COGNITIVE RADIO RESOURCE MANAGEMENT FOR FUTURE CELLULAR NETWORKS

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ABSTRACT

The heterogeneous network (HetNet) architecture, device-to-device (D2D) communications, and coexistence with existing wireless systems have been regarded as new communication paradigms introduced in LTE-A/LTE-B cellular networks. To facilitate these paradigms, considerable research has shown promise of the cognitive radio (CR) technology, particularly the cognitive radio resource management (CRRM) on the top of resource allocation to control Layer-1 and Layer-2 radio operations, thus eliminating the concerns of potential system impacts and operation unreliability to bridge the gap between cellular and CR technologies. To support diverse communication paradigms with different challenges, a variety of CRRM schemes have been recently proposed, which however significantly perplexes the system implementation. To provide a general reconfigurable framework, in this article, we reveal a software-defined design of the CRRM. Through proper configurations, this software-defined design is able to adapt to diverse communication paradigms in LTE-A/LTE-B, and provides transmission reliability in terms of quality-of-service guarantees via the optimum control of the design. Supporting diverse CRRM schemes, this design substantially simplifies the system realization to bring the development of the CRRM to the next stage of practice for the fifth generation (5G) cellular network.

INTRODUCTION

Different from previous 3GPP releases of Rel. 99 for WCDMA, Rel. 5 for HSDPA, Rel. 6 for HSUPA, Rel. 7 for HSPA+, Rel. 8 and Rel. 9 for LTE, the recent releases of Rel. 10 and Rel. 11 for LTE-A (the fourth generation, 4G) and Rel. 12 for LTE-B are evolving to the fifth generation (5G) cellular network, and thus need to satisfy very challenging requirements envisioned by the mobile and wireless communications enablers for the twenty-twenty information society (METIS) of 100 Gbps/km^2 with high mobility. To support high mobility, the evolving packet core of LTE-A is modified to simplify the handover procedure. The orthogonal frequency division multiple access (OFDMA) is also adopted to combat frequency selective channels. However, achieving a high network efficiency is never an easy task, which has been shown infeasible by link level solutions only. It thus drives the development of a revolutionary network architecture known as the heterogeneous network (HetNet) [1]. In the HetNet, in addition to conventional Macrocells formed by evolving NodeBs (eNBs), there are heterogeneous small cells including picocells formed by eNBs with smaller transmission power (than that of Macrocell eNB), femtocells formed by home eNB (HeNBs) and relay nodes (RNs), underlay the coverage of Macrocells to shorten the distance between a transmitter and a receiver, as shown in Fig. 1. However, even though such a revolutionary architecture is adopted, two challenges remain for the development of future evolutions.

Inter-network interference: Cellular networks require dedicated wide bandwidth to support high data rates for advanced releases. However, the current radio spectrum is very crowded, and only leaves very limited space for future evolutions, which results in a compact arrangement of frequency bands between 4G/5G releases and other wireless systems. For instance, the 2400–2483.5 MHz ISM band is utilized by both WiFi and Bluetooth, while the operating band of LTE-A Band-40 ranges from 2300 to 2400 MHz as an immediate neighbor. Due to the imperfect transceiver components, the compact arrangement of adjacent frequency bands introduces severe inter-network interference, not only among wireless stations but also within a device with multiple radios (i.e., the well known in-device coexistence, IDC, interference), which immensely perplexes system and device designs. From investigations by 3GPP [2], using state-of-the-art RF filters does not provide sufficient rejection to adjacent channel interference.

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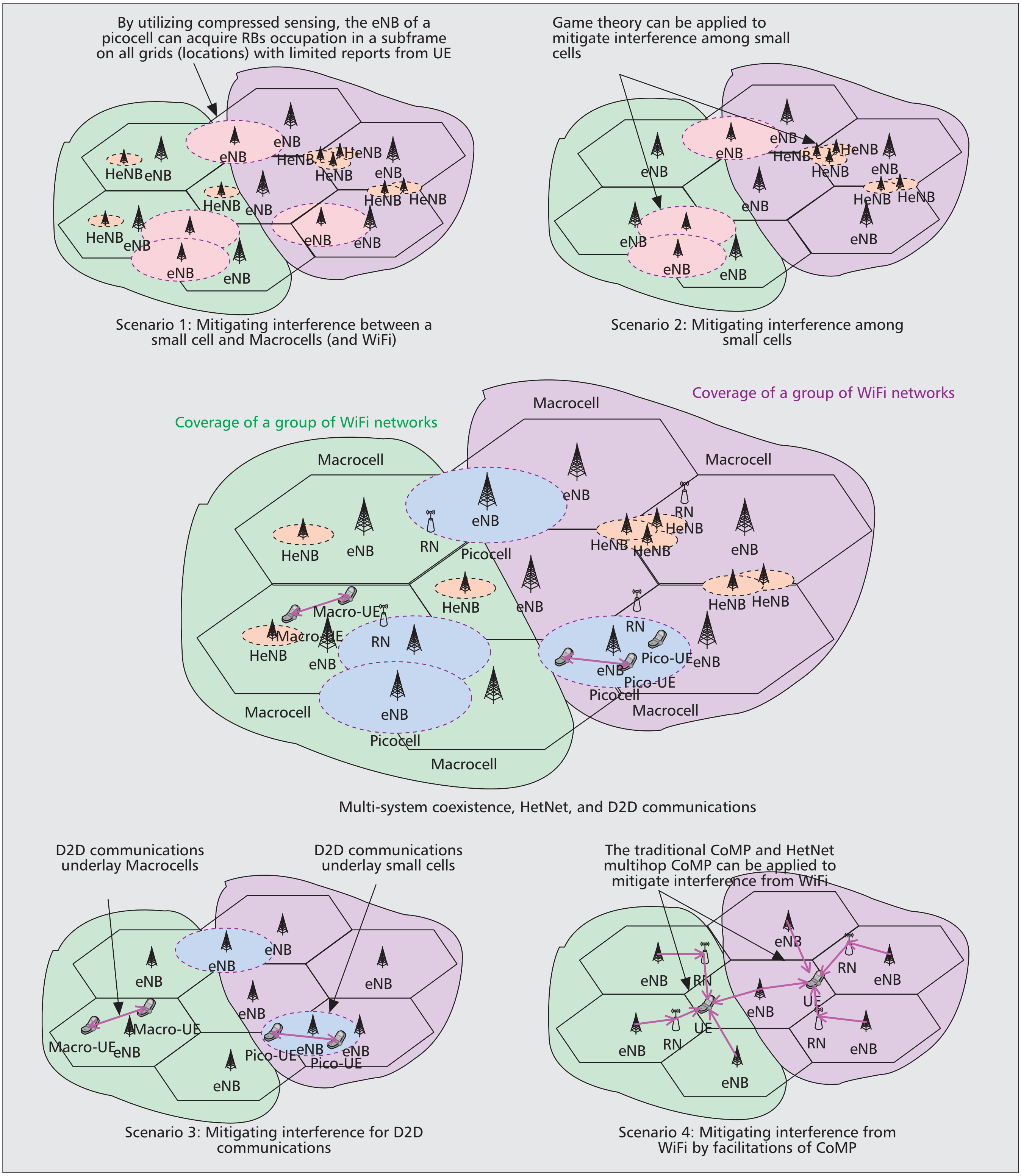

