A Survey of Self-optimization Approaches for HetNets

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Abstract

Network convergence is regarded as the development tendency of the future wireless networks, for which self-organization paradigms provide a promising solution to alleviate the upgrading capital expenditures (CAPEX) and operating expenditures (OPEX). Self-optimization, as a critical functionality of self-organization, employs a decentralized paradigm to dynamically adapt the varying environmental circumstances while without relying on centralized control or human intervention. In this paper, we present comprehensive surveys of heterogeneous networks (HetNets) and investigate the enhanced self-optimization models. Self-optimization approaches such as dynamic mobile access network selection, spectrum resource allocation and power control for HetNets, etc., are surveyed and compared, with possible methodologies to achieve self-optimization summarized. We hope this survey paper can provide the insight and the roadmap for future research efforts in the self-optimization of convergence networks.

Keywords: Self-optimization, Heterogeneous, Access Network Selection, Spectrum Resource Allocation, Power Control.

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1. Introduction

In recent years, with the rapid popularity of smart/mobile devices, users can access network more frequently and conveniently, resulting in an explosion of mobile traffic. Relying only on a single wireless access network or radio access technology (RAT) would hardly satisfy the customers' traffic requirements. A variety of RATs are thus necessarily deployed for facilitating network convergence and simultaneously satisfying the customers' service requirements. Both the channel capacity and the radio coverage can be substantially improved by combining variant RATs and enabling the users to choose the optimal access network in a heterogeneous network (HetNet).

However, it may impose extra complexity on the network operators to maintain a seamless and heterogeneous service. Accordingly, self-organization is inspired in order to provide a promising solution for alleviating the upgrading capital expenditures (CAPEX) and operating expenditures (OPEX) in the large-scale HetNets. The users are thus enabled to dynamic adapt to the varying environmental circumstances without relying on the centralized control or human intervention [1].

The concept of self-organization mainly comprises four aspects, including self-configuration, self-optimization, self-healing, and plug-and-play. In this survey, we mainly focus on self-optimization, which is the critical functionality of self-organization. Mechanisms of self-optimization have been widely emphasized in HetNets for addressing the problems of mobile access network selection, spectrum resource allocation, and power control, etc. Furthermore, with the aid of various self-optimization approaches, the network throughput can be optimized by employing algorithms such as dynamic spectrum sharing and optimal power allocation in HetNets. Mathematical methods ofgame theory, combinatorial optimization, stochastic process and stochastic geometric theory, etc. may play an important role in implementing the self-optimization paradigms. Furthermore, in the existing self-organized methodologies, bio-inspired algorithms are among the most famous techniques and have already shown their advantages in optimizing the performance of HetNets [2, 3].

In this paper, we survey various aspects of HetNets such as network convergence, coexistence of multiple RATs and heterogeneous formats. The fundamentals of self-optimization for HetNets are first investigated, followed by surveying/comparing variant self-optimization algorithms such as dynamic mobile access network selection, spectrum resource allocation and power control, etc. Furthermore, we investigate various techniques that have been employed for implementing self-optimization in HetNets.

The remainder of this paper is organized as follows. In Section 2, we classify the HetNets into three types. The fundamentals of self-optimization are introduced in Section 3, followed by the detail of variant self-optimization algorithms presented in Section 4. In Section 5 we discuss the possible methodologies for achieving self-optimization. Finally the conclusions of this article are stated in Section 6.

2. Categorizations of HetNets

HetNet is a quite broad concept, which can be classified from the perspective of network types, radio access technologies and heterogeneous cellular formats.

2.1 Convergence of Different Network Types

In this subsection, we focus on the convergence of infrastructure networks such as Long Term Evolution (LTE) and infrastructure-less networks such as Wireless Sensor Network (WSN), as depicted in **Fig. 1**, in which each structure exhibits its pros and cons. For instance, WSN is featured by the characters of flexible deployment, whilst exhibits several disadvantages such as a short radio coverage, low throughout, and limited terminals' ability, etc. LTE networks, on the other hand, have larger radio coverage, higher throughout and better mobility robustness, whereas suffering from costly and complicated operation, administration and maintenance (OAM). It is therefore attractive to converge the aobve-mentioned architectures to facilitate a better service for the users. The authors in [4] gave an overview of architecture for the convergence of mobile cellular network and WSN by emphasizing the following key challenges.

