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On Multi-cell Packet Scheduling of LTE-A Cellular Networks: A Survey of Concepts Related Challenges and Solutions

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Abstract: The upcoming generations of cellular networks are foreseen to deliver a ubiquitous access to the rapid growing volume of mobile users. Therein, a stunning key feature of LTE is the ability to adapt the advancement in Radio Resource Management entity which scales up its potential to deal with multi-transmission scenarios by employing novel multi-antenna techniques on eNBs. This survey come in place to enlighten the aforementioned notions and deeply investigates the principles and approaches of LTE/LTE-A packet scheduling that are adapted in either Dl or UL channels. The main purpose of the study is to come out with a preliminary conceptual design of an optimal scheduling techniques in multi-cell heterogeneous environment keeping in mind the effects of inter-cell interference on the model overall QoS. Finally, it is recommended that a wise packet scheduling model for multi-cell LTE-A should involve an optimal trade-off between several QoS parameters having in mind interference mitigation as a main concern. Whereby, performance features of the known LTE/LTE-A scheduling categories, opportunistic scheduling, ICIC and CoMP can be realized in a single model.

Key words: Cellular networks, LTE/LTE-A, packet scheduling, multi-cell interference coordination, opportunistic scheduling, ICIC, CoMP

INTRODUCTION

The era of 4G in cellular networks became a tangible reality in the technology life. Since the baby steps time of mobile networks, the ultimate goal was to fulfill the QoS level to the end-user and provide network of high connectivity. Therefore, the incremented demand for network-related services like VoIP, web data and video streaming, meanwhile ensuring delay limits and bandwidth requirements introduces new challenges within the design of the 4G and beyond generations of cellular networks. Since the first evolution of mobile system that based on analog technology, some drawbacks were highlighted such as unencrypted system and limited in frequency allocation and spectrum efficiency.

2G mobile systems were introduced in mid of 1990s to be the transformation from analog to digital signaling in communication channels. Therein, some mobility services were introduced such as General Packet Radio Service (GPRS) in Global System for Mobile GSM and Enhanced Data rate for GSM Evolution (EDGE). Nevertheless, 2G mobile systems suffered from unstable efficiency due to the weak digital propagated signal. 3G mobile systems were introduced by International Telecommunication Union (ITU) with an aim to support higher data transmission rates and provide enormous cell capacity (Prasad *et al*., 2000). Specifications of the 3G systems were declared in International Mobile Telecommunication-2000 (IMT-2000).

WiMAX 802.16 candidate of IEEE and Long Term Evolution (LTE) by the Third Generation Partnership Project (3GPP) are among the well-known 3G mobile systems. Kan *et al*. (2011) stated that, an upgraded version of 3G called 3.5G adopted technologies like High Speed Downlink Packet Access (HSDPA) and High Speed Packet Access (HSPA) as mechanisms to transfer data in communication channels.

4G cellular network specifications were highlighted by International Mobile Telecommunications-Advanced (IMT-Advanced) in (Kanchei *et al*., 2010). The 3GPP organization led the first evolution in 4G by introducing its candidate namely LTE-Advanced (LTE-A). The 4G systems emphasize more in optimizing channel and signal quality metrics such as cell-edge efficiency, cell

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capacity and advanced QoS metrics. Concepts like multi-cell transmissions, heterogeneous network deployments, relays, multiple antennas are being deployed to improve the performance of 4G systems and user satisfaction index.

Scheduling in 4G cellular networks are still under contrary deployments. Among the issues that resulted from inefficient scheduling is the interfere-ence of signals between neighboring base stations. Interference is often described as a criterion to indicate the effectiveness of a particular resource allocation approach complies with QoS requirements. In different mobile channels, the ratio of interference differs according to the system requirements and complexity. Dimitrova *et al.* (2009) investigated the inter-cell interference characteristics and the behavior of this interference to the UEs performance targeting the uplink channel in LTE system. Moreover, it is evident that there is a proportional relation between interference level and eNB operating power, most often in downlink channels. This can be explained in such a way that more UEs are prone to more interference as they are interacting with several eNBs.

Motivation and contributions: The motivation behind this survey is to emphasize on the current algorithms and resource allocating scheduling to mitigate Inter-cell interference and ensure spectral efficiency and sufficient fairness level. The volume of reviewing surveys from literature in multi-cell resources scheduling for LTE-Advanced cellular system is still not rich and comprehensive enough. Some of current discussions circled about scheduling of multi-hop resources in general wireless platforms as in (Lindbom *et al*., 2011). Whereby, authors explained the interference impacts on the heterogeneous networks from a technical prospective. On the other hand, after the emerged cellular system of LTE/LTE-A as expressed in Akyildiz *et al*. (2010), research efforts targeted to investigate resources allocation of OFDM-related systems. Whereby, scheduling techniques in LTE-A as a multi-hop network was presented with emphasize on static and semi-static techniques. Kwan and Leung (2010), discussed the overall baselines of scheduling for interference avoidance and mitigation in LTE-A systems, as well as the classical approaches used in inter-cell interference mitigation.

Other reviewing efforts conducted with mathematical analysis of multi-cell LTE scheduling schemes evaluation (Capozzi *et al*., 2012). Nevertheless, the major problem of inter-cell interference is not tightly highlighted and correlated with the comparative LTE-A scheduling schemes. According to Pateromichelakis *et al*. (2013), an overview is delivered in multi-cell scheduling stressed on downlink-related schemes as a contrary work of Kwan and Leung (2010), Kan *et al.* (2011), Lindbom *et al.* (2011). The analysis was handled theoretically to reveal the linkage between Inter-Cell Interference Coordination ICIC and Coordinated Multi-Point (CoMP) techniques. Furthermore, reviews of Sawahashi *et al*. (2010), Lee *et al*. (2012a, b) were conducted in advanced upcoming multi-cell scheduling schemes so-called CoMP. The design principles in several scenarios and challenging issues in LTE-Advanced were handled accordingly. However, they did not illustrate the linkage of CoMP as a multi-cell scheduling technique and its former peers like ICIC and the traditional LTE scheduling approaches of frequency reuse. To the best of our knowledge, a holistic survey on multi-cell scheduling and interference mitigation with particular emphasizing on LTE/LTE-A is not currently available yet with coherence and extensive correlations between the traditional scheduling concepts and the sophisticated scheduling that manage multi-cell scenarios dynamically. Thus, in this survey we support the theoretical concepts with analytical expressions and challenging issues in each technique involve in the scope. We greatly aim at providing a comprehensive reference of LTE evolution and the benefits that have been added in scheduling concepts by operating on Orthogonal Frequency Multiple Access (OFMA) as data access technology. This reveals the ability of scaling up the current scheduling techniques to support more dynamic and powerful approaches like CoMP and intelligent data processing schemes.

