Smart Femto-Cell Controller Based Distributed Cognitive Pilot Channel

Markus Mueck, Christian Rom, Wen Xu

Infineon Technologies AG
85579 Neubiberg, Germany
{MarkusDominik.Mueck, Christian.Rom, Wen.Xu}@Infineon.com

Ana Sierra Diaz

Telefonica I+D
28043-Madrid, Spain
asd@tid.es

Hanna Bogucka

Poznan University of Technology
60-965 Poznan, Poland
hbogucka@et.put.poznan.pl

Andreas Polydoros, Nikos Dimitriou

University of Athens
Athens, Greece
polydoros@phys.uoa.gr

Radoslaw Piesiewicz

Create-Net
38100 Povo, Trento, Italy
radoslaw.piesiewicz@create-net.org

Sven Zeisberg

Hochschule für Technik und Wirtschaft Dresden (FH)
01069 Dresden, Germany
zeisberg@htw-dresden.de

Holger Jaekel, Tobias Renk, Friedrich Jondral

Universitaet Karlsruhe (TH)
Institut fuer Nachrichtentechnik
76128 Karlsruhe, Germany
jaekel@int.uni-karlsruhe.de

Peter Jung

Universität Duisburg-Essen
Kommunikationstechnik
47051 Duisburg, Germany
peter.jung@kommunikationstechnik.org

Abstract—**This paper presents an extension of the Cognitive Pilot Channel (CPC) concept to the case of a distributed version thereof (namely, DCPC), and demonstrates a potential instantiation of this concept in the design of Smart Femto-Cell Controllers (SFC-C) for handling the management of co-existing homogeneous or heterogeneous networks. Instead of covering the various networks by a single CPC, the novel idea consists in deploying the CPC transmission in a distributed way within each of the individual Smart Femto Cell (SFC) controlled Composite Networks (CNs), an example of which can be a heterogeneous home or business deployment including the collection of a Femto-Cell Base Station (FC-BS), a Wireless LAN (WLAN) Access Point (AP), a ZigBee network controller, a Bluetooth network controller, etc. A typical implementation of this concept leads to an integration of the DCPC transmitter into a SFC which consists of the FC-BS for provision of cellular access and the SFC-C for network management and DCPC provision. In this case, the SFC owner is able to manage the attached composite network by providing suitable context and policy information within the DCPC. The paper furthermore introduces intra-network and inter-network interference scenarios and explains how the DCPC concept allows the introduction of corresponding interference management mechanisms.**

Keywords-Cognitive Pilot Channel (CPC), Distributed Cognitive Pilot Channel (DCPC), Distributed Decision Making, Femto-Cell, Policy Based Decision Making

I. INTRODUCTION

The concept of a Cognitive Pilot Channel (CPC) and its implementation as a dedicated physical (out-band) or logical (in-band) channel has been extensively studied and broadly published by the European IST-E^{2}R project [1-6]. Beyond the technical aspects, IST-E^{2}R also details business model and regulatory aspects related results [1]. In the context of the physically dedicated channel, the proposal is to use the following approach in order to organize the distribution of the information: The CPC information is mesh dependant and contains relevant updated data describing the way spectrum is locally used in mesh #i, such as context and usage policy related information. In order to make such a vision become reality, the World Radiocommunication Conference (WRC) 2011 will discuss under Agenda Item 1.19 the "Regulatory measures and their relevance to enable the introduction of software defined radio and cognitive radio systems" [7-8]. Under this umbrella, the provision of frequency bands for a global deployment of a CPC is expected to be studied.

In parallel, standardization bodies have begun to elaborate suitable solutions ensuring an industry-wide agreement on the actual implementation. For this purpose, IEEE P1900.4 recently presented the abstract concept of a "Radio Enabler" that links a "Network Reconfiguration Manager" managing the Composite Wireless Network and Terminals in terms of network-terminal distributed optimization of spectrum usage, and a "Terminal Reconfiguration Manager" managing the Terminal in terms of network-terminal distributed optimization of spectrum usage [9]. The concept is closely linked to the CPC concept of IST-E^{2}R. Moreover, the European Telecommunications Standards Institute (ETSI) recently mandated the ETSI Reconfigurable Radio Systems (RRS) Committee [10] to perform a feasibility study related to Cognitive Radio (CR) and Software Defined Radio (SDR) standardization. In this framework, the IST-E^{2}R CPC concept is currently further developed and extended. It should be pointed out, however, that the question on how to deploy such a physical channel is still unanswered and the related studies are in a very preliminary phase.