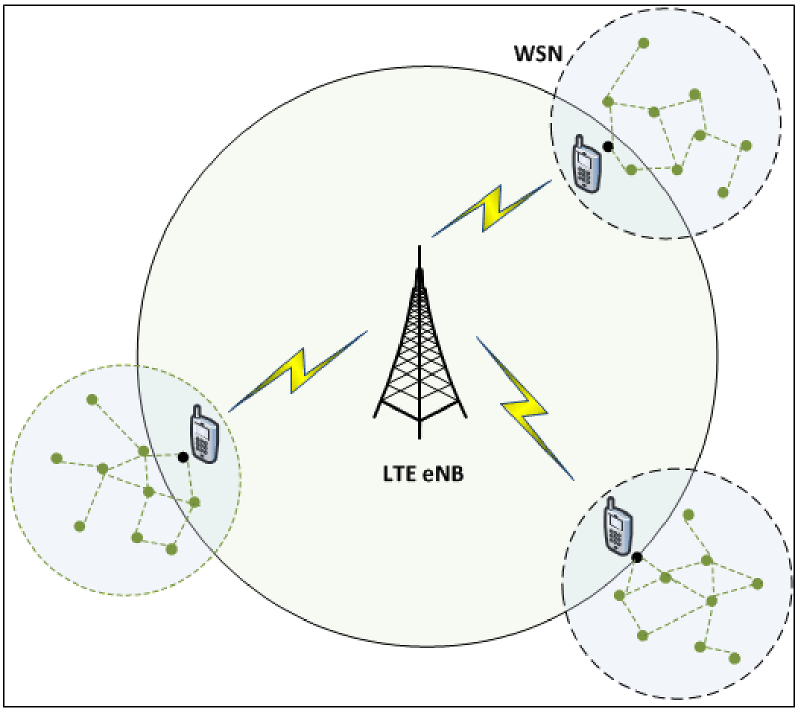

Fig. 1. Convergence of LTE and WSN

- *Network Architecture Convergence*: LTE controls and manages WSN through the mobile terminals, which also act as the gateway for the WSN devices. However, further investigating this topic is still needed by designing optimization algorithms and addressing the tradeoff between complexity and performance gain.
- *Air-interfaces Convergence:* Unlike LTE, which is a broadband system, WSNs transmit narrowband signals. Although some advanced technologies such as orthogonal frequency division multiple access (OFDMA) provide a potential solution to the problem of complicated radio resources scheduling between systems of different bandwidths, it is still challenging to achieve air-interfaces convergence via methods of carrier aggregation and multi-access interference mitigation.

- *Protocol Convergence:* Different standards require independent protocol stacks, in which each system conserve a data channel for performing information exchange. In converged networks, all the protocols should be jointly optimized to enable the data channels to be shared among variant standards.
- *Application Convergence:* LTE is a broadband mobile communication system that carries high speed data traffic. WSNs, as application-driven networks, are capable of supporting various smart applications and can thus substantially extend the applications of LTE networks from the perspective of application convergence.

2.2 Coexistence of Multiple RATs

As the rapid development of communication technologies, various wireless access networks (WANs) with different RATs, such as the second generation cellular system (GSM), the third generation cellular system, 3rd Generation Partnership Project (3GPP) LTE, IEEE 802.11 wireless standard, etc., have been deployed to facilitate an overlapped radio coverage, as illustrated in **Fig. 2**. Mobile devices such as smart mobile phones thus tend to support multiple RATs simultaneous for facilitating a ubiquitous and seamless wireless access. This tendency enables the customers to select a best WAN at any time. However, the operational costs of dynamic spectrum access control and distributed resource sharing make the wireless access much more complicated than ever. It is highly expected to employ a self-optimization approach to substantially reduce the operational cost in HetNets.

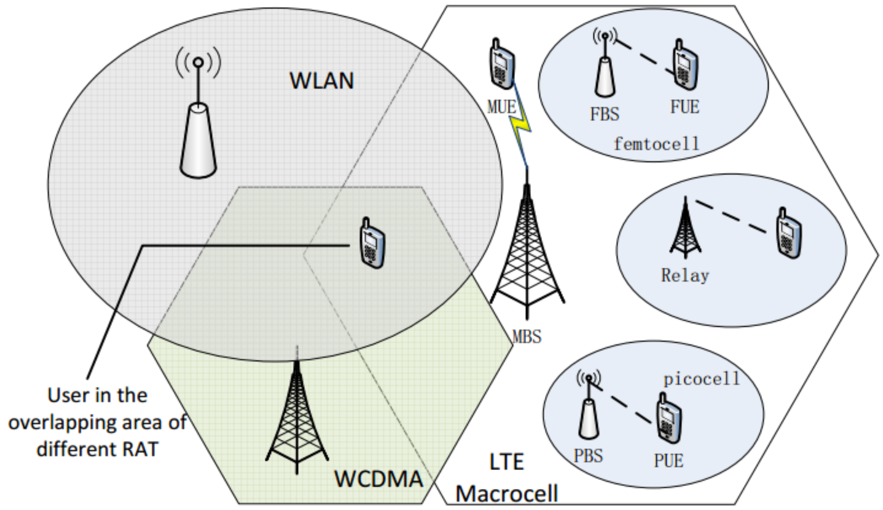

Fig. 2. Coexistence of Multiple RAT and Multiple cellular formats.