OVERVIEW OF LTE CELLULAR NETWORK

LTE is a mobile telecommunication technology standard that provides the fastest service delivery to the end users. It is the next generation towards 4G and beyond technologies that supports GSM and CDMA cellular carriers. The LTE leverages from System Architecture Evolution (SAE) and Mobility Management Entity (MME), as main components 3GPP introduced by Sengar *et al.* (2011). The LTE mainly operates on Radio Access Network (RAN) to transmit data in high rates benefiting from the radio signal persistence and wide coverage. LTE concepts have been manipulated in most of the 3G mobile devices. The history of LTE is evolved by 3GPP that was established in 1998 with a main focus on radio communication. The 3GPP work was motivated by some of the current systems that time such as Universal Mobile Telecommunication System (UMTS). Whereby, implementations of UTMS that support circuit-switched and packet switched data access were attempted by 3GPP working group and documented as R99. The target of 3GPP efforts was to meet the specifications of International Mobile Telecommunication-2000 (IMT-2000) project (Akyildiz *et al*., 2010). That time, 3GPP mobile systems were enhanced by the deployment of a bearer-independent circuit-switched model and called disassociated switch identified in release 4.

According to Ali-Yahiya (2011a), 3GPP started its attempts in 2004 to enhance the Universal Terrestrial Radio Access (UTRA) models. By the end of 2008, LTE standard specifications completed and were declared as LTE Rel-8. The 3GPP then performed minor enhancements such as Dual-layer Beam-forming and Femtocells technologies to the current release to come out with Rel-9 as 3.9G. The progressive works on the legacy LTE continued until the first complete release of 4G was declared as Release 10 LTE-A (Meredith, 2011). LTE-A aims at delivering a system capabilities and QoS level beyond IMT-Advanced. LTE Rel-10 was formally submitted to ITU in 2011. Since then, it was approved by ITU as an IMT-Advanced technology standard. Currently, 3GPP initiated the vision to cellular systems beyond 4G and IMT-Advanced on lights of scaling up the features of LTE Rel-10. It is foreseen that in Releases (11, 12) 3GPP working group will realize the horizon to 5G in a real soon.

LTE system architecture and performance features: Unlike the hierarchical fashion of other traditional mobile systems, the architecture of 3GPP LTE is more to flat distribution in its system components. LTE architectural model is generally termed as SAE. Figure 1, shows SAE reference model that consists of two main networks: Evolved Packet Core (EPC) network and Evolved Universal Terrestrial Radio Access Network (E-UTRAN). The EPC network usually provides the IP connectivity between User Equipment (UE) and external packet data network utilizing E-UTRAN.E-UTRAN is defined as a network of eNBs that supports all services, including real-time multimedia services over shared channels (Chadchan and Akki, 2010). The other part of SAE is called EPC, whereby, packet communication over the Internet is managed (Pelcat *et al*., 2013). The EPC is designed to support much higher data rates, significant low system latency and optimizing packet flows through bandwidth rotation and charging schemes. In addition, EPC supports multiple radio access technologies in seamless interest that in turn provide a feature of system backward compatibility.

E-UTRAN on the other hand, is the air interface of LTE system that connects UEs to network services. It manages radio resources and guarantees the accessibility to user data (Shirani-Mehr *et al*., 2011). Basically, E-UTRAN is a distribution of several eNBs, in which each eNB manages several cells attached to it. Multiple eNBs are also connected to each other via X2 interface as shown in Fig. 1. This linkage is important for handover processes and also for advanced resources

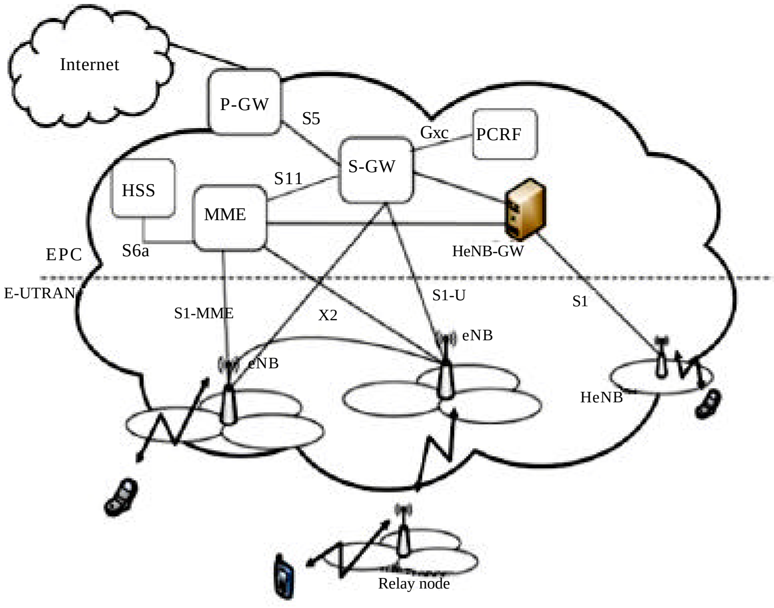

Fig. 1: Simplified SAE architectural reference model

Table 1: LTE and LTE-A basic comparison

Criteria	LTE	LTE-A
Peak DL rate	300 Mbps	1 Gbps
Peak UL rate	75 Mbps	500 Mbps
Transmission BW in DL	20 MHz	100 MHz
Transmission BW in UL	20 MHz	40 MHz
Mobility	Up to 350 km h^{-1}	500 km h^{-1}
Coverage	Excellent at 5 km	Same as LTE

management approaches like multi-cell packet scheduling. To the best of our knowledge, most of the current research deployment in LTE releases target E-UTRAN components especially in the optimization of eNB performance. Therefore, the scope of this study is directed more in this network. We will give a due care to better understand the functionality of E-UTRAN and the modality in which resources management takes place for multiple UEs.

The core part of E-UTRAN is the eNB. It is the air interface to the user and control plane protocols (Larmo *et al*., 2009) that are connected to UEs user interface. There are two special types of eNB: Home eNB (HeNB), for providing indoor coverage. The second is the Relay eNB (ReNB) that was deployed for purposes of increasing signal coverage. According to Pateromichelakis *et al*. (2013); E-UTRAN is responsible for many functions like: Radio resource management and scheduling in uplink and downlink, IP header compression and handover with other adjacent eNBs.

It is obvious that LTE-A provides a high system capabilities by supporting wide range of bandwidth to carry and process multiple UEs. The investigation on cell efficiency as a core criterion in assessing LTE-A systems performance has been given a due concern for improvement. This in turn enabled LTE-A to accommodate more traffic without any congestion that may compromise other relative QoS metrics. Moreover, system latency value is also reduced to the double-lower than IMT-Advanced. Thereby, in Table 1, illustration of the general QoS performance metrics is provided in LTE-A, the 4G mobile broadband candidate, with respect to the legacy LTE Rel-8 is performed.