Within this framework, this paper proposes a novel and practical way on how to organize and deploy the pilot channel by introducing the "Distributed Cognitive Pilot Channel (DCPC)" approach. Section II of this paper will detail the related problem statement and scenarios that are considered. A set of relevant interference scenarios is presented. Section III illustrates practical aspects of DCPC provision and SFC management. Section IV introduces an advanced distributed context information provision concept, while Section V finally gives a conclusion.

II. PROBLEM STATEMENT: SCENARIOS AND INTERFERENCE PROFILES

In this paper, it is assumed that various heterogeneous networks are operated at a given location as explained above. From the perspective of interference, the following two cases will be considered in further detail in the sequel:

A. Inter-Network Interference

In this first case, two heterogeneous networks are competing for spectrum within the same band without any mutual coordination defined in the related standards. A typical example is WLAN (IEEE 802.11a,b,g,n), Bluetooth (IEEE 802.15.1), and ZigBee (IEEE 802.15.4) competing for access in the 2.4 GHz ISM band. Without any co-existence mechanism, such inter-network interference will result in a big performance loss. E.g. for typical radio propagation values and over a range of Bluetooth network parameters, the IEEE 802.11b coverage range can be reduced by 50% in order to avoid almost all impact from Bluetooth interference.

B. Intra-Network Interference

In this case, two homogeneous networks are competing for spectrum within the same band without any mutual coordination defined in the related standards. A typical example is the operation of multiple IEEE 802.11a,b,g,n access points (APs) on the same frequency band in neighboring households.

Based on the above interference scenarios, the following usage scenarios are considered in further detail:

Scenario 1: Heterogeneous Scenario (see Fig. 1)

A single household is considered in which a multitude of heterogeneous networks are operated, typically comprising WLAN, ZigBee, Bluetooth, etc. Several of those are competing for access on the same frequency bands, such as the 2.4GHz ISM band, leading to inter-network interference.. Additionally, a FC-BS is assumed to provide Cellular access, while a SFC-C provides a local DCPC. The operator is assumed to have control over the SFC-C and thus the content of the DCPC. The operator will use the local DCPC in a given household in such a way that it distributes the required context and policy information to the devices attached to the SFC to ensure that no interference occurs and therefore, increasing the customer's satisfaction. For this purpose, the policies are typically chosen in the sense of radio resource management constraints limiting the spectrum access of the various devices in such a way that mutual interference is avoided.

Scenario 2: Inter-System Scenario (see Fig. 2)

Multiple neighboring households are considered in which a multitude heterogeneous networks are operated. Furthermore, Cellular access and DCPC provision are ensured by an operator controlled FC-BS and SFC-C, respectively. In contrast to Scenario 1, it is assumed that no inter-network interference is present. Rather, two homogeneous networks, such as WLAN for example, are operated in neighboring households competing for access in a shared band. If no actions are taking, there is a risk of "Intra-Network Interference" if both systems select an identical carrier frequency. In this case, two approaches are considered in order to avoid interference: i) Neighboring SFC-Cs are maintaining communication links to each other via a "Controlling Sub-Network (CSN)" in order to exchange information on the operational parameters of cellular/short-range networks attached. This information exchange is exploited in order to find operational parameters such that the level of interference is avoided or at least reduced to a minimum; ii) A centralized data-base is maintained at the operator or a third-party service provider. The SFC-Cs are updating this data-base with the operational parameters of cellular/short-range networks which are attached to them. By access to this data-base, any SFC-C can obtain information on the operational parameters of neighboring networks which is exploited in order to avoid interference or at least to reduce it to a minimum level. This concept will further be detailed in section III.

Scenario 3: Optimization of Resource Selection in a Heterogeneous Environment (see Fig. 3)

Here, a single household is considered in which a multitude of distinct heterogeneous networks are operated. Cellular access and DCPC provision are ensured, say, by an operator controlled FC-BS and SFC-C, respectively. User devices are considered to be reconfigurable, e.g. by Software-Defined-Radio (SDR), in such a sense that they can choose to maintain a link to any of the available Radio Access Technologies (RATs) that are available in the considered composite network. Typically, the user devices will select such a configuration to achieve their respective QoS objectives at a minimum cost (in terms of communication fee to be paid, power consumption, etc). The operator is expected to impose usage constraints via DCPC policies to the user device depending on the traffic load situation of the various RATs. For example, the operator may prevent user devices from using Cellular access if it is overloaded. The user devices may then choose VoIP links via WLAN as an alternative to Cellular voice traffic.