2.3 Coexistence of Multiple cellular formats

The traditional method for improving network throughput is performed by increasing the density of base stations (i.e., deploying more base stations in a given geographic area). However, this method does not always work well in practice due to the negative effect of serious inter-cell interference. An effective way for increasing network capacity is to overlap small cells (such as pico-cells, femtocells, and relay nodes) upon the traditional macro-cell coverage to enhance the cell-split gains (as shown in **Fig. 2**).

Currently, two-tier femtocell network has become a hot topic and attracted a lot of attentions by both the academia and industry. As a key challenge to it, cross-layer interference must be suppressed to make dynamic spectrum allocation and power control work well as a viable solution. Furthermore, self-optimization approach is likely to provide a potential way for dynamically allocating resource and effectively sharing the spectrum in a distributed manner.

3. Fundamentals of Self-optimization

Self-organization (SON), as exists in many branches of science such as biology, medicine, sociology, communication, etc, is originally regarded as an interdisciplinary and heterogenous research field that provides a promising solution for alleviating the upgrading CAPEX and OPEX in the large-scale HetNets. The most famous and successful SONs are wireless ad hoc and WSN, in which several well-known optimization algorithms have already been employed for improving the systems' performance. Furthermore, 3GPP LTE/LTE-Advanced systems have already emphasized the self-X capabilities (e.g., self-configuration, self-optimization, and self-healing) as a critical feature for achieving the systems' goals of robustness, reliability, scalability and power efficiency:

- Self-configuration is the process of network initialization when a new element joins the network without relying on manual intervention.
- Self-optimization is the process of dynamically adjusting the network parameters to adapt to the varying environments without relying on centralized control.
- Self-healing means the network's capability of recovering to a healthy state when it breaks down [2].

In this paper, we mainly focus on the self-optimization approaches in HetNets. The actual network environment is assumed to be time variant, thus the optimal network settings may not always be maintained. By employing self-optimization approach, the network states can always be maintained in an optimal or near-optimal condition by dynamically adjusting network parameters with minimal human intervention. Particularly, in HetNets, in which the network parameters become more complicated than homogeneous networks, the capability of self-optimization becomes more critical and indispensable. The critical role of self-optimization (which has been regarded as the main functionality of self-organization) in the HetNets will be analyzed in the following sections [3].

4. Self-optimization Approaches for HetNets

Self-optimization enables users to dynamically adapt to the varying environment in a decentralized manner in order to facilitate a cost-efficient performance optimization. Although self-optimization approaches has been widely studied in HetNets, the self-optimization approaches are still necessarily treated. In this section, we survey and compare variant optimization approaches that are mainly applied to the functionalities such as mobile access network selection, spectrum resource allocation and power control for HetNets (as shown in **Fig. 3**). Furthermore, variant approaches are compared in **Table 1**.

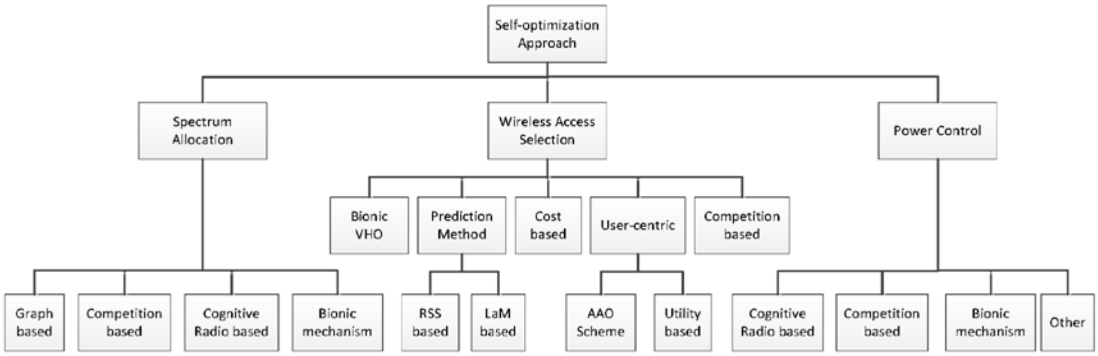

Fig. 3. Classification of the works on self-optimization approaches for HetNets.

4.1Self-Optimization Approaches for WAN Selection

WAN selection is necessarily performed in HetNets for facilitating a seamless service, whilst achieving traffic load balancing. Typical approaches for WAN selection are enumerated in follows.

1)Prediction Method

Prediction method is employed by mobile users to estimate channel information in order to enable an earlier response. The following mechanisms are emphasized in prediction method.

