A Local Cognitive Pilot Channel (LCPC) for Neighbourhood Discovery, Relaying and Cluster Based Local Cognitive Information Management

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This paper proposes a novel conceptual wireless communication framework in which Mobile Devices (MDs) are cooperating within geographically localized clusters. A Local Cognitive Pilot Channel (LCPC) is introduced for exchanging context information between such neighbouring MDs and for performing neighbourhood detection; the cluster size is hereby gradually adapted by incremental change of transmission power levels. The neighbourhood detection guarantees that the MDs are aware about the presence of neighbouring peers, followed by a corresponding exchange of context information, distribution of sensing tasks and negotiation of MDs serving as relay nodes; the distributed detection approach furthermore ensures that real-time constraints, as they occur in the presence of mobile MDs for example, are met. It will be shown that such a wireless framework can be deployed using a minimum of infrastructure equipment and is thus in particular useful for an early-phase deployment of a novel technology and/or for cost-reduction due to the minimization of the investment in network-equipment (CAPEX / OPEX reduction).

Index Terms— **Cognitive Pilot Channel, Cognitive Radio, Software Defined Radio**

I. INTRODUCTION

The general principle of Cognitive Radio (CR) has been introduced by [1], triggering a vast amount of follow-up research effort. First, key studies were focusing on high-end military and public safety applications; then, the commercial wireless communication was identified as area of high potential for CR. Funded research projects such as IST-E^{2}R, IST-E^{2}R II [2] and ICT-E^3 [3], among others, have studied and proposed corresponding solutions targeting a commercial communications framework. As a key requirement, the availability of context information has been identified to be crucial; as a consequence, IST-E^{2}R has introduced the concept of a Cognitive Pilot Channel (CPC) [4-5] as a means for centrally controlled provision of context data. In the mean-time, the basic idea has been adapted to various scenarios and needs; for example, [6] introduces a Distributed Cognitive Pilot Channel (DCPC) proposal adapted to the needs of an autonomously managed home environment.

Most recently, various standardization bodies have taken up the CR idea with a focus on two types of applications: i) opportunistic spectrum usage, mainly in the so-called TV White Spaces and ii) radio link management in a heterogeneous environment. Type i) applications are for example addressed in IEEE 802.22 created in 2004 and developing a standard for Wireless Regional Area Networks (WRAN) using White Spaces in the TV frequency spectrum; moreover, the recently created group IEEE 802.11af defines modifications to both the 802.11 physical layers (PHY) and the 802.11 Medium Access Control Layer (MAC), to meet the legal requirements for channel access and coexistence in the TV White Space. ETSI RRS [7] is currently starting to work into a similar direction taking European needs into account. Type ii) applications are for example covered by IEEE SCC41 which is developing standards related to dynamic spectrum access networks with a focus on improved spectrum usage. In this framework, the IEEE standard 1900.4-2009 [8] defines a management system supporting network-terminal distributed optimization of radio resource usage and improvement in QoS in heterogeneous wireless networks. These examples show that mass market CR solutions are likely to be available within a few years time-frame.

The above-mentioned working axes highlight the current trend towards heavily heterogeneous systems requiring a complex infrastructure deployment and thus leading to high levels of Capital Expenditure (CAPEX) and Operational Expenditure (OPEX). Therefore, the authors suggest that the next technological step consists in driving a lighter infrastructure density building in particular on CR principles. In the framework of this paper, it is proposed to realize such a vision by creating geographically localized clusters of Mobile Devices (MDs) which are autonomically interacting with each other thanks to a novel Localized Cognitive Pilot Channel (LCPC), to be operated preferably on a dedicated frequency band. New features include the detection of neighboring devices, the negotiation of multi-hop communication with MDs serving as relay nodes, assisted distributed sensing and resource allocation, etc.

In the sequel, Section II will introduce the LCPC overall concept and approach, followed by details on related relaying mechanisms and their respective negotiation in Section III. Section IV details further sensing applications of the LCPC related to the CR framework, including distributed management approaches. Section V finally gives a conclusion.