Figure 1. *Multi-system coexistence, HetNet, and D2D Communications in state-of-the-art E-UTRA of 4G/5G, and a general illustration of the software-defined design.*

Intra-network interference: Due to the underlying deployment of small cells without proper cell planning, severe interference may occur not only between a small cell and a Macrocell, but also among small cells under highly dense deployments. There are different classes of interference in the HetNet, among those, the major challenge lies in the interference from a small cell base station to a Macrocell user located within the coverage of the small cell.

To mitigate inter-network interference under the limitation without the knowledge on the presence of other wireless systems, Band-40 may be forbidden to waste precious 100 MHz bandwidth. To mitigate intra-network interference without a centralized coordinator nor fixed spec-

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trum partition (due to a low spectrum efficiency), one proposed solution is to handover the victim Macrocell user to the nearby small cell. However, the Macrocell user may consume backhaul resources of the small cell. In addition, a small cell can not be in the *close access* mode and shall always be in the *open access* mode to be available for Macrocell users. As a result, although interference could be mitigated, benefits and security of small cells are sacrificed. Consequently, these solutions in 3GPP are away from being effective.

To solve interference issues in 4G/5G, it is suggested that the distributive nature for information collections and parameter optimization empowers the cognitive radio (CR) technology [3] as a novel design paradigm [4]. However, the favorable part of the CR technology to 4G/5G is not the original idea to develop intelligent devices (with powerful RF front end, powerful signal processing capability, and powerful computation capability for sophisticated analysis, learning, and decision making) and networks formed by these intelligent devices (i.e., the cognitive radio network, CRN), due to the following critical concerns.

1. Reliability issue: The major task for a cellular network is to provide reliable services to users while maintaining the network stability. Specifically, quality-of-service (QoS) should be guaranteed for timing constrained services. In addition, continuous traffic congestion, unrecoverable link failure, and uncontrollable communication behavior should be avoided in a cellular network. These are extremely critical challenges for a CRN with a distributive design. For cellular networks, when a tradeoff between performance and reliability is encountered, reliability should have a higher priority. This is the reason that 4G engages in sophisticated network infrastructures.

2. Potential system impacts and complexity: Due to the conflictions on the design philosophy and system architecture between 4G and the conventional CRN, considerable system impacts are introduced as applying the original design paradigm of CR to 4G. This concern substantially obstructs the development of this direction, at least in this decade.

Since [5], a novel design paradigm based on the CR technology referred as the cognitive radio resource management (CRRM), using radio resource as the core of cross-layer design, opens a practical direction harmonious to the system operations of 4G. With the technical merit of the CR technology, the CRRM controls the physical layer radio operations of communication environment cognition and channel access via the upper layers resource management. Compatible to the state-of-the-art system architecture of 4G, the CRRM smoothly introduces the CR technology to 4G. In LTE-A and LTE-B, a variety of communication scenarios will be supported beyond the HetNet, such as coexisting with systems operating on the ISM band (e.g., WiFi networks), device-to-device (D2D) communications [6], and heterogeneous coordinated multipoint (Het-CoMP) communications. Targeting at these scenarios, in the literatures, a variety of CRRM schemes have been proposed in recent three years, not only for human-to-human (H2H) communications in the HetNet [7–10] but also for machine-to-machine (M2M) communications with dynamic spectrum accesses in cyber-physical systems [11, 12]. However, all these schemes suffer from a new dimension of challenge that the inherent opportunistic channel access results in a severe channel availability variation to significantly harm the QoS guarantees. To combat such an issue, each CRRM scheme needs corresponding optimum control mechanisms. However, such a diverse design perplexes the system implementation in 4G/5G.

It is the time to envision facilitation of the CRRM for practical implementation of future cellular networks. Consequently, the purpose of this article is to organize and restructure the most recent developments of the CRRM into a software-defined design. Inspired by the wisdom of software-defined communication processors [13, 14] where functions/hardwares in individual layers are reused, configured, controlled, and optimized by means of software, we illustrate a layerless design that functions in Layer 1 to Layer 3 are controlled in the central of the resource management. By such a concept, all communication scenarios supported by LTE-A/LTE-B can be taken through proper configurations. Most importantly, it is demonstrated that the QoS guarantees be achieved solely by optimizing the operation/parameters in the software-defined design. Such a technical merit leads to a straightforward implementation of the CRRM toward the 5G cellular network.

