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Cognitive Pilot Channel: A Radio Enabler for Spectrum Awareness and Optimized Radio Resource Management

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Abstract: Today's wireless communications landscape is characterized by the coexistence of a plethora of disparate radio access technologies (RATs), which exhibit varying features in terms of capacity and coverage capabilities, mobility support etc. and also offer a great number of applications and services to different types of devices. In such a miscellaneous environment, mobile terminals are provided with a great set of options while setting up the parameters of their operation including among others the RAT, carrier frequency, and must also take into account the latest trend towards a flexible spectrum framework in heterogeneous radio access networks (RANs). As a result, in order to implement the optimal action, a mobile terminal needs to be enabled to acquire knowledge of its environment and established policies. Apart from mobilizing a rather time- and power-consuming operation such as spectrum sensing, the Cognitive Pilot Channel (CPC) concept has been proposed as a solution for providing the terminal with the necessary radio awareness at a given time and place, in a possible flexible spectrum management context. Framed within the above, this paper, developed within the E^3 project, aims at describing the CPC concept by showcasing its twofold role. First, as an enabler of the switch-on process for assisting the mobile terminal to camp onto the network side and second, as an enabler of an efficient decentralized and network-assisted radio resource management during the on-going communication phase.

Keywords: Radio enabler, Cognitive Pilot Channel, Spectrum Awareness, Decentralized radio resource management

1. Introduction

Nowadays wireless scenarios are characterized by the coexistence of a variety of wireless access technologies, with different protocol stacks and supporting a number of applications and services with different Quality of Service (QoS) demands to be provided to terminals with different degrees of multi-mode capabilities to access the available networks. In principle, each mobile and wireless Radio Access Network (RAN) differs from the others by the specific air interface technology, supported services, bit rate capabilities, coverage, mobility support, etc.

On one side, the variety of RANs and QoS levels for the services provided offer a great opportunity to the users, who have more options to better fit their expectations and constraints. On the other side, the heterogeneous characteristics offered by these networks make it possible to exploit the trunking gain resulting from the joint consideration of all the networks as a whole. As a result, the additional dimensions introduced by the multiplicity of available Radio Access Technologies (RATs) provide further flexibility in the way that radio resources can be managed and, consequently, overall improvements may follow with respect to the performances of the stand-alone systems. This challenge calls for the introduction of new Radio Resource Management (RRM) algorithms operating from a joint perspective that consider the overall amount of resources offered by the available RANs.

In this heterogeneous wireless networks context, the trend towards more flexible spectrum management mechanisms is being investigated. Spectrum refarming, which allows a specified frequency band becoming available for a different kind of usage or technology (e.g. refarming of GSM spectrum for UMTS/HSxPA), can be seen as the simplest use case for flexible spectrum management. Spectrum sharing between smart radio technologies, by e.g. allowing unlicensed radios to operate in the TV broadcast bands if no harmful interference is caused to incumbent services, is a more advanced form of flexible spectrum management.

Considering a flexible spectrum management framework in heterogeneous RANs scenarios, spectrum awareness arises as a basic challenge, where a number of transceivers with flexible time-varying assignment of operating frequency and/or RAT are deployed. Spectrum awareness from the mobile's perspective refers to the mechanisms allowing the terminal to be aware of the communication means available at a given time and place. In this respect, in order to get knowledge of its radio environment, the mobile terminal may sense some parts of the spectrum, but this may result in a very time- and power-consuming operation if the spectrum bands to be sensed are too large. As an alternative, following a similar approach to the Spectrum Information Channel in [1] and the Common Spectrum Coordination Channel (CSCC) in [2], the Cognitive Pilot Channel (CPC) concept was conceived as a solution for conveying the necessary information from the network side to let the terminal know e.g. the available frequency bands, RATs, operators, etc. at a given time and place [3][4][5]. The concept of the CPC is related to a specific phase of the cognition cycle [6], consisting in observing the environment.

