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Intelligent cellular network: A Two-Tier Cellular Architecture with Robust Interference Capability and Optimal Resource Management Policy

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Intoduction

It is foreseen that the very high capacity network of the near future (Gbps access for end users) will be based on local, indoor cellular coverage (femtocell coverage – one indoor base station covering each home) with optical Fiber to the Home (FTTH) backbone, augmented by wideband outdoor macrocell coverage. This two-tier architecture (dense femtocell indoor coverage plus outdoor macrocell coverage) creates several scientific and engineering challenges in order to exploit the full potential of this novel radio network architecture. These challenges are arising because of the extreme density of the femtocell part of the network (requiring interference handling, radio resource management and mobility solutions) and the coexistence of this femto network with the macrocellular coverage (interference, resource management and mobility). The aim of this project is to assess some specific problems of this two-tier architecture, develop, and implement algorithms for solving these as well as to deeply investigate the performance of the developed algorithms and the network as a whole. The main tasks of the project are aligned according to the dedicated objectives, which are:

1. Development of advanced radio architecture for high-rate cellular communication systems with two-tier cellular structure.
2. Design and implementation of efficient and adaptive radio resource management protocol that exploits different dimensions of wireless channels to achieve optimal diversity gain.
3. Strategy formulation for cognitive radio access in femto-cell network using game theoretical approach.
4. Development of intelligent handover planning, decision and execution algorithms.
5. Analysis and simulation of the capacity and performance of the novel two-tier system.

Project activities, tasks

A brief description of the tasks within the project is given here. Tasks are organized according to the main objectives. Each task is divided into further subtasks, covering the identified research topics.

Task 1. *Advanced Radio Architecture for High-Rate Cellular Communication Systems with Two-tier Cellular Structure.*

Frequency Domain (FD) approach is the most obvious choice to overcome the limitation due to Inter Symbol Interference (ISI). The proposed architecture is based on the combination of Block Spread Code Division Multiple Access (BSCDMA) and Single Carrier Frequency Division Multiple Access (SCFDMA), with advanced Multiple Input-Multiple Output (MIMO) processing. The aim is to investigate several, so far not well understood issues, namely the effect of insufficient Cyclic Prefix (CP) on link capacity. Moreover, advanced transceiver structures will be designed with interference cancellation and equalization algorithms. As part of the system architecture, QoS modell and solution for the network will be also developed. Subtasks are hence defined accordingly:

- Subtask 1.1 Theoretical investigation on capacity limit for FD-based technique with SISO architecture employing insufficient Cyclic-Prefix (CP)
- Subtask 1.2 Theoretical investigation on capacity limit for FD-based technique with MIMO architecture employing insufficient Cyclic-Prefix (CP)
- Subtask 1.3 Design of novel interference cancellation algorithm for high-rate systems with insufficient CP
- Subtask 1.4 Design of improved equalizer with goals of enhancing system performance and complexity reduction
- Subtask 1.5 Definition of QoS architecture and QoS model of the system.
- Subtask 1.6 QoS capable extension of multiple access scheme developed in the project.
- Subtask 1.7 Detailed QoS analysis of the two-tier network, assuming the proposed advances.

Task 2*. Efficient and Adaptive Radio Resource Management Protocol that exploits different dimensions of wireless channels to achieve optimal diversity gain.*

As mentioned we intend to base the system on combining BSCDMA with SCFDMA, along with MIMO. Moreover, we employ Space Division Multiple Access (SDMA) by means of using MIMO transmission, in order to maximize diversity gain and robustness of the system. Within this task radio resource allocation and medium access methods (Radio Resource Management, RRM) applicable in this system are developed. Finally, the inclusion of Time Division Duplexing (TDD) scene further allows flexibility and service of asymmetric traffic. Several issues of radio resource management (e.g. interference avoidance, diversity selection,

interference avoiding multiple access, variable transmission) are solved within this task by means of activities divided into subtasks. The titles of subtasks are self-explanatory in terms of the targeted research directions.