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II. LOCAL COGNITIVE PILOT CHANNEL (LCPC) CONCEPT

In the framework of this paper, we are considering the heterogeneous scenario as illustrated by Fig. 1 – for sake of simplicity only cellular Macro Base Stations (Macro BS) and WiFi Access Points (APs) are included. A set of neighbouring MDs are forming a geographically localized cluster and are able to communicate with each other directly thanks to a LCPC link that can be maintained between MDs being part of the cluster. Eventually present APs, Macro BS, etc. are typically unaware of this inter-MD information exchange. For certain applications, such as the distributed sensing or resource allocation approach presented in Section IV, it is of advantage to select one MD to take the role of a Cluster Head (CH) and to perform coordination tasks within its cluster.

Note that in traditional systems, a centralized entity, such as the Macro BS in case of locally centralized schemes, handles the broadcast of cognitive information to the system using a centralized CPC [4-5]. However, in current cognitive radio protocols applying opportunistic spectrum usage, MDs are supposed to collaboratively collect the cognitive information in order to protect the primary user's instantaneous rate.

The set-up of such a cluster is proposed to be handled by the following steps:

i) A MD is not receiving any LCPC message during a predefined period $t < \tau_{LCPC}$. This MD may then decide to initiate the set-up of a cluster and is then assumed to take the role of the CH.

ii) The CH MD broadcasts via the LCPC an invitation message to surrounding MDs to join the cluster. For this purpose, there is a predefined set of output power levels $\Pi = \{\pi_0, \pi_1, \pi_2, \cdots, \pi_{MAX}\}$ with $\pi_0 < \pi_1 < \pi_2 < \cdots$. For the initial transmission of the invitation message, the MD selects output power level $\pi_{CH} = \pi_k, k = 0$.

iii) The CH MD waits during the predefined response period τ_{RESP} and receives incoming response messages from neighbouring MDs accepting the invitation to join the cluster. Typically, a random access channel scheme is used, requiring the CH MD to send acknowledgement messages to the neighbouring MDs in order to indicate the correct reception of the response message (see Figure 2, symbol '❶'). The accumulated number of accepted invitations is defined to be n_{INVIT}. The maximum number of MDs being part of a cluster is defined to be $n_{INVIT,MAX}$, i.e. $n_{INVIT} \leq n_{INVIT,MAX}$.

iv) If $n_{INVIT} < n_{INVIT,MAX}$ and $\pi_{CH} < \pi_{MAX}$, then the CH MD may choose to increase the transmission power and to resend the inivitation messages, i.e. $k = k + 1,\ \pi_{CH} = \pi_k$. As soon as $n_{INVIT} = n_{INVIT,MAX}$, the acceptance of novel MDs to the cluster needs to be rejected or the cluster size needs to be reduced again (requesting the concerned accepted MDs to leave the cluster). This increase of the transmission power is illustrated in Fig. 2 (symbols '❷' and '❸').

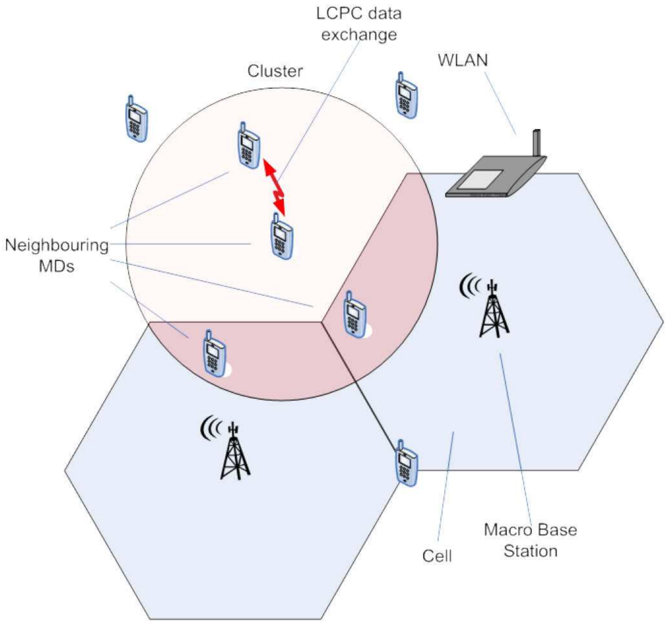

Figure 1: Considered Scenario.