Traditionally, radio resource management has been mainly centralized, based on the presumption that a central network node may have a more complete picture of the radio access status than a particular node, so that decisions can be made with more inputs. However, a centralized implementation could have some drawbacks in terms of increased signalling load or transfer delay of the radio resource management algorithm's inputs to the central node. This prevents an efficient implementation of short-term functions such as packet scheduling and explains why wireless cellular technology evolution (e.g. HSDPA) exhibits the trend towards implementing such functions on the radio access network edge nodes (e.g. base stations). Beyond that, a trend towards decentralized radio resource management functions in the mobile devices is currently under investigation. This approach has been claimed to be inefficient in the past because of the limited information available at the mobile device side. Nevertheless, this could be overcome if the network would be able to provide guidelines and policies to the mobile device driving its actions, while still keeping the control of the whole operation. In this way, while a mobile-assisted centralized decision making process requires the inputs from many mobile devices to a single node, the network-assisted decentralized decision making process requires the input from a single node to the mobile devices, which could be more efficient from a signalling point of view. The CPC could, therefore, enable such a network-assisted decentralized radio resource management.

This paper presents results obtained in the framework of the E^3 (End-to-End Efficiency) project, and intends to develop the CPC concept in two different and complementary missions. Firstly, as an enabler of the switch-on process that allows the mobile terminal to get in touch with the network side. Secondly, as an enabler of an efficient decentralized management along the on-going communication phase. Accordingly, the rest of the paper is organized as follows. Section 2 describes the vision of a CPC as an enabler for the switch-on process. The role of CPC in facilitating the radio resource management process, both after camping on and while in operation, is described in Section 3. Finally conclusions are summarized in Section 4.

2. CPC as enabler for switch-on

Let us consider the illustrative scenario depicted in Figure 1, where a number of transmitters, with possibly time-varying assignment of RATs and operating frequencies, are deployed. Furthermore, in its more general view, a stand-alone CPC transmitter separated from the rest of transmitters in the scenario is deployed. The CPC transmitter, which is physically realized on a given RAT, operating frequency and associated bandwidth, is in charge to convey spectrum awareness information related to its coverage area.

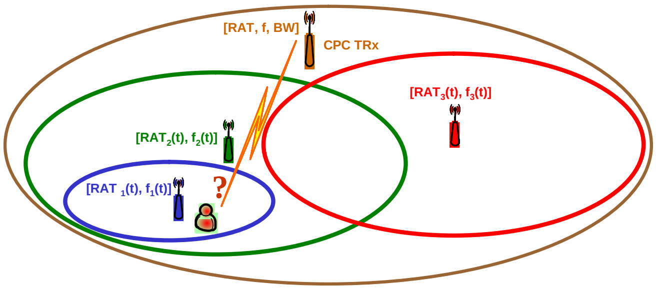

Figure 1: Illustrative scenario.

2.1 – CPC design and deployment

The different aspects to be considered when moving from CPC concept to implementation, regarding the radio part, can be identified as:

- CPC physical and link layer specification. This includes e.g. the definition of the appropriate RAT to carry CPC information, either a new one or the adaptation of a legacy one, the required bandwidth to transmit the information to be conveyed and considerations on the operating frequency.
- CPC deployment. This includes the definition of the number of CPC transceivers (TRx) with their corresponding configuration (e.g. power levels, etc.) necessary to provide the CPC information to the mobile terminals on a certain geographical region.

It is worth noting that, although business model considerations are out of the scope of this paper, the perspective provided here is generic enough to be applied to different business models regarding the CPC operation and exploitation (e.g. CPC can be deployed by a CPC-operator with its own deployed infrastructure to convey information from different access providers; CPC can be operated by a legacy cellular operator who exploits already existing sites to convey information for an association of operators; etc.).

As for the RAT used for CPC, in the switch-on context the CPC information needs to be conveyed using a CPC-specific radio access technology, in principle separate from that used for user data transmission. This approach is commonly named "Out-band CPC" (see Figure 2), opposing to the "In-band CPC", where the CPC information is conveyed using logical channels of the same radio access technologies that are used for the user data transmission, and that is more suitable for optimized Radio Resource Management operations (see section 3).

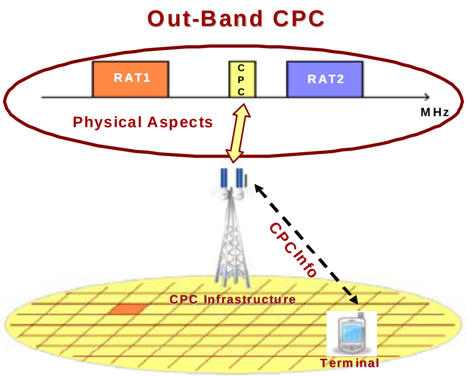

Figure 2: "Out-Band CPC" approach

As for the CPC operating frequency, a number of alternatives can be envisaged. Some possibilities are:

- It is fixed and harmonized at global/regional basis, consortium of access providers basis or only at internal level within a given access provider domain.
- It is neither harmonized nor fixed (i.e. CPC operating frequency may change). Note that in this case the CPC does not support the switch on use case (i.e. switch on relies on scanning).