Enabled features and technologies by LTE-A: LTE-A was introduced by boosting the functional capacities in the legacy LTE release 8/9. Several features are deploying in LTE-A such as Carrier Aggregation (CA), enhanced use of multi-antenna technique, improve support for heterogeneous deployments. LTE and LTE-A system are designed with some distinct features that make them so far of a different architecture from the other cellular systems like WiMAX. In the following, some of these enabling technologies are discussed. As described in Akyildiz *et al*. (2010), studies Carrier Aggregation was proposed in LTE Rel-8. The purpose of CA is to support more bandwidth in order to increase the system throughput and achieve higher peak data rates and coverage. This is done through aggregating multiple existing three types LTE Component Carriers (CCs) in the eNB. The efficiency of CC depends on channel condition and UEs QoS. Studies in (Bai *et al*., 2012) discussed and analyzed the improvements of CC approach at LTE-A systems. MIMO is the key design in LTE-A which maximizes the spectral efficiency of eNBs and reduces signal interference (Li *et al*., 2010). In LTE-A, MIMO is supported extensively in many techniques for serving both UL and DL channels. From the literature studies in Shirani-Mehr *et al*. (2011); Batista *et al*. (2012) optimized new schemes for MIMO and multi-antenna techniques in LTE-A mobile network. ICIC is another novel technology deployed in LTE-Rel-8 and later on became among the important key features in Heterogeneous Networks (HetNets) deployments by 3GPP in LTE-A. ICIC aims at providing high transmission rates and interference mitigation by adopting low-power cells called Pico-cells and Femto-cells (Bai *et al*., 2012). Kaneko *et al*. (2012) and Wang *et al*. (2012) examined the accuracy of enhanced ICIC (e-ICIC) in interference mitigation using Time Domain (TD) or Frequency Domain (FR) scheduling.

ReNB is introduced in LTE Rel-10 to improve the cellular system coverage, exactly in the remote regions (Akyildiz *et al*., 2010). Relaying concept reduces the cost in network design as there is no wired backhaul assumed. In addition to that, the cell power is wisely controlling especially when many remote UEs are connecting to the network. CoMP is introduced in LTE Rel-10 and will be fully supported in Rel-11. It is the sophisticated concept of eICIC, aims at improving network efficiency, enhanced the received power and significantly reduces cell interference through sharing the processes (Lee *et al*., 2012a). In a typical scenario of cellular network, CoMP techniques are identified by employing transmits and receives from multiple antennas sites. Nevertheless, CoMP in current schemes, still introduces some challenges like transmitting control information management and heavy load on links between eNBs.

On the other hand, a new trend introduced by 3GPP to simplify the network management and save operational expenditure; termed as self-organizing Networks (SON). The concepts are implemented within three functions self-optimization, self-configuration and self-healing (Marwangi *et al*., 2011). In LTE-A, SON has been taken advantage of in the design of femto-cells and HetNets in such a way to reduce interference and energy consumption. Buffer management in LTE-A is another aspect of improvement using Hybrid Automatic Repeat

Request (HARQ) technique. The HARQ reuses data from previous transmissions rather than discarding them to maintain higher throughput and lower latency in multi-ransmission scenarios. However, some challenges in HARQ still unaddressed in terms of storage requirements described in Bai *et al.* (2012) study, due to the huge amount of bits stored in UL and DL queues.

RESEARCH ISSUES IN LTE/LTE-A

In spite of the significant contributions that 4G LTE-A added tomobile broadband networks, there still various open research issues under investigation by the research community. Recently, some research works were introduced (Akyildiz *et al*., 2010; Bai *et al*., 2012) to discuss effective research challenges in designing LTE-A standards. Table 2, shows the most arguable issues in deploying LTE network and their effects on the overall mobile system capacity. It is obvious that cell interference seems to be a critical issue which has not been optimally covered yet. However, considering this issue solely may compromise the QoS requirements by another issue. Basically, the aforementioned issues are in somehow interrelated to each other. Whereby, the lack of resolving a particular issue may lead to another issue. Therefore, there should be an ideal equilibrating maintained in considering more than one issue in such a way that in any introduced system for scheduling radio resources to fulfill a major set of QoS requirements.

RESOURCES SCHEDULING IN LTE/LTE-A

Scheduling in LTE networks refers to the procedures of allocating radio resources and managing them in such a way that multiple users are simultaneously served. We should keep in mind that, the scheduling is performed with the aim of maintaining stable data rate, QoS requirements and the mitigation of eNBs signal interference as much as possible. Like the other modern cellular networks, in LTE scheduling processes take place in the base station; eNB. As investigated by Kwan and Leung (2010), a major distinguish between packet

Table 2: LTE and LTE-A research issues and challenges

Issue	Description	Affected QoS parameters	Possible solutions	Refrences
Traffic growth	Traffic data are doubled since last three years. Video and audio consume more bandwidth and causes traffic congestion	Low data rate, delay, SINR and PLR	Increase volume of spectral efficiency, enhance cells share	
Cell complexity	The high computational complexity in both downlink and up link affects the system performance. This is due to the use of 2-dimentional algorithm structure	Latency, high service power and low throughput	Sequence search algorithm, virtual pilots, channel state information	Ma and Xu (2012)
Cell interference	Current issue is inter-cell interference Happens when a UE moves away from one eNB toward another adjacent eNB. Signals from near eNBs are clashed as they are using same or close bands.	Low SINR, throughput, spectral efficiency and high data loss	ICIC, eICIC, CoMP, shared scheduling and processing. The use of HetNets to widen the bandwidth	Lee *et al.* (2012b)
Cell coverage	The emitted signal degraded due to adjacent cell interference, lack of eNBs. This issue happens at the remote areas. Installing full eNB is costly exorbitant, and consume more power	High PLR and delay low throughput and cell efficiency	Relay nodes, femto-cells, self-optimizing scoverage, beam-forming	Thampi *et al.* (2012)
Traffic fairness	For heterogeneous traffic transmitted, some traffic is prioritized over others. This may cause an unfairness issue for non-real time data. Scheduling schemes do not support mixed traffic transmission	High delay, packet loss rate, low fairness index and throughput	stochastic Petri nets models, Utilize ARQ in multi-hop relay, enhanced PF scheduling	Kwon and Jang (2009)
Backward compatibility	The concept of 4G LTE-A should support 3G services bands. DL and UL channels must allocate several carriers from different bands in the same channel	Low throughput, spectral efficiency, high BER	Carrier aggregation, HetNet deployments, HARQ and MIMO techniques	Qiu *et al.* (2011)
Power/Energy management	Moving toward green networks power consumption in cellular systems is a serious issue as it increased the emitted CO_2 gas. The more data rates are transmitted the more power is consumed	Power consumption, low SINR, spectral efficiency	Intelligent agents in eNB to control power. Femto-cells instead of macro for low energy	Lin and Debenham (2011)

scheduling in LTE and other earlier radio systems like HSDPA is that LTE schedule resources for users in both Time Domain (TD) and Frequency Domain (FD), whereas HSDPA involves only in TD. There are usually two types of links to be scheduled in LTE network: (1) Links between eNBs and the UEs and (2) Links between multiple eNBs connected to each other. The latter is an obvious type in which advanced scheduling technologies like ICIC and CoMP are invoked under a concept of "cooperative scheduling" to manage multiple UEs as it will be discussed later. Medium Access Control (MAC) is considered the most effective layer in LTE protocol stack, where scheduling and traffic flows control procedures take place. Therefore, we briefly discuss LTE MAC layer concepts in both TD and FD scheduling modules.