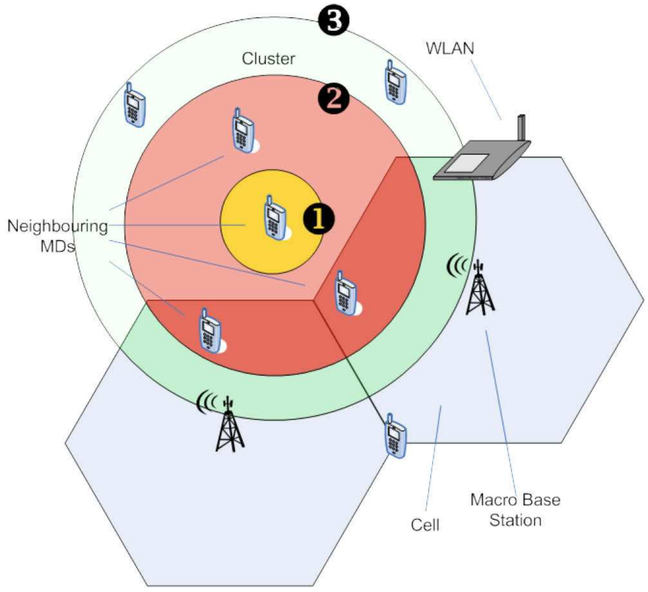

Figure 2: Cluster Set-Up.

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Once the set-up of the cluster is completed, the local exchange of cognitive context information via an LCPC is periodically initiated. It is proposed that this context information may contain, among others, the following information elements and tasks:

- Distribution of sensing tasks for cooperative sensing (frequency, bandwidth, time, …),
- Transmission of sensing information (results of detection, according to the request),
- Indication of willingness and suitability of MDs to act as mobile relaying nodes, including relevant relaying parameters, such as number of hops, etc.
- Secondary cognitive communications (according to sensing information aggregation and decision process).

III. LCPC IN RELAYING APPLICATIONS

Relaying has been under broad consideration for recent years, with studies providing proof for the possibility of considerable capacity gains, see for example [9]. The general principle is highlighted by Fig. 3, giving an illustration of a standard three-point relaying system.

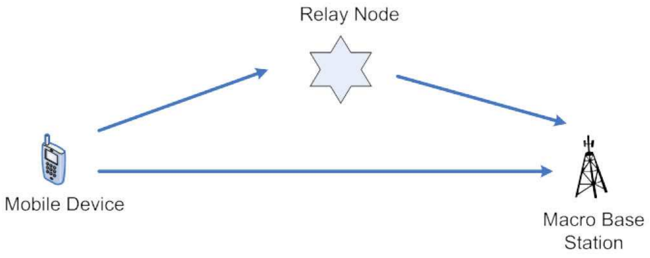

Figure 3: Example for three-point relaying system.

In this context, various relaying strategies have been considered in the literature, such as Amplify-and-Forward (AF), Decode-and-Forward (DF), etc. The proposals within this paper are independent of the corresponding relay strategies. More recently, standards bodies are dealing with relaying approaches in order to exploit the inherent advantages in commercial systems, in particular IEEE 802.16j [10] introduces relaying mechanisms to the WiMAX system and 3GPP LTE Advanced is currently investigating the introduction of such mechanisms.

Furthermore, it should be noted that the literature is often inherently limiting the usage of relaying to a single Radio Access Technology (RAT), such as 3GPP LTE, WiMAX, or others. In the context of this paper, it is assumed that a MD may choose to communicate via any neighbouring system, such as cellular systems, short range systems (WiFi, etc.), etc. if the respective communication conditions are favourable.

Based on the mechanisms introduced in Section II, the core idea of the proposed approach is related to methods to trigger information exchange between MDs in close vicinity pertaining to their respective characteristics, such as suitability and willingness to serve as a relay node, RATs being supported, etc. Corresponding relay links are finally used if they offer advantages in terms of, for example, reduced power consumption, reduced subscription cost, etc.

The following procedure is proposed for the identification and set-up of relay links:

i) Once a cluster is formed as introduced in Section II, a MD ("Source MD") is using a LCPC link to neighbouring MDs in order to request the transmission of context information from its neighbours information such as quality of links to closest Macro BS, a list of available Macro BS / APs and information on other MD locations and willingness to provide context information.