- Subtask 2.1 Interference-Robust Multiple Access Scheme for Macro- / Femto-Cell Resource Sharing.
- Subtask 2.2 Design diversity selection techniques that considers antenna, subcarrier, interference and other channel impairments
- Subtask 2.3 Design of variable transmission system with focus on macro- / femto-cell interference avoidance and reduction targeting high mobility applications.
- Subtask 2.4 Design of variable transmission system with focus on macro- / femto-cell interference mitigation and efficiency optimization to support asymmetric uplink / downlink traffic demand.

Task 3. *Strategy Formulation for Cognitive Radio Access in Femto-cell network using Game Theory.*

The concept of cognitive communications was introduced into radio networking area in order to achieve better spectrum utilization and to create a more flexible, distributed and collaborative wireless network infrastructure. Cognitive radio solutions are usually developed in an ad-hoc network environment. The aim of this task is to utilize cognitive radio paradigm in the framework of the proposed two tier macro- and femtocell network. Among the main problems of cognitive radio networks (namely: spectrum sensing, resource sharing method) the resource sharing part will be examined in the context of the two-tier network. Emerging game theory methods are to be developed to assess resource sharing between macro and femtocells and to provide optimal resource sharing strategies. The planned subtasks are:

- Subtask 3.1 Design of Potential Game with Utility Function that considers Profit / Loss with basic parameters
- Subtask 3.2 Strategy Formulation for Fully Cooperative Game
- Subtask 3.3 Strategy Formulation for Non-Cooperative Game
- Subtask 3.4 Strategy Formulation for Partially Cooperative Game
- Subtask 3.5 Design of Potential Game with Utility Function that considers Profit / Loss with advanced parameters
- Subtask 3.6 Strategy Formulation for fully / non / partially cooperative game with advanced parameters

Task 4. *Development of intelligent handover planning algorithm.*

In femto-cell-based cellular network, the handover process becomes challenging when a mobile device is making a switch from macro-cell coverage to femto-cell coverage, or

between femto-cells. The high and dynamically changing number of femto-cells means that large number of information needs to be collected to facilitate each handover decision-making process. If not designed carefully, such task could potentially consume significant network bandwidth and waste power consumption. In addition, since a femto-cell area is small, it is highly likely for a mobile device to stay within a femto-cell area for a short duration. In this task, intelligent handover planning algorithm that minimizes unnecessary handovers will be developed.

- Subtask 4.1 Estimation of user mobility under single antenna and multiple antenna conditions

- Subtask 4.2 Theoretical analysis of fundamental issues and limitations during handover process in two-tier cellular architecture

- Subtask 4.3 Design of intelligent handover planning algorithm using mobility information and network mapping

- Subtask 4.4 Improving the performance of handover planning algorithm

Task 5. *Capacity and performance of the two-tier system.*

The dense cellular deployment of the proposed femto cell based network and the overlap with the macro layer results in a high interference environment. Moreover, various advanced algorithms such as applied adaptive modulation and coding, novel medium access methods, BSCDMA spreading, along with the densely populated propagation environment leads to complex relations in analyzing and determining the capacity (network, cell and area capacities) and the achievable user throughput of the system under realistic assumptions. The present project will look into various analytic capacity estimation methods along with realistic simulation models to verify the analysis.

- Subtask 5.1 Development of analytical framework for the definition and estimation of the proposed system.

- Subtask 5.2 Development of simulation framework for system level capacity and performance analysis.

- Subtask 5.3 Enhancement of the analytical framework with taking novel radio radio resource management and medium access control into consideration.

- Subtask 5.4 Complete simulation and analytical evaluations on the system level performance, all project advancements are included.

Novel technology, product or service developed in the project

The femtocell concept as base of this project is already in primary focus of mobile industry. Based on an optical backhaul, this network architecture is capable of fulfilling the vision of seamless Gps access. As such, the novel solutions and algorithms within the project may achieve significant impact on the industry and services. The developed novel radio network architecture itself is considered as novel technology. In details, novel technologies (regarding

the architecture) delivered by the project are: interference cancellation and interference aware equalization methods; novel radio resource allocation and medium access methods; novel QoS architecture and QoS delivery technologies.