LTE mac layer structure: The MAC layer is responsible for scheduling the cell's resources in both DL and UL, meanwhile providing reasonable QoS level. As displayed in Fig. 2, DL and UL channels in LTE air interface are divided into a number of elements. Within MAC scheduler a Transmission Time Interval (TTI) of "1 msec" is used together with features such as HARQ to provide lower latency. Each frame is divided into 10 sub-frames, each of which is with length of 10 msec.

The sub-frame is also divided into two slots with a length of 0.5 msec per each. In FD mode, the slot is further divided into a number of Resource Blocks (RBs). This number mainly depends on the channel capacity.

RB is the main unit in scheduling transmissions. It is in a length of 0.5 msec and contains up to 12 sub-carriers per each symbol. The number of OFDM symbols in a single RB depends on the Cyclic Prefix (CP) being used. Whereby, Ali-Yahiya (2011b) claimed that in TD, the number of symbols per sub-frame is 7 in the normal CP and 6 for extended CP. In FD, CP is in length of 12 sequential sub-carriers (180 kHz). Data is transferred between the MAC sub-layers in the UE and eNB using Transport Blocks (Tbs). The TB is associated with Transport Format (TF) that specifies how the block is to be transmitted over the radio interface. Therefore, by varying TB format, MAC layer realizes different data rates in both DL and UL channels as described in the following.

LTE downlink scheduling model: The design of DL scheduling is a hard task (Gavrilovska and Talevski, 2011). Hence, some challenges should be considered like maximization of system capacity, boosting spectral efficiency and ensuring calibrated fairness. In LTE/LTE-A, OFDMA is used as radio transmission module in DL channel. This allows several UEs to share OFDM

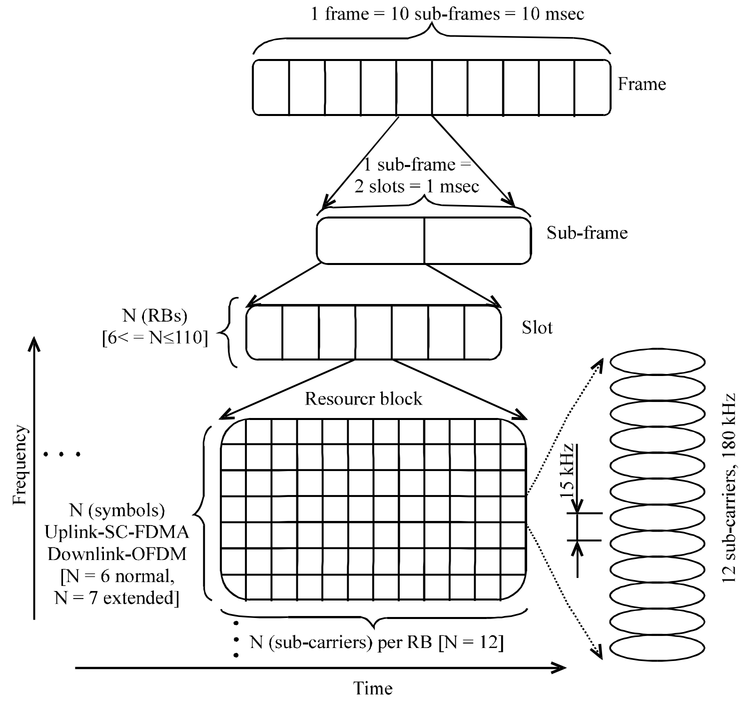

Fig. 2: Frame structure in LTE channel

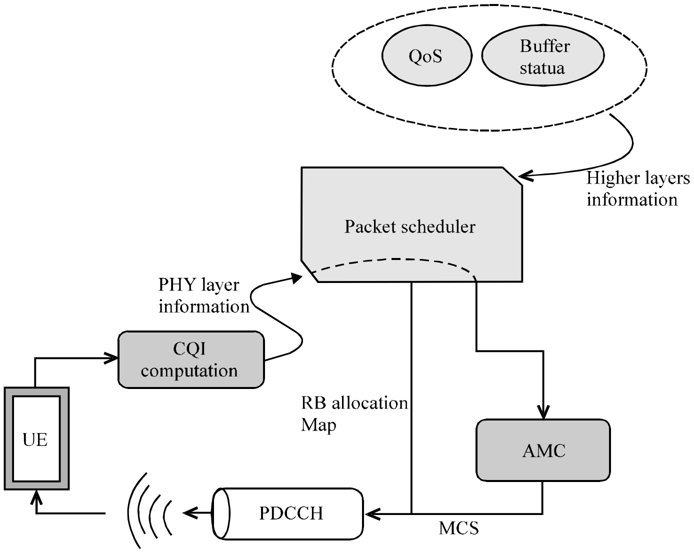

Fig. 3: A scheduling model block in an eNB's LTE DL channel

sub-carriers in parallel way. As investigated by Gao *et al.* (2012), OFDMA is an efficient variant of OFDM to be applied in LTE DL channel because of the high spectral efficiency that can be achieved, bandwidth scalability and robustness against multi-path fading. The process of DL scheduling model for RBs is clearly illustrated in Fig. 3. In DL channel, MAC scheduler uses Physical Downlink Control Channel (PDCCH) and Physical Shared CCH (PSCCH) functions for scheduling radio resources. The scheduler receives the CQI (0-15) reported by UE to accordingly indicate the efficient Modulation and Coding Scheme (MCS) to be used.

The whole process on DL scheduling is separated into sequence number of operations that triggered recursively. Firstly, reference signals are decoded by each UE to determine the CQI value and report back to eNB. Then eNB uses that CQI information for decision allocation and placing RB. After that, the Adaptive Modulation and Coding AMC module picks the best MCS aimed for data transmission by scheduled UEs. By this time, UEs are reported back with information of the allocated RB and the selected MCS via PDCCH. Finally, each UE extracts the PDCCH payload and accesses the suitable PDSCH in case if it is scheduled accordingly.