COGNITIVE RADIO RESOURCE MANAGEMENT AND THE SOFTWARE-DEFINED DESIGN

Due to potential interference to/from other wireless systems (e.g., WiFi) and intra-network interference from neighboring cells of 3GPP, each resource block (RB) in a subframe shall not be occupied by more than one cells (nor more than one systems). To achieve this goal, a centralized RB allocation scheme is infeasible, due to

- An unacceptable high computational complexity
- The lacking of an appropriate interface for information exchange of RB occupations among cells and systems

As a consequence, the key idea of the CRRM lies in that each cell obtains RB occupation situations of neighboring cells and wireless systems through Layer-1 measurements, then only utilizing unoccupied RBs based on measurement results. To full reuse functions in existing releases, the CRRM is restricted to only leverage Layer-1 procedures and capabilities approved by 4G. In the following, the Layer-1 measurement capabilities supported by LTE-A are outlined.

Received interference power: In 3GPP TS 36.214, an E-UTRAN (eNBs of Macrocell and picocell, and HeNBs) is capable of measuring interference power on each RB in a subframe basis. The original purpose of this quantity is for identifying interference from an UE located at the cell edge of the neighboring Macrocell. If an RB is identified as occupied by other UEs (interference on this RB exceeds a predetermined threshold), an eNB will avoid allocating such occupied RB to its UEs. Through measuring this quantity, an eNB or an RN can identify RBs occupied by neighboring cells (or WiFi if the Band-40 is utilized).

Reference signal received quality (RSRQ): In 3GPP TS 36.214, an UE is able to utilize reference signals to measure the signal to interference and noise power ratio (SINR) averaged over considered bandwidth. If the value of this quantity is too low, interference is severe on considered bandwidth.

Number of neighboring small cells: In 3GPP TS 25.967, a HeNB (and thus an eNB) is able to identify cell identifications (cell IDs) of neighboring cells. Thus, a HeNB (and thus an eNB) is able to identify the number of neighboring cells.

Since a Macrocell typically handles a larger number of UEs than that of a small cell, a small cell should adapt to operations of Macrocells. Furthermore, if Band-40 is utilized (2300 to 2400 MHz), WiFi is one of major sources introducing considerable inter-network interference to LTE-A. Since WiFi is typically extensively deployed (as a group of WiFi networks) to provide seamless services to users, they may affect the entire Macrocells, small cells, and D2D links. As a consequence, UE, small cells, and Macrocells should adapt to operations of WiFi networks, due to the fact that WiFi is a widely deployed legacy system. Aligning with these operating principles, a variety of recent CRRM schemes for different scenarios [7–12] are actually on a common functional structure. Consequently, a software-defined design can be constructed with the following operations.

1. Subframe boundaries of small cells align with those of Macrocells. A similar agreement is reached in TR 36.921.
2. For all E-UTRAN (eNBs, HeNBs or RNs), there are logically two kinds of subframes: measurement subframe and data subframe. In each measurement subframe, each E-UTRAN identifies those RBs are occupied. Then, in subsequent data subframes, the E-UTRAN only allocates unoccupied RBs (measured in the latest measurement subframe) to its UEs. As a consequence, an E-UTRAN can not perform data transmission and reception in a measurement subframe. The measurement period (in the unit of the number of subframes) is dynamic for small cells, while it is fixed for Macrocells and RNs.
3. By identifying occupied RBs in each measurement subframe, an E-UTRAN can further infer the traffic load and RB allocation correlation in the neighboring cells (or WiFi networks) for the subsequent optimum control.

From Step 2, it is known that a measurement subframe is an overhead for the communication environment cognition. If the measurement period is very short, most subframes are leveraged for measurement, and thus the available radio resources are significantly reduced. On the other hand, if the measurement period is very long, although the overhead is significantly reduced, dynamics of interference can not be accurately captured. As a result, the available radio resource without interference may not increase. Therefore, there exists a tradeoff between interference and the amount of available radio resources (similar to the sensing-throughput tradeoff in the CRN [3]). By above software-defined design, QoS can be provided by strike such a tradeoff under all kinds of communication scenarios. However, a dynamic measurement period is not the case for Macrocells, as Macrocells shall support a considerable number of UEs, and a dynamic measurement period may increase the burden in scheduling.

CONFIGURATIONS OF THE SOFTWARE-DEFINED DESIGN

CONFIGURATIONS FOR INTRA-NETWORK INTERFERENCE MITIGATION

To support all kinds of communication scenarios, our software-defined design consequently integrate a variety of CRRM schemes to mitigate interference under the HetNet, D2D communications, multi-system coexistence as well as Het-CoMP.

Scenario 1. Mitigating Interference between A Small Cell and Macrocells (and WiFi Networks) — As shown in Fig. 1, all small cells underlay coverage areas of Macrocells (and WiFi networks) may invoke/suffer interference to/from Macrocells (and WiFi networks). For such interference mitigation, in Step 2 of above software-defined design, an HeNB in a femtocell can identify occupied RBs in a measurement subframe by measuring the received interference power on all RBs in a measurement subframe. If this quantity exceeds a pre-determined threshold on an RB, this RB is identified as occupied by Macrocells (or WiFi networks). By only utilizing unoccupied RBs, interference can be consequently mitigated. However, this operation is not generally sufficient for picocells. Since the coverage of a picocell is typically larger than that of a femtocell, only the measurement by the picocell eNB may not completely reflect the interference situation of all UEs distributed over the coverage of the picocell. Thus, all UEs shall measure the corresponding location-based RSRQ in a measurement subframe and report the measurement results to the picocell eNB. However, if there is a large number of UEs, the uplink channel for measurement report may suffer from severe congestions. To overcome this huge challenge, the *compressed sensing* technology can be applied [15]. Compressed sensing origins as a signal processing technology, which is able to sample an audio/image signal with a sampling rate far lower than the Nyquist rate. The signal can be recovered with an acceptable error rate if certain constraints can be satisfied. Such technical merit makes compressed sensing a powerful technology for picocells. As shown in Fig. 1, the coverage area of a picocell is divided into N isomorphic grids indexed by $n = 1, \ldots, N$. By applying compressed sensing, within each measurement subframe, each UE performs channel measurement with a probability $q \leq 1$. As a result, if there are V UEs in a picocell, only $qV \leq V$ UEs are responsible for performing the measurement and report. Upon receiving feedback from UEs,