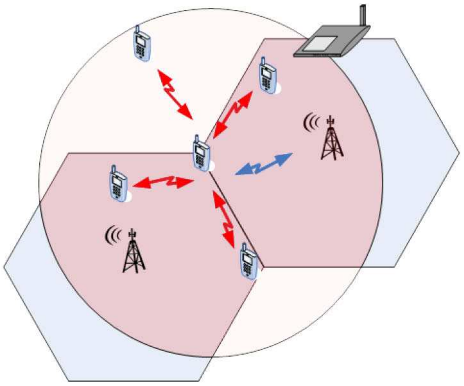

Figure 4: A "Source MD" communicating with "Target MDs" by a LCPC link (red arrow), the LCPC output power is increased in order to increase the communication range.

ii) The MD gets indications from one or several surrounding "Target MDs" that they are willing to exchange context info and/or serve as relay node.

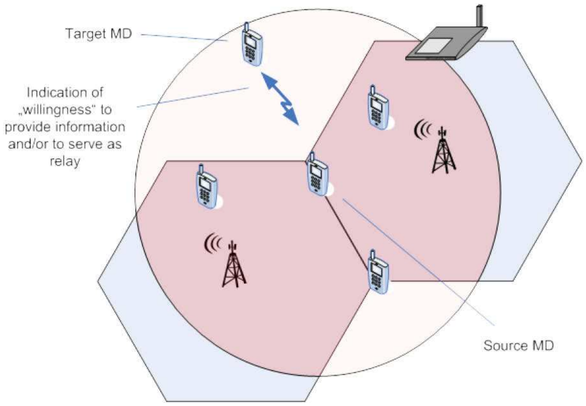

Figure 5: A "Target MD" agrees to provide context info and/or to serve as a relay node.

iii) The Source MD selects the target MD from which it desires to receive the information. The Source MD contacts the target MD again and requests the transmission of the context info and/or confirms that it will be used as relay node. In case it becomes a relay node the 'multi-hop grade' (i.e., total number of hops to closest Macro BS / AP / etc.) is incremented by '1'.

iv) In case that the provision of context information is requested: The selected Target MD will broadcast the Context Information requested by the Source MD. This broadcast message is available to all MD in the communication range.

As illustrated by Fig. 5, the proposed communication system allows to enable MDs to communicate via relays with distant Macro BS and/or APs. In this illustration, this is typically the case for the highlighted "Target MD". As such, this concept allows for a lighter infrastructure approach, i.e. fewer Macro BS and/or APs need to be deployed. Since the presence of MDs is required, which are able to serve as relay nodes, the final infrastructure density is expected to depend on the target outage probability of communication links and the statistical presence of MDs in the concerned area.

IV. LCPC BASED SENSING APPROACHES

The scenario depicted in Fig. 6 consists of deploying a Cognitive Wireless Ad hoc Network which acts as secondary network (SN) co-located with a Primary Network (PN) and operating in the same bands. In this context, ad hoc SN scans the spectrum usage, and is thus aware of the holes that are currently available and can potentially be used for cognitive communication with the insurance that the PN will not be disturbed.

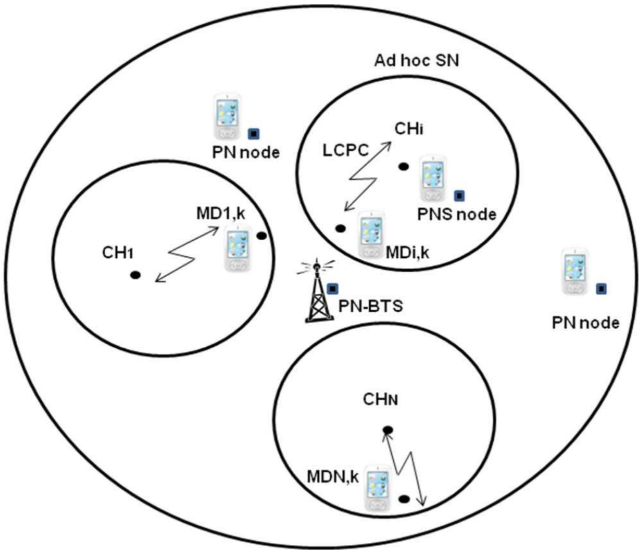

Figure 6: Cognitive Ad hoc Network

The idea here consists of implementing a Local Cognitive Pilot Channel (LCPC) broadcasted at each Cluster Head (CH) to carry local information such as:

i) Sensing measurements,
ii) Spectrum monitoring,
iii) Cognitive parameters (primary system features, Interference avoidance criteria, etc…),
iv) Distributed sensing and resource allocation algorithms parameters.