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Uplink scheduling: Unlike DL scheduling, work flow in UL differs for being simple procedures are involved since eNB does not require any additional information of the UL channel quality. Fushiki *et al.* (2011), claimed that OFDMA suffers from a major issue of instantaneous transmitted RF power that may vary significantly within a single OFDM symbol. This entails a large Peak to Average Power Ratio (PAPR) to end up with more power consumption. Therefore, SC-FDMA was introduced as an access module for LTE UL channel. Although, Capozzi *et al.* (2012) stated that SC-FDMA limits the scheduler freedom to transmit RBs only in a single carrier mode which is translated into less channel capacity and data rates. In terms of the channel design, UL channel often encompasses the same model as in the DL channel. UL is a bit simpler which returns lower-cost UE. SC-FDMA in LTE UL channel consists of two sub-carriers schemes. The first is Localized FDMA (L-FDMA) that assigns UE with adjacent sub-carriers and Interleaved-FDMA (I-FDMA) in a second scheme, whereby, the assigned sub-carriers are distributed over the entire frequency band. Generally, UL and DL scheduling in LTE focus on maximizing system capacity through treating a certain set of QoS metrics. However along the evolution way from 3G LTE to 4G LTE-A the concern became more toward inter-channel related metrics, unlike the legacy LTE that involves more about the intra-channel QoS metrics.

QoS performance metrics in LTE scheduling: In LTE, QoS is a board term used to describe the overall experience that a user or application will receive over a network. LTE has been designed with different QoS frameworks and tools to enable transmission of the evolving Internet applications. Thus, providing end-to-end QoS brings the need to deploy mechanisms in both control and user planes, where each of which is with different QoS measurements. For end-user applications, to achieve QoS, a group of performance requirements for that application should be predefined and quantified in terms of metrics that determine the target perform-ance level. Therefore, Table 3 summarized the discussions of Ekstrom (2009) and Taha *et al.* (2012) regarding the quantitative performance parameters involved in transmission channels of LTE mobile network.

SCHEDULING ALGORITHMS IN LTE/LTE-A

LTE mobile network in Release 8 and before, are classified as 3G systems. This means that the network specifications can cope to some extend with the other 3G

Table 3: Illustration of LTE performance metrics

Perf. metrics	Description	Effects on network's QoS	References
Guaranteed bit rate GBR	In GBR, network resource are fixed and do not change after establishing a single bearer. So it guarantees more service and good to for VoIP data	GBR value is decreased by the incremented number of involved UEs or relay cells. High GBR value degrades SINR	Venkatkumar and Haustein (2011)
Maximum bit rate MBR	It's the upper limit on the bit rate which can be expected from GBR Traffic-shaping functions are applied for punishing the contrary flows	Same as GBR. However MBR in LTE is limited by the channel rate as it reflects the max value	Pedersen *et al.* (2011)
Aggregated max bit rate AMBR	AMBR provide a control to the bandwidth allowed to UEs. It is used for the non-GBR flow s for a group of bearers. It identifies the max bit rate for non-GBR	High AMBR reflects higher priority to a data flow. It estimates most sensible control channel size for specific UE	Chung *et al.* (2012)
Priority	Uses Allocation Retention Priority to indicate priority of bearers' to Ues handover process during congestion situations. Flow with low ARP is dropped	ARP highly influences fairness in channel and CQI value. High ARP means higher throughput and low packet dropping ratio	Bae *et al.* (2009)
Delay	Using Packet Delay Budget parameter, max time the packet should spend transiting through MAC layer is determined. Different delays values used for applications	Bigger value of end-to-end delay increases the packet loss and decreases the average data rate and cell utilization	Khan *et al.* (2012)
Packet loss	Packet error loss rate (PELR) is used in MAC HARQ, identified through 9 categories. It's the maximum rate of packets which are not successfully delivered to the destination	Low PLR means more system throughput.PLR increased the load (Ues) and also increased the value of PELR	Pham *et al.* (2011)
QoS Class indicator QCI	Indicates the access level of QoS parameters set to be used between a UE and eNB. Each data flow is mapped to a QCI value. Different QCI values have different Bit Error Rate (BER)	High QCI value means high SINR for cell-edge. QCI value is somehow related to channel q uality indicator CQI value	Bultmann *et al.* (2010)
Fairness	It is an implicit principle metric that determines whether data flows in DL channel or UE control packets in UL channel are receiving a fair share of system resources	Probability of selecting packets should be adjusted carefully to give a fairness level. Fairness is proportional to traffic load	Kwon and Jang (2009)
Spectral efficiency	It's the amount of information transmitted over the given bandwidth in eNB channel up to MAC layer Peak spectral efficiency parameter to determine the value of this metric	Cell spectral efficiency value is proportional with number of eNBs and the inverse of bandwidth	Racz *et al.* (2008)
Cell-interference	Uses SINR to reflect cells interference level. It usually occurs during the handover procedures and the termination of transmitting resources from eNB to UE. This metric can be in inter-cell or intra-cell	Low Interference as UE moves away from the serving eNB but high BER and thus low throughput percentage and cell-edge efficiency	Lescuyer and Lucidarme (2008)

systems such as WiMAX. Scheduling algorithms and concepts can also be inherited and manipulated in LTE for resource management and interference mitigation. However, such legacy approaches might not be exactly adapted when the latest releases of LTE-A were announced as a 4G technology. Whereby, channel capacity is scaled up beyond the algorithms measurements. Therefore, scheduling techniques should be deployed to suit the current system requirements and keep the QoS in the satisfaction level with optimal trade-off between utilization and fairness as discussed in Ali-Yahiya (2011a). In the following subsection we provide a brief discussion on opportunistic scheduling as the traditional packet transmission techniques in LTE systems.

Opportunistic scheduling: The study of opportunistic scheduling in LTE was started in an early time of 3GPP evolutions. Wherein, the deployed LTE netw-ork schemes focus more on certain QoS metrics like throughput, delay and fairness to be fulfilled. Al-Rawi *et al.* (2008), defined the opportunistic scheduling as a specific behavior of the channel toward controlling the transmitted data in such a way to overuse the entire available bandwidth to allocate resources with a high throughput. Pham *et al.* (2011) conducted several evaluation studies on the main three well-known opportunistic schemes: Proportional Fair (PF), Maximum-Largest weighted Delay First (M-LWDF) and Exponential PF (EXP-PF) to indicate the efficiency level in each one over the another. These schemes attempt to make the best trade-off as possible between several performance metrics like cell throughput, fairness and delay.