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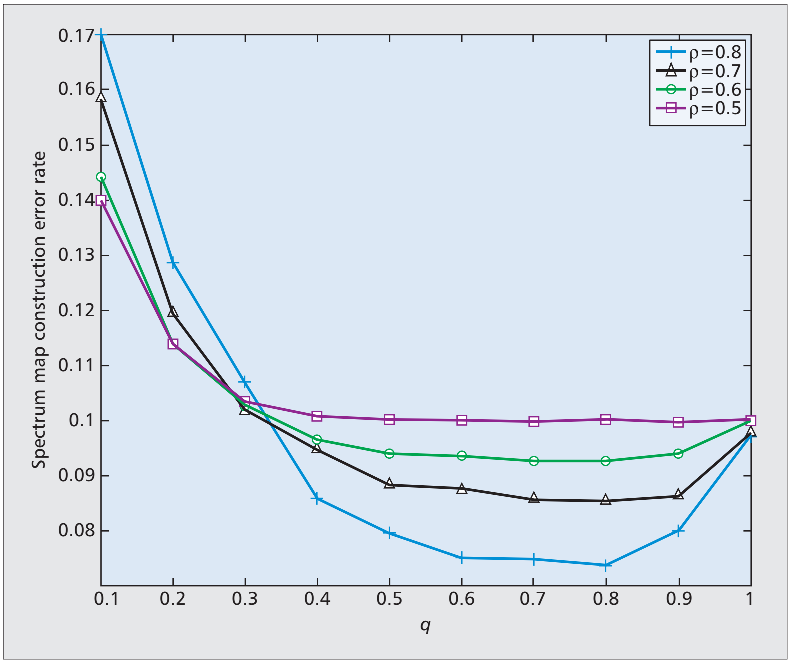

Figure 2. *Error rate of the spectrum map construction under different* q*. In this simulation, there are 7 hexagonal-grid Macrocells with wrap-around and three picocells within the coverage of Macrocells. All Macro- and picocells share a 20MHz bandwidth with* M = *100 RBs per subframes.* ρ = M′/M *denotes the traffic load of Macrocells, where* M′ *is the number of RBs utilized by Macrocells in each subframe. Other parameters and assumptions for simulation follows the definition in 3GPP TR 36.814.*

compressed sensing takes place in the eNB by multiplying a $R \times N$ sampling matrix $\mathbb{A}$ (with each element taking "1" with probability

$$q\frac{V_n}{V},$$

and taking "0" with probability

$$1-q\frac{V_n}{V}, V_n$$

is the number of UEs within the nth grid) on the true RBs occupation $\Psi = [\psi_1 \psi_2 \ldots \psi_N]^T$ of Macrocells (and WiFi networks), where ψ_n indicates RB occupations among M RBs in a measurement subframe on the nth grid. That is,

$$\mathbf{y} = \mathbb{A}\Psi + \varepsilon. \qquad (1)$$

We particularly call the RB occupations at all the grids as a "spectrum map." The spectrum map can be constructed by searching the minimum l_1 norm of Ψ

$$\Psi^* = \arg\min \|\Psi\|_1 \text{ s.t. } \|\mathbb{A}\Psi - \mathbf{y}\|_2 \leq \varepsilon, \qquad (2)$$

if

$$R = O\left(K \log \frac{NM}{K}\right),$$

where K is the sparsity of $\mathbb{A}$, $\varepsilon = |\Phi\varepsilon|_2$ and Φ is a random basis.

The accuracy on the spectrum map construction by compressed sensing depends on the sparsity of the true RBs occupations in Macrocells (and WiFi networks) and q. The sparsity of the true RBs occupations in Macrocells (and WiFi networks) is uncontrollable for a picocell. However, through the evaluation on the error rate of the spectrum map construction in Fig. 2, it shows that there is only a 7.5 percent error (7.5 RBs are occupied by Macrocells but they are estimated as unoccupied, or 7.5 RBs are not occupied by Macrocells but they are estimated as occupied, among 100 RBs in a subframe) by properly setting $q \in [0.6, 0.8]$. Please note that it suggests that only 60 percent among V UEs are adopted for channel measurement. This result sufficiently shows practicability and effectiveness of the software-defined design on supporting compressed sensing.

Scenario 2. Mitigating Interference among Small Cell — By the software-defined design, all small cells can autonomously mitigate interference to/from Macrocells and WiFi networks. However, the subsequent challenge is interference among small cells deployed closely with each other (referred as collocated small cells), as shown in Fig. 1. For collocated small cells, an identical "pool" of unoccupied RBs are identified. To avoid interference among small cells, each small cell shall utilize distinct RBs from each other. However, in LTE-A, there is no interface provided for femtocells to exchange information. For picocells, although the X2 is available for data exchanges via wired link, the large latency may not fully reflect the resource variation in Layer 1. As a result, lacking an appropriate interface for a centralized coordination among small cells in LTE-A, each collocated small cell should randomize the utilization of unoccupied RBs to minimize interference among small cells. However, there is another factor that can significantly affect the performance. Since demands in small cells are typically different from one to another, if a small cell decides to utilize as many unoccupied RBs as it needs, interference may become severe when all collocated small cells have heavy demands. On the other hand, if a small cell decides to utilize unoccupied RBs in a very conservative manner, RBs are underutilized if all collocated small cells have light demands. Since the traffic demand in a small cell is unavailable to other small cells, an effective solution to determine the optimum number of unoccupied RBs for utilization lies in *game theory* [16]. In the following, for interference mitigation among femtocells or among picocells, the following enhancement can support the software-defined design for collocated small cells.