Novelties of the R&D approach in national/international comparison

Task 1. *Design of Advanced Radio Architecture for High-Rate Cellular Communication Systems with Two-tier Cellular Structure*

In future high data rate high mobility systems, there is no such luxury as inserting guard interval that is too long would bring down spectral efficiency and/or increase processing complexity. When insufficient guard interval is used, self-inflicted intra-user interference will set in. The effect of insufficient guard interval was not previously tackled in the proposed context of BSCDMA/SCFDMA combination. Moreover, deployment of such combined scheme in two-tier cellular environment would create new interference scenarios that have not been addressed in the literature so far. Fundamental analysis and understanding to the interference-related issues are critical in measuring the suitability of such scheme as uplink air interface in future mobile communication systems. Furthermore, the ultra high density of the femto based network and the interaction with the macro overlay, along with the bandwidth hungry services used require this novel architecture to be tackled and analyzed from QoS point of view, that has not been so far done in open literature.

Task 2. *Efficient and Adaptive Radio Resource Management Protocol that exploits different dimensions of wireless channels to achieve optimal diversity gain*

As it is considered widely that future generations of RRM protocols are expected to combine several layers of the protocol stack such as physical, network, transport and possibly application layer. In this project, we plan to design innovative RRM protocols that sits between physical and network layer. Having previously worked on advanced radio transceiver design such as exploitation of MIMO architectures, time and frequency-domain processing and interference-limited multiple access schemes, the investigators plan to design efficient RRM protocol that intelligently adapts its strategy based on different physical channel conditions of different users to allow each user to achieve maximum system diversity. Although lot has been done in the research of cross-layer RRM solutions, the main novelty brought by this proposal is the use and assessment of combined BSCDMA/SCFDMA scheme with SDMA and TDD duplexing and focusing on achieving maximum diversity gain while supressing interference.

Task 3. *Strategy Formulation for Cognitive Radio Access in Femto-cell network using Game Theory*

Recently, the use of Game Theory has been applied to the realms of wireless communication engineering, particularly in the context of resource sharing among cognitive radio users. In many ways, resource sharing within a cognitive radio environment can be modeled as a game where cognitive users are competing for access to the limited licensed spectrum (that happens to be absent of its rightful owner). A Game is made up of three components: 1. Players; 2. Strategy; and 3. Utility Function. In many of the existing works, the utility function is generally defined as the total interference that a player generates and receives to and from all the neighboring players. Essentially, such utility function considers only the loss associated

with a certain strategy / decision. In this project, a novel approach that will be taken is to include the profit in the utility function definition. What can be referred to as profit is subjective and depends on many factors that include but not limited to power consumption reduction, rate guarantee and QoS guarantee in the proposed femto-cell based network. In this project, novel games and strategy formulations will be developed for different scenarios where the degree of coordination among femto base stations may vary.

Task 4*. Optimized Handover Planning Algorithm in Two-Tier Cellular Architecture with overlapping Femto-cell networks*

The handover from a macro-cell to femto-cell generates real challenge in the proposed architecture. Since femto base stations are designed to reside on subscribers' premises, theoretically there is no limit to the number of femto-cells that can co-exist within a macro-cell radius, moreover this number may change constantly as user switch their home base stations on and off. In this project, the femto deployment is assumed to be extended to outdoors, to provide very high capacity dense network coverage in the dense urban area. In this project, algorithms that can be used to obtain accurate mobility information will first be proposed. The mobility information would then be used to assist in the handover planning. By knowing the direction in which a user is likely to move and the travelling speed, the central coordinating gateway could make a prediction on the route that will be travelled by a user, plan for the best handover schedule, inform the affected femto base stations, reduce the administrative procedure such as authentication and hence the handover timing. As a result, the network overhead and service interruption will be reduced.

Task 5. *Capacity and performance of the two-tier system.*

The network based on the proposed femto and macro coverage is seen as a likely scenario for future Gbps wireless systems. Due to the extreme density and time-varying topology of femtocells (users may by chance switch them on and off), as well as due to the special properties of the proposed radio interface technology, the assessment of system level capacity of this architecture is challenging and yet unsolved in the open literature. Although numerous papers deal with several particular issues or achievable throughput in femto deployments, these studies do not consider the dynamic nature of femto coverage, nor the achievable performance over macro attachment is examined. Moreover, the proposed radio interface's system level performance is still unknown. This task will investigate on these issues and come up with solutions that ultimately will be leveraged into a network planning methodology.