As for the information delivery mode, two main options are identified [5]:

- Broadcast CPC. This strategy only uses a downlink broadcast channel, where the information is periodically and continuously transmitted.
- On-demand CPC. In this case, the information is transmitted only when needed and requested by a terminal. Therefore, the on-demand CPC requires both the uplink and downlink components.

As for the information to be conveyed by the CPC, the amount of information will depend on the complexity of the scenario (on the basis of the deployment of available RATs in the considered area) within the CPC transmitter coverage range. As a consequence of the way to convey the information, the required bandwidth could be determined.

At this stage, it is worth remarking that knowing the position of the mobile terminal is not a strict requirement for the CPC operation but a capability that enables higher efficiency in gaining spectrum awareness:

- In the event that positioning is not available, as long as the mobile terminal is able to detect (for the Broadcast CPC delivery mode) or contact (for the On-demand CPC delivery mode) the CPC transceiver, the information about the different regions in that area are available.
- In the event that positioning is available, a subset of the information of RATs and frequencies at the actual position could be identified. The mobile terminal could then try to connect using that information.

For both cases above, in the worst case the mobile terminal has to make a scanning over the possibilities indicated by CPC to find out what RATs and frequencies are available at its actual position.

2.2 – A feasible CPC solution

In the following, a possible Out-band CPC solution is presented, facing the different aspects related to the implementation of the CPC for the switch-on case.

As for the RAT to be used, the solution assumes to re-use the already existing RATs, considering the GSM system as bearer. The approach is based on the following points, taking into account the architecture and main feature of GSM system:

- the L1-L2 are entirely GSM-based, thus not requiring any modification
- the CPC messages are RR-layer signalling, conceptually analogous to the System Information messages
- the CPC messages are transmitted over the BCH.

The present solution assumes to dedicate a single GSM carrier frequency to the CPC, possibly located in a band harmonized, and not necessarily inside the band typically assigned to GSM. Therefore, the bandwidth requirement is about 200 kHz plus guard bands. Since the GSM system is TDMA/FDMA based and for each carrier 8 time-slots are available, each one with a minimum bit-rate of 9.6 kbps using the lowest GSM coding (higher bit-rate per time-slot could be available using newer coding schemes, such as (E)GPRS encoding), in theory one GSM carrier could offer a minimum bit-rate of 8x9.6 kbps = 76.8 kbps.

As for the information delivery mode, the Broadcast CPC approach is considered, requiring only a downlink channel and thus simplifying the solution and the deployment. On this basis, a specific RR-layer signaling message is continuously repeated over the BCH channel, instead of the System Information messages.

The structure of the specific RR-layer CPC message is reported in Figure 3.

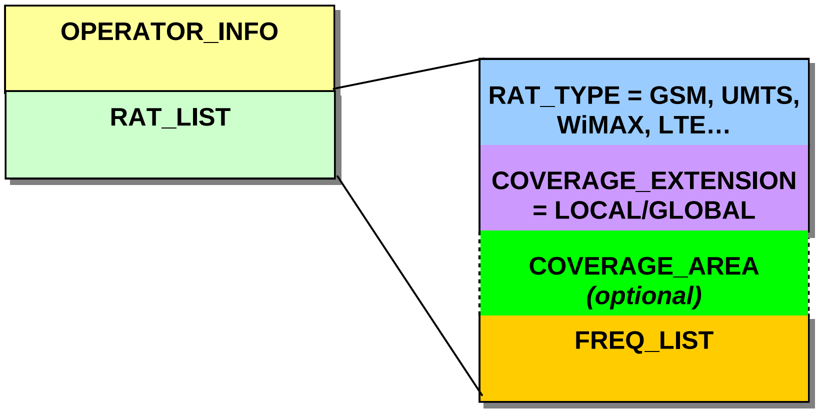

Figure 3: CPC Broadcast message structure.