1. By measuring the number of neighboring small cells (i.e., the number of players in the game) with the Layer-1 capability defined in TS 25.967, the number of unoccupied RBs in the measurement subframe and the number of total RBs in a subframe, the utility function can be formulated as the number of available RBs without interference.
2. The optimum number of unoccupied RBs for utilization is determined by the equilibrium solution.
3. After determining the optimum number of unoccupied RBs for utilization, these RBs are utilized by a small cell in a randomized manner.

Scenario 3. Mitigating Interference for a D2D Link — D2D is a new type of communications that will be supported by 3GPP Rel. 12 to reduce burdens of eNBs by localized communications. There can be two possible cases for D2D communications: the eNB allocating RBs for D2D links, and UEs autonomously identifying unoccupied RBs for D2D communications. The first case is suitable for D2D links underlay small cells, as shown in Fig. 1. Since a small cell typically handles a smaller number of UEs, scheduling for D2D communications does not introduce significant computational burdens. Furthermore, a small cell typically has a smaller coverage, and thus the impact to other UEs from a small cell can be precisely characterized. The second case is suitable for D2D links underlay Macrocells due to similar reasons. For D2D links underlay small cells, an HeNB or an eNB of a picocell can identify unoccupied RBs from Macrocells (and WiFi networks) and neighboring small cells through the configurations for the Scenario 1 and Scenario 2. For D2D links underlay Macrocells, an UE can also utilize the configuration for the scenario 1 to identify unoccupied RBs from Macrocells (and/or WiFi groups) and neighboring D2D links, respectively. Under this case, the measurement period of an D2D link is also adjustable.

CONFIGURATION FOR INTER-NETWORK INTERFERENCE MITIGATION

Scenario 4. Mitigating Interference between Macrocells and WiFi — Similar to the above three scenarios, to mitigate interference to/from WiFi networks, Macrocells also adopt measurement subframes for interference estimations. However, different from the above three scenarios for small cells and D2D communications, Macrocells face a huge challenge of handling a large number of UEs. As a result, the measurement period of Macrocells and RNs may have to be fixed, as a dynamic measurement period may perplex the system operation for stability to support and coordinate a large number of UEs. In addition, communications in a small cell enjoy a stronger signal strength than that in a Macrocell. Therefore, data rates in a small cell typically are invulnerable to interference from WiFi groups. However, data rates of longer distance communications in a Macrocell are typically vulnerable to WiFi groups. As a result, most RBs in data subframes may be unavailable for Macrocells due to severe interference under concurrent transmissions of WiFi networks and a Macrocell. For IEEE 802.11, the network allocation vector (NAV) for each station can be set to the maximum of around 33 ms for continuous packet transmissions. Under this circumstance, communications in a Macrocells may be suspended for 33 subframes, which may disable a Macrocell from providing QoS guarantees for services with timing constraints. For the traditional link between an eNB and an UE, such interference is never alleviated. To combat this critical issue, a powerful multi-antenna technology of CoMP transmissions [17] can be applied. For traditional CoMP transmissions, multiple eNBs transmit an identical packet to an UE via different links. By such transmission diversity, the timing constraint of a service is violated only if none of the links can successfully deliver the packet before expiration of timing constraints, thus the QoS is enhanced. Although, by CoMP transmissions, additional radio resources in the spatial domain are required, the communication suspension due to interference from WiFi can be alleviated. In future releases of 3GPP, eNBs are no longer the only transmitter in CoMP transmissions. In addition, RNs are involved as a major part of CoMP transmissions. Thus, the traditional CoMP evolves to the Het-CoMP, as shown in Fig. 1. To support this new feature, the software-defined design can be configured by the following way.

1. All eNBs and RNs involved in CoMP transmissions identify interference from WiFi based on the operation of the software-defined design. The measurement period of these eNBs and RNs are set to a fixed value.
2. When a packet with timing constraint is required to be transmitted to an UE, eNBs involved in CoMP simultaneously transmit identical packets (the duplication of the packet) to the UE (or to an RN if there is one) via different links.
   - –RNs transmit the packet to the UE or the next hop RN as they receive the packet from an eNB or the previous hop RN.
   - –The eNBs and RNs only utilize unoccupied RBs in each data subframe, and it may take multiple subframes to transmit a packet to the UE. In addition, since eNBs (and RNs) suffer from different levels of interference from WiFi, it also takes distinct numbers of subframes to deliver a packet to an UE from different links (with or without RNs). Since all these eNB deliver an identical packet, the timing constraint is violated only if none of the links can deliver the packet by the timing constraint expiration.
3. For packets without timing constraints is required to be transmitted, eNBs are involved in CoMP transmissions distinct packets to the UE (or to an RN if there is one) via different links to enhance the throughput.
   - –RNs transmit the packet to the UE or the next hop RN as they receive the packet from an eNB or from the previous hop RN.
   - –The eNBs and RNs only utilize unoccupied RBs in each data subframe.

In future releases of 3GPP, eNBs are no longer the only transmitter in CoMP transmissions. In addition, RNs are involved as a major part of CoMP transmissions. Thus, the traditional CoMP evolves to the Het-CoMP.