In this context, two options are proposed:

i) CH based sensing decision: the CH gathers local measurements from ad hoc surrounding nodes and takes decision on spectrum availability,
ii) MD based sensing decision: MDs collect measurements from neighboring nodes, take their decision in a distributed way and inform the CH about the bands they are willing to occupy. In this case, the CH is in charge of handling resource allocation conflicts between nodes and broadcasting spectrum occupancy information using LCPC to inform the other nodes.

In both cases LCPC is used to carry:
i) Cognitive access information,
ii) Acknowledgement of spectrum sensing and allocation decisions taken in a distributed way at MDs,
iii) Spectrum allocation coordination information,
iv) Inter cluster cooperative communication parameters.

CH based sensing decision:

The messages defined in this case could be mapped to LCPC as follows:

- **Initiate sensing** message from the CH to the sensing MD, to instruct for starting continuous scanning on all frequencies considered for cognitive operation. The parameters provided here are: MD id, Synchronization parameters, Start frequency, Stop frequency, Measurement bandwidth, Sensing time, Number of subbands, average time duration, monitoring period, etc.
- **Update sensing result** periodic message from the sensing nodes to the CH with sensing result parameters such as: Ambient noise power, Average signal power, Maximum signal power, Signal statistics, etc.
- **Update frequency assignment** periodic message from the CH to the transmitting MDs to inform them about the new cognitive band where they need to move.

MD based sensing decision

In this case, MD will perform locally cooperative sensing. MD collects sensing measurements from neighboring nodes to improve its local decision before to send it to the cluster head.
In this case the CH has two roles: it initiates sensing after network set-up and coordinates spectrum occupancy among secondary transmissions. The exchanged messages between CH and MDs include:

- **Initiate sensing** message from the CH to the sensing MD, to instruct for starting continuous scanning on all frequencies considered for cognitive operation. The message is issued when the ad-hoc network is set up and contains the same parameters as in CH based decision.

- **Update sensing result** periodic broadcast message from the sensing node to its neighbors with sensing result parameters.
- **Frequency allocation report** periodic message from MDs to the CH, with parameters such as: List of sensed free bands, the band that the MD is willing to occupy, Source and destination ids, etc.
- **Frequency allocation ACK/NACK** acknowledgment messages sent by the CH to the MDs to handle frequency allocation coordination among attached MDs
- **Update frequency allocation status** periodic broadcast message to inform all attached MDs about frequency allocation list at each node.

Local cognitive pilot channel is broadcasted trough dedicated narrow band which is used when the network is set up and then switched to the detected cognitive bands, as shown on Fig. 7, during monitoring phase to increase signaling rate and allow high transmission performance during sensing and reporting phases.

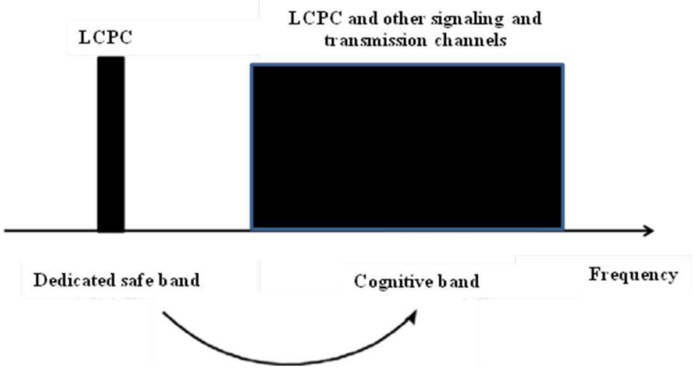

Figure 7: LCPC broadcasted on safe and cognitive Bands.

V. CONCLUSION

In this paper, a novel Local Cognitive Pilot Channel (LCPC) approach has been introduced, ensuring peer-to-peer communication between MDs within a geographically localized cluster. A novel mechanisms for the set-up of such a cluster has been detailed with the corresponding initiatives being taken by MDs (in contrast to classical network centric approaches). It has been shown that the proposed system concepts allows for a lighter infrastructure deployment density and thus in particular useful for an early-phase deployment of a novel technology and/or for cost-reduction due to the minimization of the investment in network-equipment (CAPEX / OPEX reduction).

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