Previous preliminary work and results of the applicants

Although the set of tasks targeted within the project are mostly novel and contain novel approaches, preliminary research by project members was already done in similar fields. Preliminary research was carried out in the field of adaptive guard periods in BSCDMA systems. One way of increasing the bandwidth efficiency is to shorten the guard interval during low mobility and adjust its length depending on the vehicular condition. Our preliminary analysis shows that in the specific context of BSCDMA system, the use of adaptive guard duration considerably improves the spectral efficiency of the system. Improved performance can be obtained as shorter block length means smaller amount of variation within a block and hence lower multi user interference. Several research publications show the experience of the project members on MIMO systems and radio resource management topics. Research on cognitive radio and application of game theory methods is also a preliminary work carried out in NTU. BME had a bilateral contract with T-mobile, where researchers did analysis on the achievable penetration density and performance with femtocellular coverage. This was done in 3G context; however this is a perfect preliminary experience for studies in Task 5. BME researchers were involved in several theoretical and practical development activities where mobility assisting protocols were developed (e.g. HIP implementation/versions, vertical handover implementation, IPv6 mobility testbed, etc.)

Previous R&D activities in related fields

Investigators of Nanyang University were part of several research projects in related areas, for example:

- Advanced Baseband Algorithms and Low Power Implementations for Wireless Communications
- Algorithms for Scalable Cooperative Communication of Multi-hop Relay Networks in a Distributed Environment
- Project Striker-Modeling of under water Acoustic signal and noise fields and techniques for detection and localization of weak sources in shallow ocean Spectrum
- Sensing and Resource management for Cognitive Radio Applications.

Researchers of BME participated in several bilateral contracts with T-mobile, mainly targeting capacity and performance analysis and planning of 3G and LTE radio networks. Several Hungarian and EU founded research projects were also conducted in related fields. Without the need of completeness, some examples are:

- EU FP7 SAMURAI. Activities: Multi-User MIMO system level performance, effect of channel estimation errors, channel modelling
- EU FP6 PHOENIX, FP7 OPTIMIX: development and simulation of joint, cross layer optimization of channel and source coding EU FP6 ANEMONE: pan-European IPv6 mobility testbed

Dissemination plan

The project incorporates respected top level scientists, whose number of publications well exceeds three hundreds in total. Hence it is planned that project results are immediately going to be published. The fora of publications is not concretely known yet, as this depends on the special issues of journals, selected set of calls for papers and the time and venue of high level international conferences, as well as on the appearance of novel research results. The planned and measurable number of publications is given in the Indicator Tables of this proposal. In the firs quarter of the project a website will be set-up (requiring no extra budget) containing relevant info of the project. During the course of this project (third year) an international workshop will be held, preferably together with another international event, where wider scientific community may see the results and progress.

Exploitation plan

As being academic institutions, both partners will naturally exploit the results of the project in the framework of their lecturing activities. This means creation of novel laboratory practices, where students get first hand experiences on the development/performance/algorithms of the proposed two-tier networks. Moreover, talented MSc students will be involved into the research and development activities of the project, resulting in their theses. This means that new engineers will be released from the universities who have deep knowledge and experience of the femto- and macro based network that is foreseeing the future of cellular communications. Moreover, this project will set the base for future, industrial driven cooperations targetting deployment and performance issues of the femto based networks. The liason coming from this project will be used to build further partnerships not just among the two partners, but other institutes, corporations between the Middle-European and South-East Asian regions. This will be utilized mainly by means of further joint research proposals. With regards the exploitation potential for outside the partners of the project, the models developed in this project may serve as the starting point for future feasibility study if the revolutionary cellular architecture is ready to be implemented in Singapore. Fundamental understanding of the technology and potential problems created by highly dense environment such as those encountered in big cities, would be useful for network planning purpose in order to ensure harmonious co-existence and smooth transition of the technology. Results from this project can also be used to formulate the business strategy that should be adopted by the telco providers in order to maximize revenues.