As for PF, it was proposed by Kelly (1997) and firstly introduced for single-cell cellular network in Choi and Bahk (2007). The PF scheduling is suitable for managing non-real time traffic. Therein, experience channel quality and past user throughput are two factors considered in radio resource assignment. The PF aims at maximizing the total network throughput and guarantee fairness among various flows. In spite of the fairness level that PF maintains, the algorithm is limited for non-real time traffic only. Hereby, the M-LWDF came in place. M-LWDF was initially introduced in Andrews *et al.* (2000) to treat delay sensitive traffic. It also supports multiple data users with various QoS requirements in TDPS. Pham *et al.* (2011) stated the two reasons behind preferring M-LWDF for delay-aware scheme: (1) The optimal gained throughput, (2) The use of time stamping makes it easy to be implemented. The main idea in this approach is to induce the scheduler to balance the weighted delays of packets and make an efficient use of the channel state information. The EXP/PF algorithm was proposed by Rhee *et al.* (2003) based on the traditional PF and studied thoroughly in Rhee *et al.* (2004). Unlike PF and M-LWDF, the algorithm schedules both real and non-real time traffic with more focus in prioritizing delay sensitive traffic. The main idea is to combine the benefits of the exponential rule in Shakkottai and Stolyar (2001) and PF with the aim of balancing between guaranteeing high system throughput and maintaining a level of fairness.

Based on the aforementioned discussions; it can be stated that opportunistic scheduling algorithms does not support more dynamic scenarios with multi-antennas. They also neglect the impact of some metrics like cell power and cell interference. Whereby, the ultimate goal is to provide throughput while maintaining fairness level. In addition, schemes under this category are mostly based on time domain; this means more bandwidth will be unwisely consumed to end up with cell efficiency degradation. Adhere, having cell interference as a major issue in this context, it is advisable to deploy mechanisms that handle this issue by either mitigation or cancellation in order to come out with LTE/LTE-A system that cope with the dense of UEs and various eNB types. This is thought of as the motivation of ICIC techniques in LTE-A scheduling as will be described hereafter.

ICIC scheduling techniques: ICIC was introduced as a provisioning technology in LTE-A resource management. It was highlighted in LTE Rel-8 and thereafter officially implemented in LTE Rel-10 (LTE-A). ICIC is deployed to mitigate the issue of cell-edge inter-cell interference (Pateromichelakis *et al.*, 2012). Therein, coordination mechanisms are defined among the neighboring cells to allocate orthogonal resources to the overlapping highly interfered area. Unlike the previous resource scheduling approaches, ICIC consider both of frequency and time domain packet scheduling. That means more cell efficiency and bandwidth utilization is provided to the coordinated services. Thanks to concept of multi-carrier resource management in ICIC, eNB is able to simultaneously transmit UE data in several sub-carriers using some enabling LTE technologies like MIMO, Femto-cells and relays. In light of the inter-cell interference phenomenon that was described above, the rule of ICIC is to control the link power allocation in frequency domain with respect to the time domain scheduling in order to provide the Ues with low-interference resources. On the other hand, Kimura and Seki (2012) stated that ICIC is considered as

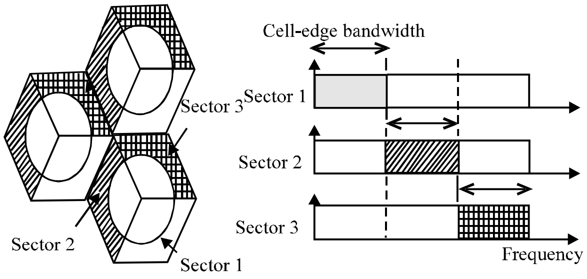

Fig. 4: Concept of fractional frequency reuse

a promising technology for mitigating the degradation in cell-edge bit rate that results from interfering adjacent eNBs and improving the cell-edge throughput. In ICIC and its' enhanced version (eICIC) by Lindbom *et al.* (2011), they are classified based on the method of frequency utilization into three techniques: (1) Static ICIC that includes Fractional, Partial Frequency Reuse (PFR) and Soft Frequency Reuse schemes (SFR), (2) Semi-static ICIC that includes Adaptive Frequency Reuse scheme, (3) Dynamic ICIC (eICIC) that includes Utility-Based and Graph-Based techniques.

Static-ICIC techniques: In static-ICIC schemes resource allocation is constant and is not affected by the channel status and traffic density. Static-ICIC concepts are still of a good interest assuming that they can be deployed within LTE without radical modifications (Mills *et al.*, 2011). FFR concept was firstly introduced by Halpern (1983). FFR basically, reduces the interference effects by assigning different frequency portions for UEs in various areas. Figure 4 depicts the concept of FFR in scheduling. Whereby, provided bandwidth is divided in two parts; cell-center area with high signal quality and lower interference level and cell-edge area with lower signal and higher interference. As discussed by Fushiki *et al.* (2011), the Frequency Reuse Factor (FRF) here is set to less than one and is defined as the number of times a given Physical Resource Block (PRB) is used in the system.

For the clarity, high reuse factor means high cell-edge performance gain, low interference effect, low spectral efficiency and vice versa. Another frequency allocation technique is called PFR, which was firstly presented by Sternad *et al.* (2003). The mechanism is graphically depicted in Fig. 5. Like FFR, in PFR the total bandwidth spectrum here is shared between cell-center UEs of low power and cell-edge UEs with a relatively higher power. The interference is thus mitigated by restricting cell-edge from exceeding certain value bandwidth utilization. Major issue in both PFR and FFR is the non-optimal tradeoff between throughput and interference mitigation since both do not manage an efficient way to benefit from the entire bandwidth.

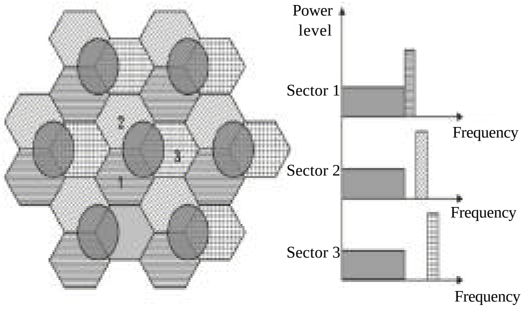

Fig. 5: Concept of partial frequency reuse

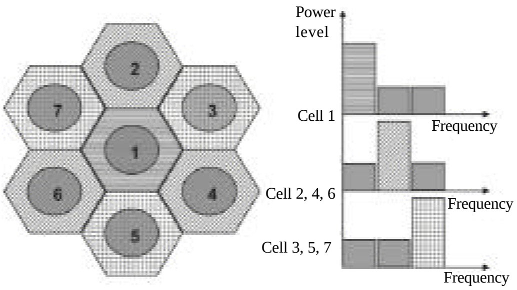

Fig. 6: Concept of soft frequency reuse

On lights of the aforementioned issue, SFR was introduced for GSM by 3GPP to make full utilization of the bandwidth. According to Zhang *et al.* (2008), the value of FRF in the cell-center UEs is set to one, whereas, at the cell-edge FRF is set to three. Moreover, the cell-center UEs use a number of bands three times equal to cell-edge users. Unlike the previous schemes, in SFR the available bands at the cell-edge areas can be utilized by the cell-center UEs as long as they do not create any interference with the adjacent bands.