- *Adaptive received signal strength (RSS) prediction vertical handoff (VHO) mechanism* [5]: First, RSS can be estimated by using the polynomial regression to predict the orientation of a mobile device. Based on this criterion, whether VHO can be performed or not will be decided. After that, based on the Markov decision process (MDP) analysis, the network with lowest handoff cost (i.e., bandwidth cost) rather than the strongest RSS can be selected as the target network for achieving both a better load balancing and a lower call-drop rate.
- *Location and mobility-based (LaM) VHO mechanism* [6]: Based on the Markov chains, an adaptive common-radio-resource-management scheme, which employs a WAN selection algorithm to activate a new connection and a VHO algorithm for the mobile node moving across networks, can be developed. The aforementioned algorithms are operated spontaneously according to both the location information and the prediction model of the mobile devices.

2) User-Centric Method

User-centric method emphasizes the initiative of users in order to satisfy their requirement preferably.

- *Active application oriented (AAO) mechanism* [7]: In the AAO scheme, users can beproactivated to make VHO decision if and only if the application running on mobile devices is necessarily maintained. Power consumption can thus be reduced by minimizing the unnecessary VHO, leading to a more efficient power management.

Table 1. Comparison among variant self-optimization approaches for WAN selection, Spectrum allocation and power control.

Category		algorithm	Advantage	Disadvantage
WAN Selection	Prediction method	RSS-based [5]	1) Less unnecessary VHO 2) No dropping probability	Chooses WAN with a lowest handoff cost and might waste the best access network
		LaM-based [6]	1) Less unnecessary VHO 2) Low service cost	High call blocking probability
	user-centric	AAO scheme [7]	Executes handoff only in need	May fail to find a network with high enough QoS level
		Utility-based [8]	Different users could select the not-best but most-suitable network	Multiple intelligent users operating in the same region may cause congestion
	Competition based	Evolutionary games [10]	Investigates dynamics of user behavior	Slow convergence rate
Spectrum Allocation	Graph-based	Wang [12]	Achieves a tradeoff between the system throughput and user fairness	Lack of local optimizations
	Competition based	Niyato06 [13]	Low connection-blocking probability	Do not consider multiple users with different types of services
		Niyato08 [14]	Considers both network-level and connection-level bandwidth allocations	Ignores the impact of interference
	Cognitive radio-based	Lien [15]	1) Enables autonomous interference mitigation 2) Achieves fully radio resources utilization	Potential errors obtained in estimating macrocell RBs usage
Power Control	Cognitive radio-based	XieEnergy [18]	Energy-Efficient	Hard to attain perfect channel information
		XieDynamic [19]	Needs imperfect channel information	Local sensing may be degraded by shadowing phenomena
		Sardellitti [20]	Adopts cooperative sensing to mitigate local fading problems	Extra time and power costs in sensing
	Competition based	Chandrasekhar [22]	SINR of cellular users is well protected	Lots of FUEs cannot obtain their SINR target
		Ma [23]	Improves the SINR of FUEs while guaranteeing the target SINR of MUE	1) Needs accurate CSI 2) Do not consider the situation that an ideal channel reallocating to the interference FUEs is unavailable
	Other [25]	Open-loop	High macrocell throughput	Low femtocell throughput
		Closed-loop	High femtocell throughput	Low macrocell throughput

- *Utility-based VHO mechanism* [8]: In practical systems, the optimal network cannot be always selected either because the radio environment is time varying or because congestion happens if everyone wants to access the best network. A utility-based VHO mechanism can be proposed for addressing the aforementioned challenge, in which delays of variant WANs are estimated for enabling different users to select their most suitable network actively, whilst subjecting to the users' own constraints on transmission delays and service costs.

3) Cost-based VHO Method
This method can be designed based on the cost of possible target networks considering user/application's preferences for performing an optimal handover decision and network selection [9]. A cost function with weights of bandwidth’s and monetary’s costs can be defined in order to decide whether to perform a VHO or not. Furthermore, the cost function can be optimized by considering both service types and user preferences in HetNets. According to the cost function, the required delay and processing complexity can be reduced. In addition, the throughput for mobile terminals with multiple active sessions can be improved by employing the adaptive and intelligent VHO protocol.

4) Competition-based VHO Method
Although the optimal network usually allows limited users to access simultaneously, users may still try to select the optimal WAN to maximize their own reward, causing severe network-access competition among the users. Existing methodologies such as game theory can be employed as a ideal guidance to manage the competition and guide users to dynamically adjust their behavior according to the time-varying network conditions without relying on external control [10].

5) Intelligence-based VHO Method
In order to deal with the complicated conditions in practical network, it is necessary to make the handover decision more intelligent. A fuzzy Q-learning vertical handoff control strategy has been proposed to support the mobility management in vehicular HetNets [11], enabling an optimal handoff decision relying on the always-best-connected concept based real time learning. However, only throughput and delay aspects are taken into consideration in this strategy.