In a typical implementation, the FC-BS and SFC-C functionalities will be provided by a single physical device owned by an operator. It should be pointed out, however, that the concept presented here is not limited to this specific case and other ways of providing a SFC-C are possible.

III. PRACTICAL ASPECTS ON DCPC PROVISION AND SFC MANAGEMENT

As detailed above, the DCPC typically carries context and policy information in order to control the composite networks which are attached to the corresponding SFC. This information will support the various networks, among other objectives, to

•   obtain a comprehensive overview of the total wireless composite network by cooperative signaling,

•   identify neighboring networks,

•   obtain support for adapting the signaling and routing processes,

•   avoid or diminish interference and to identify idle resources, and

•   identify gateways which connect the wireless composite network to the backbone.

Since all SFC-Cs are considered equal in functionality, the DCPC is proposed to be physically carried by a given time slot structure. Assume that no communication is ongoing and the first SFC-C appears in the network. After sensing its environment it starts to send a beacon channel, establishing this time slot structure. This concept can further be extended to networks in which SFCs handle and synchronize composite networks using two or more independent DCPC. In addition, this typically guarantees multi-hop operation,. With this scheme, a flexible and yet robust communication can be established, and the generation of unnecessary interference can be avoided.

In the case of multiple overlapping SFC controlled composite networks, interference management requires inter-SFC-C information exchange. This can be interpreted as a resource negotiation process of neighboring SFC-Cs. The context and policy information context of the relevant DCPCs are assumed to be jointly chosen such that no interference occurs between the various composite networks. In the sequel, two approaches for inter-SFC-C cooperation are considered:

A. Peer-to-peer communication between neighboring SFC-Cs via a CSN

In this case, a SFC-C is able to maintain a link to neighboring SFC-Cs in order to exchange state information on the corresponding attached composite networks. Based on this information, a negotiation process is typically started in order to align the content definition of the various DCPCs. Ideally, the corresponding context and policy information to be provided by the various DCPCs is chosen such that any interference is avoided or at least reduced to an acceptable level.

A simple example can be given by considering the deployment of two WLAN APs within two distinct but overlapping SFC controlled composite networks. Typically, the SFC-C will communicate via a CSN, negotiating a set of WLAN channels for each of the composite networks. Ideally, the set of WLAN channels are shared in such a way that no interference occurs between the two WLANs.

B. SFC-C information exchange via a centralized data-base

In this case, SFC-Cs are assumed to be able to interface to other existing infrastructure, therefore, allowing the access of data bases existing at network providers. In this data base, the actual network structure of the vicinity of the gateway SFCs can be stored and held up-to-date. This piece of information can also be used when admitting further SFCs. Hence, the network management is not only based on spectrum sensing schemes, but also on the exploitation of existing architectural information in a distant data base. The distant data base typically holds information about the identity and the resource allocation of each SFC as well as a functionality profile and the current use of functionality. In addition, the allocation of frequency resources and, in addition, the knowledge about unused spectrum is favorable information.

Consider a simple example in which a network consists of two composite networks, each served by a single SFC. Assume that both SFCs have a given spectrum and owing to changes in the cellular deployment the modification of the frequency resources is required. Both SFCs shall be acting as gateways. Both SFCs report their actual status to the distant data base and both request information about available frequency resources. The data base itself makes suggestions similar to an air traffic controller to both SFCs about which resources will be available and which can be used consequently. This scheme is much more efficient than a pure spectrum sensing based cognitive scheme. It can in addition be used when a connection to the distant data base is not possible.

The presented concepts can incorporate elements of the system architectures and protocols that have been defined in the related standardization [9,13] to facilitate the optimization of radio resource usage, by exploiting context information exchanged between the network and mobile terminals.

In order to depict this context information exchange and policy dissemination within the framework illustrated by the aforementioned scenarios, it could be assumed that each SFC-C includes (or coincides with) a Network Reconfiguration Manager (NRM) that can regulate the resource usage of all the covered RATs within the Femto-Cell. The NRM could collect context information from each individual RAT and its respective terminals and then, following specific radio resource usage optimization algorithms, it could derive suitable radio resource selection policies that need to be transmitted via the Distributed Pilot Channel to the respective terminals (in the way that was described in the previous sections). These policies may be related to changing the operating spectrum for each RAT, switching the operating frequency of a specific terminal, limiting the maximum terminal transmitted power, suggesting the vertical handover of a reconfigurable terminal among different co-existing RATs, etc. This procedure could be updated regularly to ensure a stable operation of the heterogeneous networks within the Femto-Cell and the optimum resource usage among different terminals within the Femto-Cell coverage area. In the case of a scenario involving multiple neighboring SFC-Cs, this context and policy information could be exchanged among them to ensure the co-ordinated operation of the neighboring Femto-Cells.