In Fig. 6, soft reuse scenario in LTE adopted the sharing of the entire bandwidth in number of bands equal to three. From the former reuse schemes, we can conclude that there is a tradeoff between spectral efficiency and ICI controlled by FRF Wherein; the lower value of FRF returns higher spectral efficiency, meanwhile, using higher reuse factor significantly mitigate the interference but affects the cell-spectral efficiency on the other hand.

Semi-static ICIC techniques: Static-ICIC schemes relay on an unrealistic assumption that is traffic load remains stable along the life-time of the deployment within each eNB. Semi-static ICIC concept takes an advantage over static-ICIC such that it employs adaptive techniques

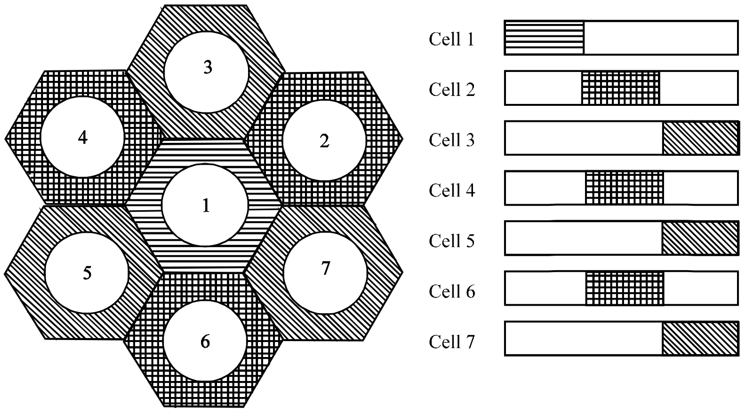

Fig. 7: Adaptive soft frequency reuse as semi-static ICIC

based on traffic changes over different areas in cell. Toufik and Knopp (2009), stated that, interference coordination is more effective in cases of non-uniform load distribution in eNBs and uneven cell coverage across the network. Adaptive Frequency Reuse (AFR) is among the major concepts in Semi-static ICIC. It is basically an enhanced notion of SFR. For example, (Zhang *et al*., 2008) a solution was provided for ICI using PRB minimization and cell-edge bandwidth breathing to utilize more bandwidth and increase the cell-edge spectral efficiency.

Illustrated in Fig. 7, changes in traffic loads and UEs distributions were adapted dynamically. Wherein, the number of sub-bands were tuned based on the traffic load in a semi-static fashion of coordination between neighboring cells. On the other context, Adaptive FFR proposals (Angelakis *et al*., 2011) were introduced as a semi-static ICIC to alleviate the problem of low cell-edge spectral efficiency using de-centralizing frequency allocation.

Dynamic ICIC: Analysis of differences between semi-static and Dynamic ICIC (D-ICIC) were conducted in Wang *et al.* (2012). It is concluded that static and semi-static ICIC suffered from failure to adapt the rapid changes of operating scenarios. Moreover, schemes are not built realistically that in turn led to performance degradation and impractical network implementation as comparing with D-ICIC. Therefore, D-ICIC has been deployed to deal with interference without prior frequency planning. For the essence of resources scheduling and bandwidth allocation; D-ICIC includes Utility-based and Graph-based approaches. Utility-based solutions handle resources allocation problem by realizing utility maximization and optimization of QoS parameters as described in Shi and Gu (2011). Besides that, the notion of network utility can be defined in this context as a metric to keep fairness, resources delay channel throughput in an equilibrate level in multi-cell environment. On the other hand, the concept of integer programming is also considered one of utility-based approaches (Rahman and Yanikomeroglu, 2010). Therein, the network utility is maximized by improving the cell-center UEs' data rates, as it is crucial to avoid interference in such UEs; especially when dealing with delay-sensitive traffic. In addition, game theory was adopted (Ali and Zeeshan, 2012) based on distributed utility function in two-level scheduling to minimize delay and provide user satisfaction criterion in multi-cell scenario.

Graph-Based techniques are another approach of D-ICIC in which the issue of interference and spectrum allocation is formulated as an interference graph. Whereby, graph coloring is used to guarantee that connected UEs are not scheduled with the same set of bandwidth resources (Zheng *et al*., 2012). As in Fig. 8, the graph consists of vertexes, edges to connect vertexes and path weight values.

The aim is to assign each UE node in the graph a color in such a way that no UEs linked with an edge are assigned to the same color. Hence, optimal cases of throughput are gained by minimizing the net weight that implies ICI level. This technique is called weighted graph (Chang *et al*., 2008). Color assignment task is usually the rule of eNBs. Nevertheless UEs still need to report back to eNB the information of measured interference paths losses as colors are assigned accordingly. Another technique in graph-based ICIC is named jamming graphs; that is investigated by Necker (2009). The basic idea is similar to the weighted graph explained above. However, the objective in jamming is to the minimum number of colors needed to label the UEs as depicted in Fig. 9. The

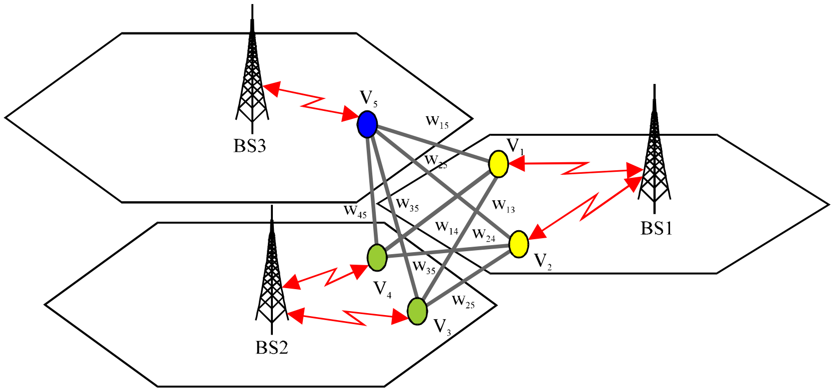

Fig. 8: Scenario of graph-based approach in ICI mitigation by weighted graphs

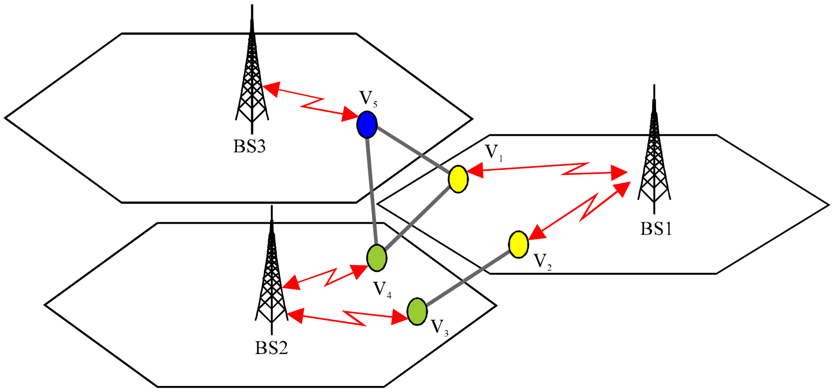

Fig. 9: Scenario of graph-based approach in ICI mitigation by Jamming graphs

edge connection is only established between UEs in high interference to adjacent eNBs located in a close distance from each other.