4.2 Self-Optimization Approaches for Spectrum Resource Allocation

A challenge arises in HetNets due to the limited spectrum resource and the ever increasing requirements of user services, inspiring effective spectrum allocation mechanisms that attracts extensive studies in recent literatures.

1) Graph-based Mechanism
In this mechanism, the channel assignment can be modelled as a problem of multi-coloring graph, in which each node represents a femtocell and each edge between two nodes represents the interference between two femtocells. A distributed and adaptive scheme comprising three steps for graphic radio resource allocation can also be developed for improving the fairness among users [12]: i) a graph-based model can be developed according to the received signal to interference and noise ratio (SINR) in femtocells, ii) an initial random-subchannel-allocation algorithm is performed, and iii) a tradeoff between system’s throughput and user’s fairness is achieved by executing an iteratively distributed adaptive-subchannels-allocation algorithm voluntarily in each femtocell.

2) Competition-based Mechanism

In a distributed resource-allocation mechanism, each mobile station tries to select the most unoccupied subchannels. With the help of a non-cooperative game, a Nash equilibrium subchannel allocation can be proposed for maximizing every mobile station's payoff as well as each networks' utility in a distributed fashion by considering the bandwidth allocation for various applications. Furthermore, a self-optimized bandwidth allocation for the new connections can be performed by using a bankruptcy cooperative game. In addition, based on the non-cooperative game, the bandwidth-allocation scheme can also be divided into network-level and connection-level self-optimized functionalities, where the former stands for a long-term viewpoint for different access network, but the latter is a short-term viewpoint for each new connection [14].

3) Cognitive Radio-based Spectrum Allocation Mechanism

Cognitive radio technologies have been employed in the femtocells by utilizing a self-organization approach to allocate the spectrum resource [15]. Methods of mixed integer-nonlinear-programming and decomposition can be utilized for processing the spectrum-sharing problem among macro/femtocells and achieving a lower user-blocking rate than using the coloring method. A four-step method for cognitive radio resource management can be performed: i) periodically sense the available spectrum hole, ii) select unoccupied resource block (RB) based on the received interference power, iii) allocate the unoccupied RB, and iv) extract other important parameters.

In order to address the tradeoff between the spectrum utilization and interference avoidance in HetNets, a partial spectrum reuse (PSR) scheme can be performed to leverage the spectrum reuse and interference mitigation between macrocells and small cells [16]. In PSR, small cells only partially reuse the system spectrum to reduce the intensity of interfering small cells, and consequently the inter-cell interference can be reduced. Furthermore, the energy efficiency of HetNets can also be improved by choosing the optimal spectrum reuse factor.

4) Intelligence-based Resource Allocation

Swarm intelligence inspired approaches can also be employed in a dynamic resource allocation mechanism for improving the spectral efficiency of an OFDMA system. An evolutionary algorithm called Particle Swarm Optimization (PSO), which is originally used to exchange information between biotic population, has exhibited an ideal benefit in distributing OFDMA subcarriers due to its capabilities of learning and forgetting in performing parameter control [17].

4.3 Self-Optimization Approaches for Power Control

Although low-power nodes can be deployed in an overlay fashion in HetNets, the appendant interference may substantially erode the systems' capacity. Power control, which is regarded as an effective approach for mitigating the interference and maximizing system performance simultaneously, has been widely studied.

1) Competition-based Power Control Mechanism

A non-cooperative game can be employed by a distributed utility-based SINR adaption for implementing an effective power control [21], in which the utility function consists of an SINR-dependent reward and the interference can be manipulated. A scheme of link-quality protection can also be proposed for protecting the cellular user from the strongest femtocell interference. However, a lot of femtocell users cannot achieve their SINR target at Nash Equilibrium point due to the interference imposed by macrocell users. In order to alleviate the aforementioned condition, femtocell users can be divided into two classes, i.e., the qualified users, whose channel gain is lower than that of the interference link, and interference users. The number of users not achieving their SINR target can be reduced due to the removing of users in the severe radio conditions [22]. Furthermore, power control based on Stackelberg game can also be performed, where each user prices its power and sells it to subchannels under the total power constraint. The optimization problem can be solved by using a distributed power-bargaining algorithm and emphasizing self-organization paradigm in it. In addition, a distributed power-optimization scheme in femtocell network can also be proposed based on non-cooperative game in order to mitigate inter-tier interference and reduce the strongest femtocell power when cellular users cannot achieve their SINR target.