IV. AN ADVANCED DCPC CONCEPT FOR DISTRIBUTED CONTEXT PROVISION

As explained above, the DCPC is typically providing context and policy information to an SFC controlled composite network. In the simplest case, this information is centrally managed within the SFC-C. This section extends this scheme to a more efficient distributed context information management concept.

In order for the network to operate efficiently, each node has to learn about its environment (spectrally and physically) and has to provide this information to its neighbors via the DCPC. So, individual detection is used for distributed detection on a system level [11]. Important parameters are the available RATs, available power, and possible connectivity to the outside world. Some of these parameters may be estimated individually by each node doing spectrum sensing in pre-defined sensing times and to spread its information in a boosting manner [11][12].

The information learned by individual nodes must be spread to all neighbors. Additionally, in order to ensure dissemination of complete information, nodes should also spread the information they learned from their neighbors. This leads to large amounts of signaling since each signaling is repeated by many stations. Therefore, a lot of traffic is generated on the DCPC which potentially leads to collisions and thus results in inefficient usage of the DCPC.

Reduction of signaling can be achieved by larger signaling intervals (lower duty cycle), which may lead to circulation of out-of-date information. Thus, minimum necessary and maximum tolerable signaling times have to be identified, depending on the dynamics of the ad hoc network. Finally, as an important side effect, extensive signaling reduces the net data rate, since transmission resources have to be allocated to the DCPC. So, economical aspects and power constraints bound the relative amount of resources allocated for signaling.

As a possible method to reduce overhead, data compression may be conducted by smart information filtering. If, for example, two nodes have the same RATs, then, for sake of efficiency, the information about the distant node may be discarded in the next signaling hop. On the other hand, this leads to loss of information. The compromise between extensive signaling and incomplete information has to be carefully analyzed.

In order to provide information on the network status to all nodes in the ad hoc network, suitable and practical communication mechanisms have to be designed. In principle, there are two possibilities how the status information can be communicated through the network by either communicating via RATs (physical) or via IP channels (logical)

A RAT approach is the assignment of a fixed channel. This may lead to enormous gains since signaling and information exchange is possible simultaneously which relaxes delay constraints in the network.

The use of logical channels is based on inband transmission on a per-hop basis. This approach does not require overall network synchronization which may simplify the organizing overhead relative to the RAT approach.

Update of DCPC information is divided into a data gathering (DG) and a data broadcasting (DB) phase. During the DG phase, each node monitors its environment to find its one-hop neighbors and listens to the DCPC. The node then merges the two information streams and sends this information over the DCPC. Access to the DCPC may be based on a random access reservation phase followed by contention-free access to ensure collision avoidance. For the signaling phase, each node forms a mini-cluster with itself being the cluster head. DCPC information has to be updated on a periodical basis to capture dynamic processes and mobility within the ad hoc network. Since every node transmits information about its own mini-cluster, each node in the network will finally be able to gather knowledge about the status of the whole ad hoc network (assuming no isolated clusters or isolated nodes).

V. CONCLUSIONS

This paper presents a novel CPC concept moving from a globally available information source to a distributed one (DCPC). A practical deployment approach is given by proposing an implementation of corresponding information provision and management functionalities into SFCs. As a result, interference mitigation is achieved in the context of a variety of composite networks. While the concept is capable of solving interference coordination issues in the long term (due to its policy based and distributed approach) it is also well suited to be applied to the very recent problems in the 2.4 GHz ISM bands, where the IEEE January 2009 sponsor ballot approval of IEEE 802.11n creates potentially strong interference problems to other radio systems operating in that band.