CoMP scheduling techniques: CoMP Scheduling concepts are extended from ICIC and eICIC schemes. The aim of CoMP techniques of MIMO-OFDM systems is to increase the cell-edge performance, meanwhile maintaining a minimum imposed system's complexity (Biermann *et al*., 2012). Nonetheless, the notion of distributed antenna systems and group cell theory were pointed as the main dominant in deploying CoMP scenarios. For example, radio resource management and bandwidth allocation have been discussed extensively (Lindbom *et al*., 2011; Lee *et al*., 2012a) using CoMP case scenarios. Whereby, the concept here is defined as set of Channel State Information Reference Signal (CSI-RS) resources, in which the UE is needed to measure and report back to the eNBs group. This UE-eNB interaction controlled by CoMP Resource Management (CRM) procedure, that limits resources number invoked to avoid signaling overhead issue. The efforts of scheduling at CoMP scenarios in LTE-A Rel-11 mainly focuses on two transmission concepts for both DL and UL links: Coordinated Scheduling/Beamforming (CS/CB) and Joint Transmission (JT). The concept of CS/CB states that the RB was assigned and transmitted only from the serving cell, (Katiran *et al*., 2011). However, the decisions of transmission were made in a coordination manner between adjacent cells, eNBs and Radio Resource Entity (RRE) as illustrated in Fig. 10. Usually MIMO antenna capability is used through the process of CS/CB. This results in a rapid and tight coordination of resources to well control of Inter Cell Interference (ICI).

What is arbitrary to be wondered in CS/CB, is the way UEs were assigned such that no inter-cell interference occurs. In this case UE need to send feedback information about its CSI based on their SINR value via the uplink channel to the closest serving eNB. Nevertheless, as a developing technique, (Pateromichelakis *et al*., 2012) debated that CS/CB still had some open questions in terms of beams from different

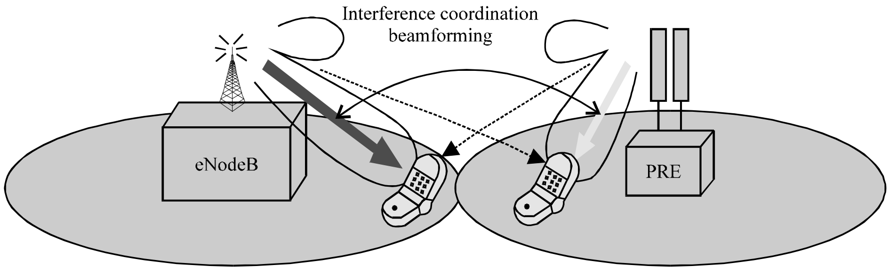

Fig. 10: Concept of CS/CB in CoMP

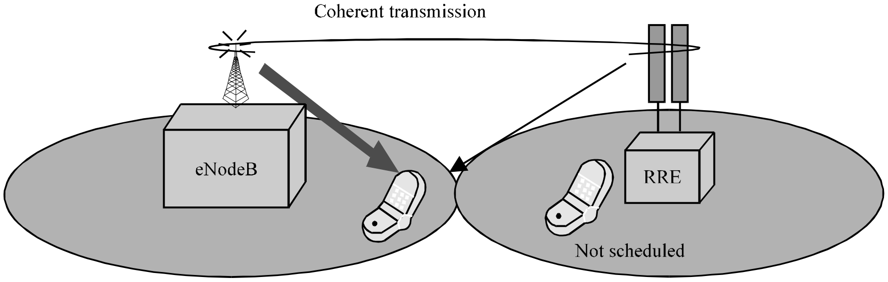

Fig. 11: Concept of JP in CoMP

cells and the duly level of predictability from the adjacent cells in interference occurrence. Another technique in CoMP resource scheduling is named Joint Processing Wang *et al.* (2011). Whereby, multiple eNBs simultaneously transmit on the same physical resources to provide constructive interference at the UE or the UE performs a Dynamic Cell Selection (DCS) to nominate the best eNB for the current data transmission.

As shown in Fig. 11, the process of shared transmission between eNBs to a UE takes place. The aim from JP is to reduce feedback signal overhead by improving SINR value at the UE via pre-coding matrixes candidates (Sawahashi *et al*., 2010). Besides that it converts the interfered signals to provide a useful and desired signals to that carry UEs data. As discussed by Lee *et al.* (2012b); there are two types of transmissions in JP schemes: Coherent JP, wherein, the transmitted RBs are jointly pre-coded and received by UE as a coherent block. The second type is Non-coherent JP; in which UE receive multiple transmissions from each eNB without considering for coherent pre-coding. Nonetheless, in principle, JP is efficient for lightly loaded network more than the heavily loaded one.

CONCLUSION

In this survey LTE-A has been introduced as a 4G mobile system on lights of the legacy LTE, the landmark for 3GPP contributions in cellular systems. From the LTE unique architecture, it is clear that the flat distribution of components as well as employing radio access network as a carrier for the signals give the system more flexibility to be upgraded and scaled up rapidly. Some of LTE-A research issues have been investigated with discussions to indicate their impact on QoS performance level.eNB tends to be the targeted scope of this article, as all of the resources scheduling and bandwidth allocation take place in this entity. Therein, MAC layer as one of the LTE protocols has been explained in terms of DL and UL channels that use OFDMA and SC-OFDM respectively. For the seeking of more accuracy in this study, scheduling in LTE was investigated in terms of some related performance metrics that affect the overall system performance. After that, LTE/LTE-A scheduling approaches were explained from three categories: opportunis-tic, ICIC and CoMP scheduling techniques. Whereby, the latter is the most dynamic and sophisticated.

Within the demonstrated extensive works, it is obvious that packet scheduling as one of the main concerns in LTE mobile networks used to be an active topic to the research leaders. Some issues as discussed earlier in this paper brought the need for several proposals in this term starting from proportional scheduling until the multi-cell scheduling that emphasize on bandwidth allocation and inter-cell interference. We argue that a gap is existed between opportunistic techniques and ICIC and CoMP techniques in terms of the QoS performance metrics they utilized to achieve resources scheduling in high QoS level.

Currently, some of the developing scheduling schemes in LTE are realizing both channel-based (intra-cell) QoS and link-based (inter-cell) QoS metrics in hybrid models. As a result, majority of the analysis ended up with the notion that an optimal trade-off between parameters should be considered to have the best QoS level. Some of these trade-offs are for example fairness and throughput, channel quality and power, interference and spectral efficiency, interference and bandwidth, bandwidth and spectral efficiency, power and spectral efficiency. This at the end may link the bridge between legacy and novel scheduling models that operate in more dynamic environments.

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