However, most of the existed power control games perform active user selection in a random manner, resulting in a lose sight of user-diversity. In the following, we first compare different user–pairing methods and find an optimal way in considering user-diversity gain to maximize the macrocell capacity, and then perform the power control game. The user-pair-scheduling-based power control game shows a superior performance compared to the traditional stochastic schedule strategy based power control game, as illustrated in **Fig. 4** [24].

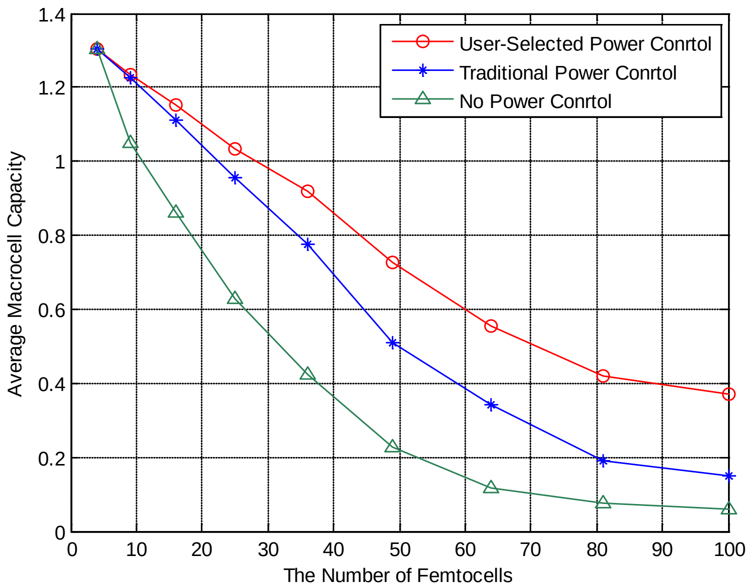

Fig. 4. Average macrocell capacity under schemes of no power control, traditional stochastic schedule strategy based power control and user-pair-scheduling-based power control.

2) Power Control in Cognitive Radio Environment

In cognitive radio networks, users in both macrocells and femtocells are assumed to have the cognitive capability and can dynamically sense/utilize the available licensed spectrum resource. Power control and spectrum allocation can thus be jointly performed in cognitive radio by using a decentralized radio resource allocation mechanism, which is part of the self-organization features. A three-step joint-resource-allocation scheme can be performed:

a） Primary network sells the spectrum with a given price;
b） Cognitive femtocell base station decides whether to buy the spectrum or not;
c） Femtocell base station performs power allocation.

The above-mentioned approach can be regarded as a Stackelberg game, in which a gradient based iteration algorithm can be used for achieving the Stackelberg equilibrium. However, a joint resource-allocation scheme with imperfect channel information and under some constraints (e.g., minimum-rate and proportional-fairness constraint [19]) is necessarily performed, because it is practically hard to obtain a perfect channel state information. In order to avoid the local sensing degradation owing to the local shadowing phenomena, cooperative sensing mechanism can be performed by employing a consensus algorithm for aggregating the sense result in a decentralized manner.

In light of the fact that the secondary users in cognitive radio do not know the interference power imposed by primary users, the interference constraint can be formulated in a probabilistic framework. In order to make the overall non-convex problem solvable, the solution can be decomposed into two parts, i.e., i) find the optimal power allocation scheme for each pair of false alarm rate and sensing time, and ii) maximize the cost function with respect to false alarm rate and sensing time [20]. A tradeoff between the collaborative/sensing power and transmission power can also be achieved in this solution.

3) Base Station Sleep (BSS) Scheme

In contrast to the traditional power control scheme, in which base station power can be set to arbitrary value between zero and its maximum value, Base Station Sleep (BSS) scheme just supports two power levels corresponding to the active and sleep states. BSS scheme is regarded as an effective method for network energy saving by turning the BSs with small activities to sleep. In [21], the authors derived both the success transmission probability and energy efficiency under BSS strategies by formulating the optimization problems in the form of power-consumption minimization and energy efficiency maximization in HetNet. In order to further reduce the energy consumption, the benefits of both PSR and BSS scheme can be combined to improve energy efficiency in terms of two dimensions: spectrum reuse factor and BS active probability. The simulation results in Fig.5 show that the proposed joint PSR and BSS scheme outperforms the method relying on any individual scheme in terms of energy efficiency.

