providing seamless and enhanced service delivery. These HetBands might encompass a range of spectrum types and opportunities,

including licensed spectrum, license-exempt spectrum, and "white space" among others.

B. Scenarios

Aggregation could be seen at different level as illustrated by Figure 3. Firstly, the aggregation could be done at radio access level, using the same or a different RATs, either at the same frequency band or in a different band. 3GPP CA falls into this category, but one could imagine to aggregate several different RATs in this way. Secondly, aggregation could be done at core network level, by aggregating for example flows from different tiers in a HetNet (macro and small cells). This case only applies to 3GPP type networks as there is no core network in WiFi networks. Thirdly, aggregation could be done above the IP layer, as for instance techniques of multi-flow or multiple connectivity involving split and merge of traffic rather at the application layer than at the lower layers. In SOLDER, we focus on the CA at RAN level and we do not plan to address the topic of aggregating flows at a level above IP.

In SOLDER we start from the simple scenario corresponding to nowadays CA deployment: collocated sites having the possibility to transmit with at least two frequency bands. We consider mostly DL CA with no aggregation on the UL since this corresponds to current industry assumption.

From this scenario, SOLDER will then expand to more fancy ones, namely by aggregating existing LTE bands with other RATs and/or with other spectrum access schemes. The possible combinations of RAT and spectrum access schemes considered in SOLDER are given in Table II. The possible aggregation scenarios are given in Table III.

C. Proof-of-concept

It is planned to develop and demonstrate one or more proof-of-concepts according to the scenarios described above. The proof-of-concept will be based on the Eurecom OpenAirInterface platform [28]. The OpenAirInterface platform implements a software-defined radio of the 3GPP LTE Rel-8 standard (with some features from LTE-Advanced Rel-10), which runs on common x86 Linux machines and uses the Eurecom ExpressMIMO2 board for real-time signal acquisition and transmission. In the SOLDER project, this platform will be extended to support operation of LTE in TVWS and/or ISM bands as well as aggregation of LTE with other RATs.

Table II
POSSIBLE OPERATING BANDS FOR WIFI AND LTE

	WiFi	**LTE**
Licensed	No	Yes
Unlicensed (e.g. ISM)	Yes (e.g. 802.11n)	Yes (LTE-U)
License-exempt (e.g. TVWS)	Yes (802.11af)	Yes (LTE-TVWS)

Table III
AGGREGATION SCENARIOS CONSIDERED IN SOLDER

	WiFi	WiFi-TVWS	LTE	LTE-U	LTE-TVWS
802.11n			X		X
802.11af			X		
LTE			X	X	X
LTE-U					
LTE-TVWS					

V. CHALLENGES

A. PHY and RF

CA is a big challenge for the physical (PHY) layer and radio frequency (RF) frontend design, especially for the non-contiguous scenarios. In the case on intra-band non-contiguous CA, two design choices are possible: (1) Signals can be generated in the digital domain using a clustered OFDM approach and digital-to-analogue (DA) convertors that can cover a band large enough to accommodate all the carriers. (2) Independent RF chains can be used for each of the CCs. The latter case is also the only choice that can be used for inter-band CA.

In h-RAT scenarios, the situation is even more complicated due to the fact that different RATs may use different sampling rates. For example the base sample rate of LTE is 30.72Msps, while for 802.11n is 40Msps. A flexible architecture should thus be able to resample the signals to the right sampling rate.

A further challenge for the RF design are the stringent emission masks, especially when it comes to the regulation of use of TVWS. The UK operator OFCOM for example has defined an adjacent frequency leakage ratio of 74 dB (class 1) for its TVWS trials [29]. This is way above current requirements for cellular systems and thus will be a challenge to fulfill.

B. MAC and Link Level

In LTE-Advances carriers are aggregated at a MAC layer. The physical layer procedures (including hybrid ARQ procedures) are replicated for each carrier independently and it's the responsibility of the MAC to multiplex the UE's data to the different carriers. Carriers can be established and released by the radio resource controller (RRC) and activated and de-activated on the fly by the MAC. One important consideration in radio resource management for aggregation in LTE-A is the choice of CC that are aggregated, based on considerations such as the resulting utility that is achieved through CA, and the interactions with traffic loads/requirements and better sharing among users. One first step is given in reference [30], which attempts to aggregate CCs more appropriately by taking their diversity into account.

For LTE-U, the challenge is to make LTE more fair such that it can be used in unlicensed bands. In particular this requires that the system should be able to accept interference and at the same time not cause significant interference to others. Today LTE is not designed to do this.

C. Radio Resource Management

A few publications treat RRM methodologies for heterogeneous RATs such as LTE and WiFi [31], [32], but they remain on a theoretical level with simple system level simulations and a high level of abstraction of the radio interfaces. In the SOLDER project we plan to implement a practical RRM scheme for both WiFi and LTE based on the media independent handover function of the IEEE 802.21 standard.

This standard provides a unified framework for the abstraction of link-layer performance independent of the RAT and thus allows to create set of common measurements for both RATs [33]. These measurements will allow the RRM to efficiently and dynamically aggregate traffic using both RATs.

VI. Conclusions

The capability of having high data rate along with flexibility in spectrum usage for wireless communications is a key requirement for 5G mobile wireless communications. Cognitive radio technologies are slowly maturing and some trials—especially for the usage of TVWS—are being carried out. However, to really become successful these technologies need to be integrated tightly into existing cellular systems such as LTE-A in order to have a significant impact. The SOLDER project will work towards this goal by integrating the existing carrier aggregation concept of LTE-A system with other RATs and spectrum access schemes.

Acknowledgment

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