The following fields are considered in the CPC broadcast message structure:

- *Operator information:* operator identifier. This information is repeated for each Operator to be advertised by the CPC.
- *RAT list*: for each operator, provide information on available RATs. This information is repeated for each RAT of *i*-th Operator.
    - *RAT type*: could be “GSM”, “UMTS”, “CDMA2000”, “WiMAX”, “LTE”…
    - *Coverage extension*: could be GLOBAL (i.e. wherever the CPC is received) or LOCAL (i.e. in an area smaller than CPC coverage)
    - *Coverage area*: to be provided in case of LOCAL coverage (e.g. reference geographical point).
    - *Frequency information*: provide the list of frequencies used by the RAT.

2.2.1 – Assessment of proposed CPC solution

In order to verify if the proposed solution is self-consistent and the required bandwidth is sufficient for the bit-rate needs of the CPC message structure, in the followings a preliminary analytical evaluation is presented. Similar assumptions already considered in the dimensioning exercise of previous CPC broadcast solution have been used [5].

The scenario considered in the evaluation is the one defined in [5] as the upper bound for practical deployments, where 5 operators are available, each one with 5 different RATs, each RAT with 10 advertised frequencies:

- N_{OP} = 5 (i.e. number of operators)
- N_{RAT} = 5 (i.e. number of RATs for each operator)
- N_{freq} = 10 (i.e. number of advertised frequencies for each RAT of each operator)

The CPC information to be provided is supposed to be bit-encoded using the same approach of [5]:

- Operator information B_{OP}: 20 bits (corresponding to OPERATOR_INFO field in Figure 3)
- RAT information B_{RAT}: 4 bits (corresponding to RAT_TYPE field in Figure 3)
- Coverage extension B_{COV}: 1 bit, 0 = GLOBAL and 1 = LOCAL (corresponding to COVERAGE_EXTENSION field in Figure 3)
- Geographical coordinates B_{GEO}: 41 bits (corresponding to CENTER_LAT and CENTER_LONG fields in Figure 3)
- Coverage area B_{radius}: 12 bits
- Frequency information B_{freq}: 16 bits (corresponding to each item of FREQ_LIST field in Figure 3)

Additional assumptions compared to [5] have been also considered:

- CPC infrastructure is based on a cellular approach: in principle, in each cell a different CPC content is broadcast
- Preliminary evaluations are on a per-cell basis
- Coverage extensions of each RAT are supposed to be LOCAL (i.e. no GLOBAL coverage)
- Each RAT of each Operator is supposed to be available only in one local area in the reception area of the broadcast CPC message

On this basis, the number of required bits to be transmitted by the CPC for each cell are:

$$\mathrm{B_{TOT}} = \mathrm{N_{OP}} \cdot \left(\mathrm{B_{OP}} + \left(\mathrm{N_{RAT}} \cdot \left(\mathrm{B_{RAT}} + \mathrm{B_{COV}} + \mathrm{B_{GEO}} + \mathrm{B_{radius}} + \left(\mathrm{N_{FREQ}} \cdot \mathrm{B_{freq}}\right)\right)\right)\right)$$

In the considered example:

$$\mathrm{B_{TOT}} = 5 \cdot (20 + (5 \cdot (4 + 1 + 41 + 12 + (10 \cdot 16)))) = 5550 \text{ bits}$$

Assuming that each user should be able to gain knowledge of broadcast information in maximum T_{Delay} = 0.5 seconds, the net bit-rate that should be available to the CPC is:

$$R_b = \frac{B_{TOT}}{T_{Delay}} = \frac{5550}{0.5} = 11.1 \quad kbps$$

As a conclusion, the assessment performed on the proposed approach for CPC broadcast message operations resulted in a relatively low bit-rate requirements in the considered scenario. In particular, with the proposed approach the required bit-rate is very low compared to the results obtained for previous CPC broadcast approaches [5] and it can fit well with the assumption of using GSM as bearer. The reason for this lower bit rate requirement in the solution proposed here with respect to [5] relays on the way how the information signalled by CPC is transmitted. In particular, while in [5] the scenario is divided into homogeneous areas (denoted as *meshes*) and for each mesh the combination of RATs and frequencies available is explicitly transmitted, in the proposal here it is not needed to consider the meshes. Instead, the information transmitted includes the coverage extension of each RAT, which allows the terminal to determine whether it is in the coverage area of a given RAT or not.

3. CPC as enabler for decentralised resource selection optimization

As described in the previous section, in both a qualitative and quantitative way, the CPC can efficiently play the role of assisting the switch-on process at the mobile terminal. In addition, after switching on and while the mobile terminal is in an operational state, the CPC could also be used to provide an optimized, decentralized radio resource management operation. This section aims at providing such a vision of the CPC.