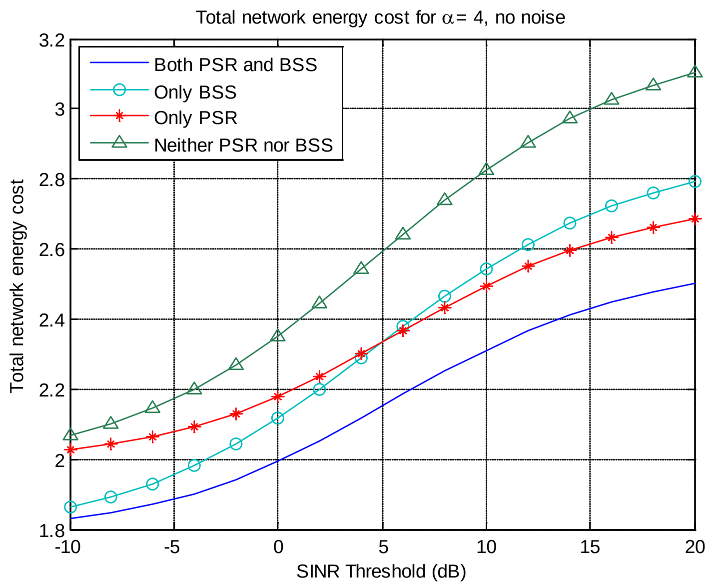

Fig. 5. The total heterogeneous cellular network energy cost of four conditions.

4) Other Mechanisms for Power Allocation

Authors in [25] proposed two power control schemes for mitigating cross-tier interference. The first scheme uses open-loop control to adjust the maximum transmit power of femtocell users in order to reduce the cross-tier interference to the level of lower than a fixed interference threshold. The second one, on the other hand, uses closed-loop control to make the cross-tier interference meet an adaptive interference threshold based on the SINR level at macrocell base station. It is shown that the closed-loop control can significantly improve the femtocells throughput compared to the open-loop control, whilst suffering only a minimal degradation of macrocell throughput.

5. Methodologies

In this section, we summarize the possible methodologies (including modelling, learning and optimization) for realizing self-optimization functionalities of HetNet, as shown in **Fig. 4**. The comparison among variant methodologies is given by **Table 2**.

Table 2. Comparison among variant methodologies.

Methodologies	Advantage	Disadvantage
Graph theory	Effectively mitigates the co-channel interference of inter-cell in sub-channel allocation	Failed to express the stochastic interference of small-scale fading channel model like rayleigh fading
MDP	1) Partly random and partly under the control of a decision maker 2) The next state only depends on the current state and action	Unable to model the interaction of more than one decision maker
PPP	1) Reasonably approximates the potential unplanned deployment of femtocells 2) Suitable to analyze capacity extension and dynamic BS sleeping[1]	Base stations will be located very close together in some cases, whilst guaranteeinga significant coverage area
Game theory	Provides an efficient way to analyse the dynamic interactive behaviors of multi-consumers in resource allocation	1) Requires the existence of nash equilibrium 2) High convergence complex due to the large number of iterations
Convex Optimization	Simple and effective	Requires the objective function and feasible set to be convex
Bionic Theory	More intelligent and better tradeoff between multi-objectives	1) Incomplete 2) Needs more theories and frameworks

5.1 Modelling

A general model of automatic management, which comprises five steps, i.e., knowledge-based monitor, analysis, plan, evaluate and execution (MAPE^2-K), was proposed in [26]. In order to give a quantitative description of the self-optimization functionality, several mathematical tools associated with modelling are employed:

[1] The superposition of two or more independent PPPs and the independent thinning of a PPP are still PPPs

- *Graph theory*: Problem of multi-coloring graph has been studied in last decades for channel assignment. In this theory, each node represents a femtocell and each edge between two nodes represents the interference between two femtocells. The channel-assignment problem can thus be modelled as a problem of multi-coloring graph.
- *MDP*: MDP is a useful method for solving the optimization problems by using dynamic programming and reinforcement learning, which can be used for modelling the random mobile connection in wireless communication systems. An MDP usually comprises five elements, i.e., decision epochs, system states, available actions, state/action dependent immediate rewards or costs, and state/action dependent transition probabilities.
- *Stochastic geometric theory*: Stochastic geometric theory is usually used for modelling the deployment of base station. In particular, poisson point process (PPP) is regard as a tractable and accurate model for describing the distribution of base stations.