THE OPTIMUM CONTROL OF THE SOFTWARE-DEFINED DESIGN

THE OPTIMUM CONTROL FOR INTRA-NETWORK INTERFERENCE MITIGATION

To provide QoS guarantees while maximizing resource utilization for interference mitigation intra LTE-A/B, the measurement period as well as the allocation of unoccupied RBs shall be optimized. For this purpose, a novel control theory joint queueing theory and information theory, i.e., the *effective bandwidth theory* and the *effective capacity theory*, can be exploited. The *effective bandwidth theory* specifies the minimum service rate to serve a given arrival process subject to a given QoS requirement. On the other

Since the measurement period is fixed for Macrocells and RNs, to provide QoS guarantees while maximizing resources utilization, the key is to determine the optimal packet transmission time for different services in Het-CoMP transmissions, as identical packet transmissions from multiple eNB may waste spatial domain radio resources.

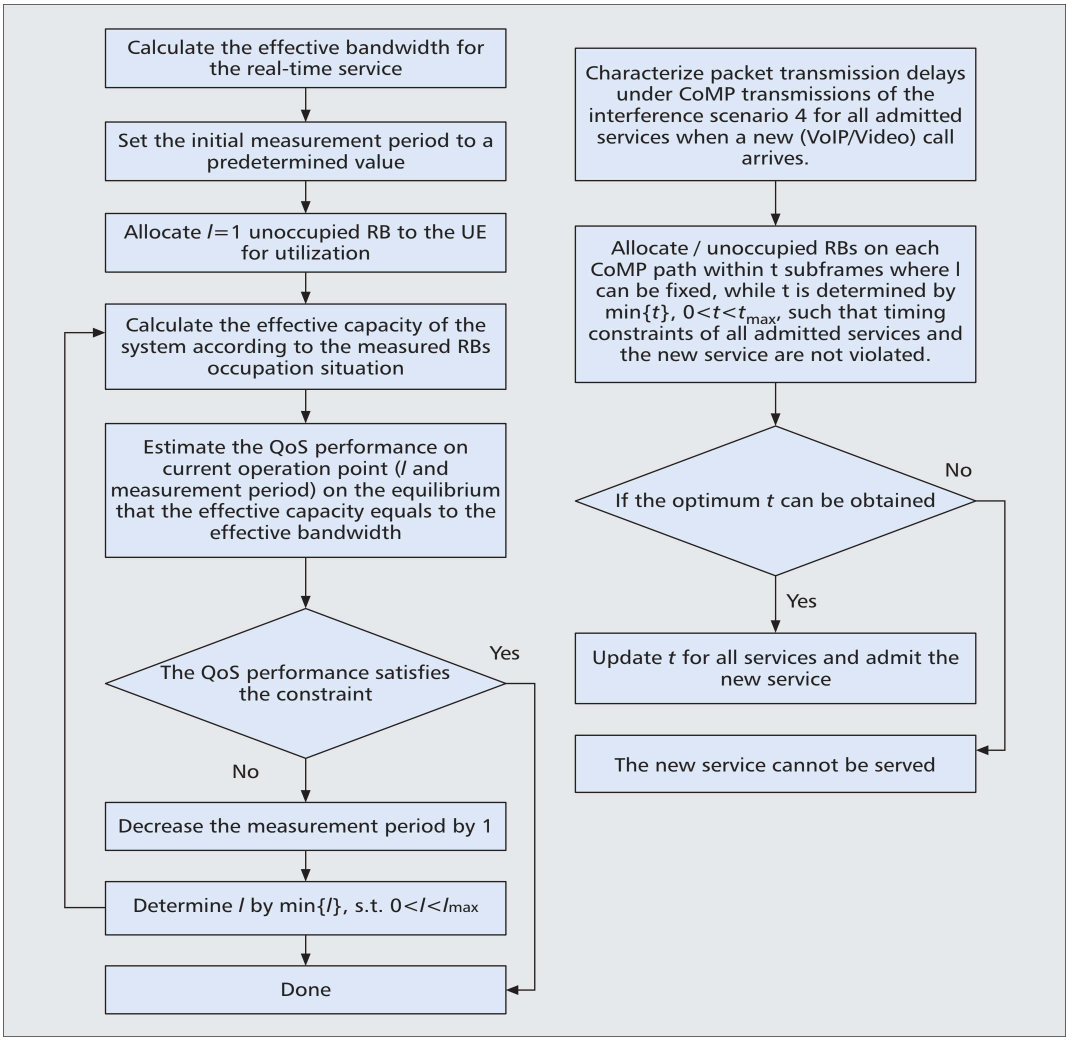

Figure 3. *The optimal control procedures for the software-defined design. For a HeNB, an eNB of a picocell, or an UE performing D2D communications, the optimum control calculates the effective capacity denoted by* $\mathrm{E}_C^{l,T_s(\theta)}$ *under different values of allocated unoccupied RB* l *and measurement period* T_s*, and calculates the effective bandwidth of voice/video traffic denoted* $\mathrm{E}_B(\theta)$*, where* θ *is a parameter known as the QoS exponent.* l *and* T_s *are optimized by achieving* $\mathrm{E}_C^{l,T_s}(\theta) = \mathrm{E}_B(\theta) = \delta$ *such that the delay violation probability* $Pr\{Delay > d_{max}\} = e^{-\theta\delta d_{max}}$ *satisfies the requirement. For a Macrocell eNB, the optimum control calculates packet transmission delays under different number of paths supported by Het-CoMP transmissions. If the optimum solution on the number of allocated RB and the number of Het-CoMP paths can be obtained such that QoS requirements are satisfied, the service can be admitted.*

hand, the *effective capacity theory* specifies the maximum constant arrival rate that can be supported by the system subject to a given QoS requirement. When the effective bandwidth equals to the effective bandwidth, an equilibrium of a statistical delay guarantee can be reached (that is, the probability that packet delivery delay exceeds the required value is upper bounded by a certain value). To apply this in cellular networks, a HeNB, an eNB of a picocell, or an UE performing D2D communications calculates the effective bandwidth of timing-constrained services [18], and calculates the effective capacity of the configurations for interference Scenario 1, Scenario 2 or Scenario 3 according to the traffic load and RB allocation correlation of neighboring cells under different measurement periods and numbers of utilized RBs. The measurement period and the number of utilized RBs can consequently be optimized under the condition that the effective bandwidth equals to the effective capacity, and the corresponding QoS performance satisfies the requirement, as detailed in Fig. 3.