Traditionally, radio resource management has been mainly centralized, based on the fact that a central network node has a more complete picture of the radio access status than a particular node, so that decisions can be made with more inputs. Nevertheless, newly appeared factors like the introduction of novel services, frequently changing environment subject to users' traffic or mobility fluctuations, and also space-time varying spectrum and carrier usage render operators' legacy radio resource management functionality not always able to ensure best offered connectivity and service provision. In such situations, the use of a centralized manager would impose large communication signalling overhead due to fast context changes. On the contrary, the complexity can be relaxed by moving part of the radio resource management functionality into more decentralized solutions. CPC appears as an appealing possible future solution for enabling such a network-assisted decentralized radio resource management.

As for the RAT used for CPC in case of radio resource management operations, the "In-band CPC" approach seems to be the most convenient (see Figure 4), conveying CPC information using logical channels of the same radio access technologies that are used for the user data transmission, and allowing to bear information to both uplink and downlink.

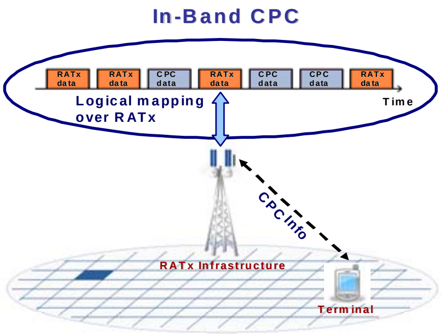

Figure 4 : "In-Band CPC" approach

Indeed, in this case, two mainstream categories are identified for both reverse and forward links, namely: *context information* and *policies*.

- *Context information*: Context information can have either the network or the mobile terminal as its source. In the former case, the mobile terminal collects from its network context information such as radio resource optimization objectives, network radio capabilities, network measurements etc. In the latter case, the mobile terminal may send context information to the network like device capabilities, user preferences, required applications and QoS levels, locally conducted measurements, geo-location information etc. Furthermore, in this case an instance of the CPC must be also present in the uplink.
- *Policies*: An efficient way for an operator to allow a decentralized type of radio resource management, while keeping at the same time the control of its network's mobile terminals could be consisting in mobilizing policies. Policies are derived in the network[1] side and sent to the terminal via CPC to serve as directives that must be taken into account during each individual terminal's radio resource usage optimization process. In order not to confuse this type of policies with other types like high level

[1] More precisely, by the special management software within the network side

rules pertinent to operators and/or spectrum regulator general goals and policies, it is referred to as Radio Resource Section policies (RRS policies)

The terminal[2], driven by those RRS policies together with network context information and other types of policies as stated above, as well as profile information being kept in the terminal and corresponding to terminal capabilities and user preferences, can implement the action(s) of the optimization of its operation e.g. for the (re-)configuration of its operating parameters like RAT, frequency, modulation type etc.

Such a type of decentralized radio resource management and optimization is a really challenging and complex problem. While solutions based on proprietary protocols might temporarily solve the problem, this could be done for a small set of terminals and also would complicate the tasks of learning and using different management systems and management protocols for each different terminal type. Therefore, the need for a common, standardized interface appears to be of high significance for getting over those hindrances. CPC could play a pivotal role of this interface. It should also be noted that such approaches that use either policy based efficient, decentralized management or radio enablers similar to CPC, or both, have been under study by working groups within major standardization bodies such as IEEE [6].

4. Conclusions

This paper has presented the development of the CPC concept for heterogeneous wireless network scenarios with flexible spectrum capabilities. In this context, CPC can address two different and complementary missions. Firstly, as an enabler of the switch-on process that allows the mobile terminal to get in touch with the network side. In this respect, this paper has detailed a feasible CPC solution based on a broadcast approach, obtaining that the required bit-rate is very low (11 kbps in the considered example) and can fit well with the assumption of using e.g. GSM as bearer. Secondly, CPC can act as an enabler of an efficient decentralized management along the on-going communication phase. In this respect, this paper has presented the categorisation of the information that could be transmitted. Future research on CPC requires the analysis of the different alternatives mentioned in various scenarios with respect to the CPC operating frequency, CPC deployment, CPC delivery, etc. Similarly, for the on-going phase future research involves the development of the appropriate decentralised RRM strategies.

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