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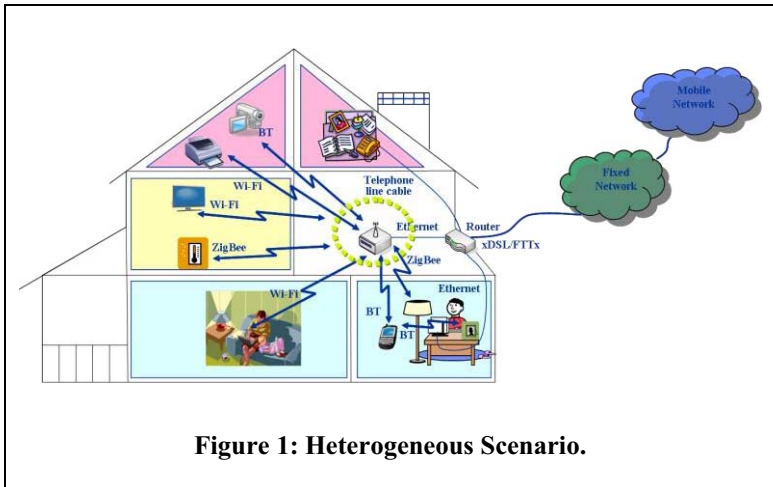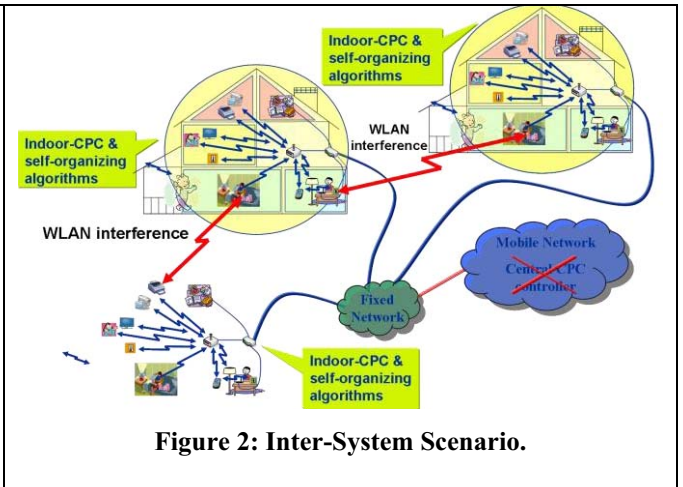
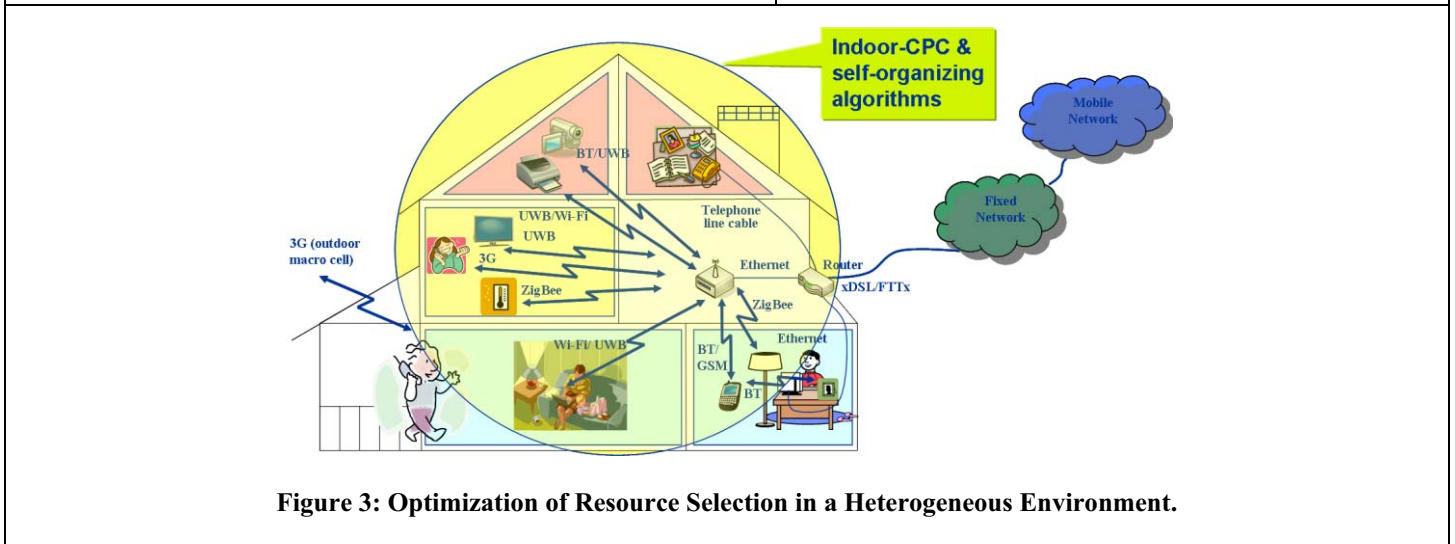Figure 1: Heterogeneous Scenario.

Figure 2: Inter-System Scenario.

Figure 3: Optimization of Resource Selection in a Heterogeneous Environment.