THE OPTIMUM CONTROL FOR INTER-NETWORK INTERFERENCE MITIGATION

Since the measurement period is fixed for Macrocells and RNs (and thus the overhead is fixed), to provide QoS guarantees while maximizing resources utilization, the key is to determine the optimal packet transmission time for different services in Het-CoMP transmissions, as identical packet transmissions from multiple eNB may waste spatial domain radio resources. To achieve this goal, packet transmission delays under Het-CoMP transmissions shall be characterized by eNBs for different (voice/video) services based on different activities of WiFi networks. After analytically characterizing packet transmission

Traffic	Delay-bound	Delay-bound violation prob.	Violation prob. software-defined design (low correlation)[a]	Violation prob. of software-defined design (high correlation)[b]	Violation prob. of Randomization (low correlation)	Violation prob. of Randomization (high correlation)
Star Wars	40ms	≤ 0.02	0.0199	0.0066	0.0464	0.0331
Die hard	40ms	≤ 0.02	0.0172	0.0058	0.0398	0.0313
Jurassic Park	40ms	≤ 0.02	0.0181	0.0055	0.0415	0.0299
VoIP	20ms	≤ 0.02	0.0012	0.0003	0.0013	0.0008

[a] There is a low correlation of RBs allocation in Macrocells (and WiFi networks) among subframes (that is, if a particular RB is occupied in a subframe, this RB is occupied by Macrocells (and WiFi networks) in subsequent subframe with a low probability of 0.3).

[b] There is a high correlation of RBs allocation in Macrocells (and WiFi networks) among subframes (that is, if a particular RB is occupied by Macrocells (and WiFi networks) in a subframe, this RB is occupied in subsequent subframe with a high probability of 0.8).

Table 1. *QoS requirements and simulation results on the delay bound violation probability for the VoIP and high quality MPEG4 video transmissions in a small cell for intra-network interference mitigation.*

delays for different services, eNBs can make the optimum RB allocation as well as admission control such that timing constraints of all admitted services can be satisfied. Such the optimum control for Macrocells is also illustrated in Fig. 3.

PERFORMANCE EVALUATIONS

To show technical merits of the software-defined design of the CRRM, reliability in terms of QoS guarantees is evaluated under different interference scenarios. These simulations are conducted based on system parameters and assumptions defined by 3GPP TR 36.814 for LTE-A with 20MHz bandwidth. Each RB is composed of 12 subcarriers over 7 OFDM symbols. There are 7 hexagonal-grid Macrocells with wrap-around, and 5 clusters of small cells deployed over the coverage areas of Macrocells. Each cluster is composed of 1 to 5 small cells. Transmission power of a Macrocell, a picocell, a femtocell, an RN, and a WiFi network is set to 46 dBm, 30 dBm, 20 dBm, 30 dBm, and 3dBm, respectively. By the software-defined design, a station in LTE-A/LTE-B can autonomously acquire RB occupation situations of neighboring cells to proceed to an optimized action according to acquired RB occupation situations. Without autonomous acquisition of RB occupation situations, a station has no information about RBs occupation in a subframe (and the potential trend of such RB occupation) by neighboring cells. Under this constraint, the optimal scheme for interference mitigation lies in the *randomized* scheme. That is, each eNB, HeNB or UE in D2D communications randomizes the RB utilization in a subframe to avoid interference on successive RBs. In the following simulations, the performance on the support of real-time voice and video services is particularly evaluated.

MITIGATING INTRA-NETWORK INTERFERENCE

Table 1 shows the simulation results of a small cell on the support of real-time voice and video transmissions. For the voice traffic, a VoIP stream is considered. The arrival process of the VoIP is the well-known ON-OFF fluid model. The holding times in "ON" and "OFF" states are exponentially distributed with the means 6.1s and 8.5s, respectively. The data rate of the "ON" state is 32Kb/s. The delay bound is 20ms and the delay bound violation probability is 0.02. For video traffic, a high quality MPEG4 movie trace is considered. The delay bound of the video traffic is 40ms and the delay bound violation probability is 0.02. The results in Table I show the effectiveness on the support of the statistical delay guarantees by the software-defined design, while the video traffic can not be supported by the randomized scheme.

MITIGATING INTERFERENCE FROM WIFI NETWORKS

For inter-network interference mitigation, Table 2 shows simulation results of the timing constraint violation probabilities of 5 VoIP and 5 video streams. The results are demonstrated in the form of (timing constraint violation probability, average activity of WiFi networks on each Het-CoMP link) under different number of Het-CoMP links that shall be involved (denoted by S). We can observe from Table 2 that, for $S = 1$, QoS of all VoIP and video can be guaranteed when the average activity of WiFi networks on each Het-CoMP link does not exceed 0.8. For $S = 3$ and $S = 5$, QoS can be guaranteed when the average activity of WiFi networks on each Het-CoMP link does not exceed 0.5 and 0.4, respectively.

