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## 論文の内容の要旨


The exponential growth in capacity demand and ubiquitous coverage/connectivity requirement of wireless cellular networks has shifted mobile network operators' interest toward base station densification. Base station densification is essential to meet the capacity demand and coverage requirement by massive deployment of small cells by covering areas that are much smaller as compared to the coverage area of macrocell base stations. Small cells are attractive choice for operators due to its low cost and ease of deployment, and flexible coverage capability allowing them to reuse the available spectrum and thus increasing the area spectral efficiency. However, the advantages of small cells could come short whenever neighboring small cells compete to utilize common spectral resources that would result in severe interference. Also, centralized control for resource allocation can be infeasible due to potentially dense and random deployment of small cells either by operators or customers. Hence, radio resource management in small cell networks becomes essential to achieve the expected gains from small cells.

In this regard, I propose a cooperative and collaborative resource management (CCRM) framework that enables cooperative intra-connection among small cells of an operator and collaborative interconnection among multiple operators for proper utilization of network resources (both infrastructures and spectrum). The cooperative resource management performed at the network edge, i.e., among small cell access points, in-cooperates information exchange mechanism among small cells allowing them for distributed resource allocation to mobile stations. The collaboration formation among multiple operators offers users with multi-operator small cells support. This facilitates network users with an extension of network coverage and services availability regardless of their operator's network coverage, and evolves small cells to meet the expectation of a networked society.

To look for distributed resource (subchannel) allocation, first, I study the performance of best-response strategy as a game theoretic solution analyzed under the physical interference model. However, in "traditional" best-response strategy, players are assumed to be coordinated and restricted to take turns while updating their strategies. To overcome these requirements of coordination among players and restricting at most only one player to update their strategy, I model strategy update criteria of players in a game such that multiple players can repeatedly and simultaneously take actions following best-response strategies. Through the proposed algorithms, stochastic best-response distributed subchannel selection (SBDSS) and cooperative best-response distributed subchannel selection (CBDSS), I study for cases and associated limitations when multiple players may update their subchannel allocation strategies that could inevitably speed-up the convergence process to steady-state. In SBDSS, no information exchanges and coordination among players are required and each player updates its strategy of subchannel selection following stochastic best-response. The randomness in strategy updates result in uncoordinated sequential updates and avoids the problem of simultaneous moves that would have resulted in oscillations between some set of strategy profiles. However, this results in a slow convergence to steady-state. To speed-up the convergence, in CBDSS, I assume coordination among neighboring small cells to act cooperatively while best-responding to their strategy. Here, I limit multiple players to update to the same strategy at a given time, such that the number of players who can simultaneously update their strategy is equal to the number of available strategies. This provides notable improvement in terms of rate of convergence to steady-state.

Although the problem of distributed resource allocation can be addressed through the pro- posed schemes following best-response dynamics, the existence of a steady-state solution, i.e., a pure strategy Nash equilibrium cannot be guaranteed. To guarantee for the existence of a steady-state solution, I utilize the concept of marginal contribution and propose marginal contribution-based best-response (MCBR) algorithm to cope with dynamic and limited information in the small cell network. Here, the objective is to find a distributed subchannel allocation that maximizes the welfare of the small cell network, defined as the total system capacity. MCBR is theoretically proven to be an exact potential game, which is a class of potential game that guarantees convergence to a pure strategy steady-state, i.e., the Nash equilibrium. I also validate the convergence property and evaluate the performance through simulations for various performance metrics.

Finally, to offer multi-operator small cells support, I formalize a mechanism for multi-operator collaboration through negotiation to establish mutual agreement acceptable to each involved party. This provides operators with collaboration gains, and motivates them to utilize their exclusively owned network resources to serve others' subscribers. Such collaboration would enable subscribers of one operator to utilize other operators' network resources and maintain ubiquitous connectivity. Collaboration, in turn, enables: to enhance service levels to users with improved network resources availability, to avoid situations of under-utilization of radio network resources, to improve revenue generated by serving an increased market share, and to create a bring-your-own-device environment by maintaining small cell network services to subscribers regardless of coverage availability from their operator.

**Keywords**: Small Cells; Distributed Subchannel Selection; Game Theory; Best-Response Strategy;

Simultaneous Move; Cooperative Games; Non-Cooperative Games; Potential Games; Marginal Contribution; Collaboration; Negotiation.

## 論文審査の結果の要旨

The Evaluation Committee recognizes that the presented research work in the dissertation is the cooperative and collaborative resource management in the exploration of game theory technique for improving area spectral efficiency of smart cell networks. A cooperative and collaborative resource management (CCRM) framework that comprises of both cooperative resource allocation (CRA) scheme and collaborative multi-operator (CMO) scheme. The CRA scheme exploits the marginal contribution concept to cope with dynamic and limited channel allocation and guarantees a convergence to maximize the overall system capacity through the proof of exact potential game. Meanwhile, the CMO scheme not only utilizes the simultaneous bilateral negotiation to encourage the operators to share their competitors' radio channel with acceptable mutual agreement, which is depending on the operator policy profile, but also avoids underutilization of network resources and improves the operator's overall revenue. The CCRM framework has reached a very good competence with clear vision, purpose and objectives of research works in small cell networks. The proposed two schemes of CCRM framework are well-examined by comparing to the state-of-the-art other schemes and their results and discussions are clear-demonstrated. The Evaluation Committee identifies that the dissertation contains the appropriateness of the given literature backgrounds, the wide-ranging related research works, and the research methodologies for the numerical evaluation studies. Besides that, the numerical results are validated and extensively well-discussed to justify the correctness, efficiency and effectiveness of the proposed schemes. The dissertation also includes clear and specific conclusions, contributions and recommendations for future works. Furthermore, the references are appropriately presented in the dissertation.

The Evaluation Committee validates and confirms that the research works in each chapter of the dissertation have been disseminated to the four international conferences, one accepted journal (IF □ 2.5), and one submitted journal. The Evaluation Committee agrees that Shah Shashi did make good achievements and momentous contributions to the radio resource management of small cell networks, in particular the realization of cooperative and collaborative approach. Furthermore, this research work is a frontier step toward the collaborative management and control for the future wireless networks. The Evaluation Committee observes that he speaks frequently in English and his ability in oral presentation is very good. Hereby, the Evaluation Committee concludes that he with no doubts deserves to obtain the doctoral degree (Information Science).