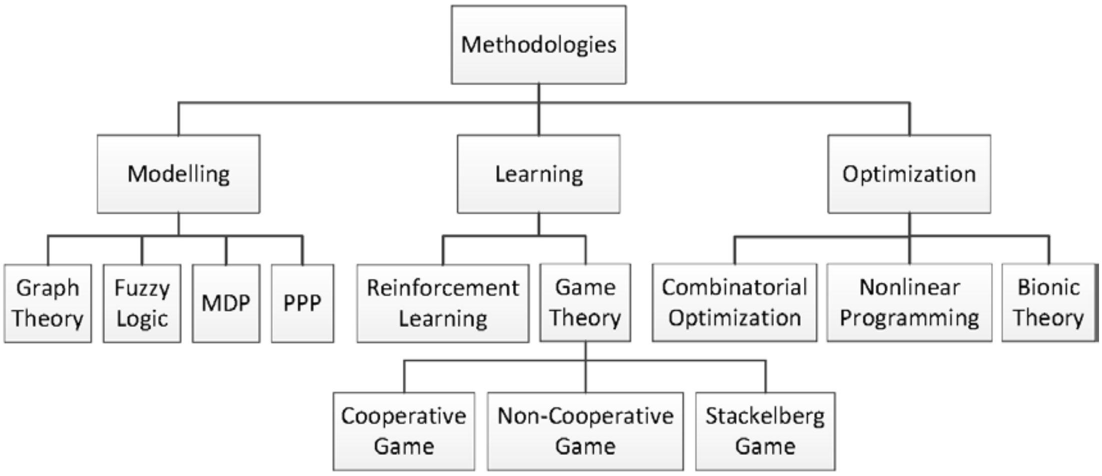

Fig. 4. Classification of the possible methodologies.

5.2 Learning

One of the major features of self-optimization is shown in that the system could improve its performance via self-learning from previous actions. As one of the most well-known learning approaches, game theory has been widely studied for scheduling resource in mobile communication systems, in which non-cooperative games play an important role in performing distributed self-optimization schemes. A game is usually expressed as $G=[N,\{S_i\},\{P_i\}]$, where N denotes the set of game players, $\{S_i\}$ represents the set of all possible strategies, and $\{P_i\}$ is the set of utility function corresponding to all the strategies in $\{S_i\}$ (i.e., payoff). Players in a game insist to maximize their own selfish objectives, which usually damage other nodes' performance. Furthermore, Nash equilibrium, in which each node cannot unilaterally take an action to improve its state, can be reached under the given state of other nodes in the system, i.e., $p_i(s_i \mid n_i) \le P^*(S^*), \forall s_i \in S$.

5.3 Optimization

Compared with the learning approach, classic optimization approaches such as convex optimization and intelligence optimization (e.g., that using bionic theory) can also be employed for designing self-optimization functionalities in HetNet.

- *Convex Optimization:* Our purpose, in most cases, is achieving maximal capacity subject to the limited resources such as power and frequency spectrum in HetNet. Convex optimization is such a simple and effective approach that finds extreme point in a closed convex set. Furthermore, convex optimization is the foundation of optimization problem and it is often combined with other methodologies.
- *Bionic Theory based Method:* This method has attracted a lot of attentions, because swarm intelligence, a well-known component of bionic theory, shows an ideal performance in solving self-optimization problem in complicated HetNets. Bio-inspired technique has already been applied to several practical systems for addressing critical issues such as power control, dynamic resource scheduling and allocation, etc. Furthermore, this technology shows three better tradeoffs [17]: 1) Tradeoff between local rule and global optimization; 2) Tradeoff between the scalability and controllability; 3) Tradeoff among availability, consistency and reliability of control information.

6. Conclusion and Remaining Challenges

HetNets have been developed rapidly due to the coexistent of various RATs and cell infrastructures. Self-optimization plays an important role in alleviating the upgrading CAPEX and OPEX in the large-scale HetNets. In this paper, we summarize the architecture of different HetNets and survey variant self-optimization approaches. Furthermore, some well-known methodologies have also been surveyed and compared, followed by discussing a number of potential research directions.

1) Ultra-Dense Network

User density may become extremely high in some specific time and/or place, such as assembly, airports, and subway stations. In order to meet the traffic demands of users, ultra-dense network deployment has been regarded as one of the future research directions. In particular, ultra-dense HetNets have already become the major characteristic of future wireless network (5G) [27]. Furthermore, interference management and resource virtualization have been regarded as two critical technologies in densely deployed networks. In dense HetNet, self-optimization approaches have exhibited enormous advantages in improving the network robustness, adaptation and load balancing capabilities and simultaneously decreasing the CAPEX/OPEX compared with the traditional approaches.

2) Energy Efficiency Issues

Green communication has attracted more and more attentions to both academia and industry. The development of HetNets has been motivated by the fact that deploying a high density network with low-power BSs can substantially improve the energy efficiency compared to the conventional macrocell deployment. Apart from it, the energy-cost problem is still a challenge in the dense HetNets due to the existence of "data traffic tidal effect" in practical systems.

3) Millimeter Wave and Massive MIMO

Cell size is becoming more and more small in future HetNets for the purpose of achieving more spectrum reuse gain. The shrinking cell sizes are attractive for the mmWave spectral band where RF path loss (PL) increases with frequency. The radio coverage can be effectively extended by employing massive MIMO technology, in which the the large beamforming gains may help overcome the high mmWave path loss [28]. However, a high complexity in terms of signal processing is observed in the above-mentioned technologies, highly requiring some self-optimization approaches to be performed to relieve the complexity burden of 5G systems.

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