Although Table 2 shows that QoS of all VoIP and video can be guaranteed, it does not reveal the efficiency on the utilization of the spatial domain radio resources in the Het-CoMP, as transmitting identical packets via multiple eNBs potentially wastes radio resources. In Fig. 4, the numbers of required Het-CoMP (or CoMP) paths of the software-defined design and the state-of-the-art CR transmission scheme. We can observe from Fig. 4 that, to provide QoS guarantees for 5 VoIP and 5 video streams, the existing CR scheme requires a larger number of Het-

Stream	VoIP1	VoIP2	VoIP3	VoIP4	VoIP5	Video1	Video2	Video3	Video4	Video5
$S = 1$	(0.001, 0.9), (0.008, 0.8)	(0.001, 0.9), (0.008, 0.8)	(0.001, 0.9), (0.008, 0.8)	(0.002, 0.9), (0.008, 0.8)	(0.002, 0.9), (0.008, 0.8)	(0, 0.9), (0, 0.8)	(0, 0.9), (0, 0.8)	(0, 0.9), (0, 0.8)	(0, 0.9), (0.006, 0.8)	(0, 0.9), (0.007, 0.8)
$S = 3$	(0, 0.9), (0, 0.8), (0, 0.7), (0.002, 0.6), (0.007, 0.5)	(0, 0.9), (0, 0.8), (0, 0.7), (0.002, 0.6), (0.007, 0.5)	(0, 0.9), (0, 0.8), (0, 0.7), (0.002, 0.6), (0.007, 0.5)	(0, 0.9), (0, 0.8), (0, 0.7), (0.002, 0.6), (0.007, 0.5)	(0, 0.9), (0, 0.8), (0, 0.7), (0.002, 0.6), (0.007, 0.5)	(0, 0.9), (0, 0.8), (0, 0.7), (0, 0.6), (0.007, 0.5)	(0, 0.9), (0, 0.8), (0, 0.7), (0, 0.6), (0.007, 0.5)	(0, 0.9), (0, 0.8), (0, 0.7), (0, 0.6), (0.007, 0.5)	(0, 0.9), (0, 0.8), (0, 0.7), (0.001, 0.6), (0.005, 0.5)	(0, 0.9), (0, 0.8), (0, 0.7), (0.002, 0.6), (0.005, 0.006, 0.5)
$S = 5$	(0, 0.9), (0, 0.8), (0, 0.7), (0, 0.6), (0.001, 0.5), (0.003, 0.4)	(0, 0.9), (0, 0.8), (0, 0.7), (0, 0.6), (0.001, 0.5), (0.004, 0.4)	(0, 0.9), (0, 0.8), (0, 0.7), (0, 0.6), (0.001, 0.5), (0.004, 0.4)	(0, 0.9), (0, 0.8), (0, 0.7), (0, 0.6), (0.001, 0.5), (0.004, 0.4)	(0, 0.9), (0, 0.8), (0, 0.7), (0, 0.6), (0.001, 0.5), (0.004, 0.4)	(0, 0.9), (0, 0.8), (0, 0.7), (0, 0.6), (0, 0.5), (0, 0.4)	(0, 0.9), (0, 0.8), (0, 0.7), (0, 0.6), (0, 0.5), (0, 0.4)	(0, 0.9), (0, 0.8), (0, 0.7), (0, 0.6), (0, 0.5), (0, 0.4)	(0, 0.9), (0, 0.8), (0, 0.7), (0, 0.6), (0.001, 0.5), (0.003, 0.4)	(0, 0.9), (0, 0.8), (0, 0.7), (0, 0.6), (0.001, 0.5), (0.003, 0.4)

Table 2. *Simulation results of QoS provisioning for the scenario of inter-network interference mitigation.*

CoMP (or CoMP) paths as compared with that of the software-defined design. These results sufficiently demonstrate the effectiveness of the optimum operation of the software-defined design.

CONCLUSION

The CRRM reforms the original concept of the CR to a realistic layerless technology to solve challenging interference in cellular networks. Considering all practical scenarios, we present a software-defined design with the optimum control relieving individual sub-system function. Such design thus enables the development of the CRRM from a promising concept to a successful practice, and leads to a novel realization of software-defined network processor architecture for LTE family of systems. At this standpoint, we delineate the new research opportunities toward the next evolution of cellular network designs.

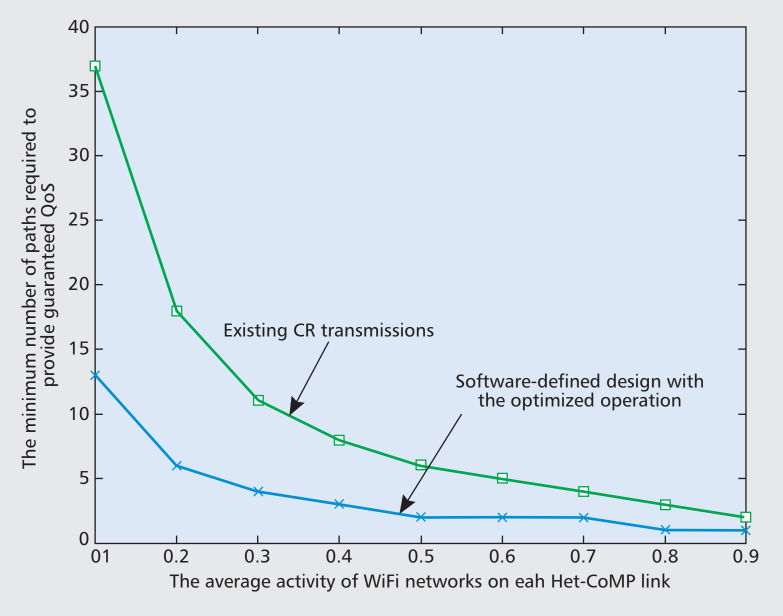

Figure 4. *The numbers of required Het-CoMP paths to provide QoS guarantees for 5 VoIP and 5 Video streams.*

ACKNOWLEDGEMENT

This research is sponsored by MediaTek Inc. with project number 102H32048 under the MediaTek-NTU Advanced Research Center.

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