THE APPLICATION OF SOFTWARE DEFINED RADIO IN A COOPERATIVE WIRELESS NETWORK

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ABSTRACT

This article describes the use of Software Defined Radio over the Software Controlled Radio in a cooperative wireless network in an OFDM based downlink scenario. The article argues that although the state of the art of SCR is considered superior with respect to implementation factors such as complexity, cost and efficiency, the SDR offers a degree of flexibility together with the use of cooperative wireless networks that proves a potential to outweigh the disadvantages traditionally associated with SDR implementations.

1. INTRODUCTION

Currently wireless communication is approaching the so called fourth generation (4G). Higher data rates for the end terminals are the main goal of the next generation. Unfortunately, this goal can only be achieved by larger energy consumption and more complex terminal design. In [1] a novel architecture for wireless communication is motivated to overcome the aforementioned described problems. Instead of the traditional peer to peer communication between base station and each terminal using a cellular link, where each terminal is operating autonomously, cooperation among terminals is introduced. In such a scenario the terminals are communicating over a short range communication in parallel to the cellular communication. Such architecture offers virtual high data rate, lower energy consumption and new business models.

An essential precondition for the functionality of cooperative access is a highly flexible capacity distribution between the cellular and the short range communication. The capacity needed is a function of the number of cooperative users. In this paper we utilize the principle of OFDM sub-carrier distribution for this purpose. OFDM has inherent capabilities as a composable channel, but further flexibility is needed.

Considering the required architecture of a cooperating terminal to benefit from the potential advantages of the cooperative wireless network architecture, it is clear that it need to support the flexible capacity distribution in terms of flexible OFDM subcarrier allocation together with associated communication parameters for the cellular and short range links. Looking at Figure 1, the number of terminals taking part in a cooperation is flexible and cooperating need not only adapt communication parameters, but also to dynamically create and close additional receive chains according to number of cooperating terminals as the number of cooperating terminals are considered to be dynamic. We argue that considering the scenario depicted in Figure 1, i.e. a scenario of an unknown and dynamically assigned number of cooperating terminals, an SDR approach will likely prove to be more advantageous in terms of cost and complexity whereas improved efficiency is inherent in the application of the above network architecture. We therefore argue that although SCR has until now been proven to be the preferred implementation technology, we argue that in cooperative wireless network scenario, the SDR, [3] [4] is an important and feasible implementation technology necessary to facilitate the demand for flexibility needed to achieve the gains described in [1]

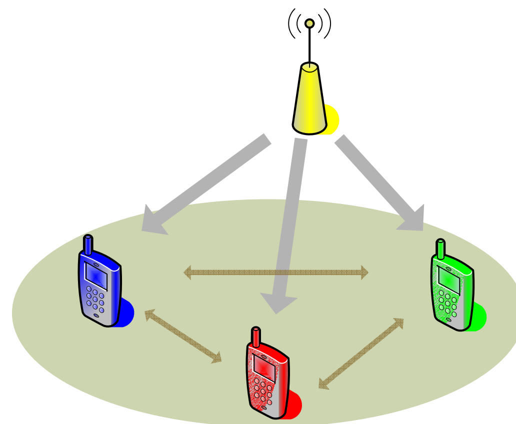
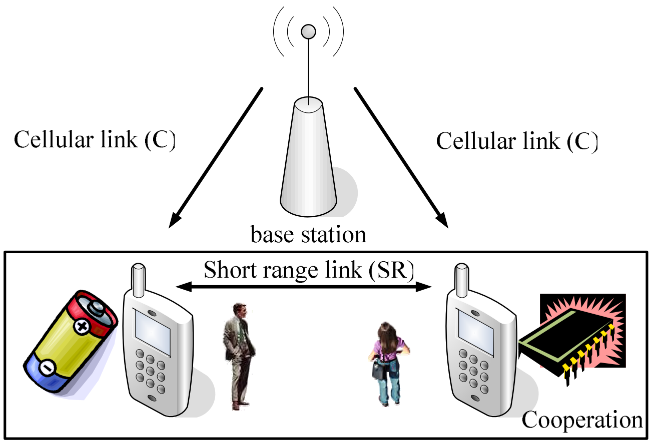


Figure 1 Cooperative wireless network scenario

2. MICRO COOPERATION

The concept of a Micro cooperative wireless net is illustrated in Figure 2. As illustrated the cooperation can be



understood by the abstraction of resource sharing, where resources is understood as energy resources in terms of battery, processing resources in terms of processing power, memory and the sharing of RF resources such as frequency spectrum.

By sharing energy resources, the cooperating terminals inherently share processing as well as spectrum resources. This makes cooperation a paradigm of gaining energy efficiency by sharing processing and spectrum resources among cooperating terminals. It is apparent that proper incentives, e.g. in terms of energy efficiency has to be in place before each terminal agrees to participate in a cooperating network and to spend energy resources to serve the needs from other cooperating terminals. Studies [1] made on a downlink cooperative scenario show an energy gain for the participating terminals. This achieved energy gain can be as high as 40%, with two cooperating entities, and compared to non-cooperating energy consumption. An important precondition for the success of a cooperative wireless network is the assumption of increased link quality in a short range communication due to the proximity of cooperating terminals. The assumption of improved link quality facilitates the use of higher order modulation schemes with less coding overhead and less transmit power, leading to an increased efficiency in terms of energy resources while still enabling the required performance in terms of data rate.

3. REALIZING MICRO COOPERATION

We will now consider two possible approaches of realizing the concept of Micro cooperation. The two approaches is the concept of multi-modality using omni present cellular and short range technologies. The second approach is the concept a unified frequency domain access scheme where cellular as well a short range communication is carried out using a common frequency spectrum.

3.1 Multi-modality

Micro cooperation using the principle of multi-modality takes advantage of existing cellular and short range wireless technologies for establishing cooperative wireless network. The advantage using this principle is the already available technologies and implementations available in state of the art mobile devices. [3] Exemplifies the advantage using state of the art mobile phones and a file sharing application. The technologies used are GPRS for the cellular link and Bluetooth for the short range link. The example shows a 44% reduction in energy consumption

From an architecture point of view, the principle of multi modality lends itself to a traditional SCR implementation. The drawback of using existing technologies is the lack of flexibility as the cooperative scenario relies on the characteristics of the available technologies.

3.2 Common frequency spectrum

We now turn to the concept of a unified frequency domain access scheme using a common frequency spectrum for cellular as well as short range communication. The motivation for introducing such an access scheme is to accommodate the flexibility needed to exploit the full potential in a cooperative scheme i.e to accommodate a dynamic scenario of cooperating terminals and to adapt cellular as well as short range links to actual channel characteristics

In this scenario we argue the use of a multicarrier transmission scheme and in particular OFDM as this recognized as a potential transmission scheme for future communication systems because of its ability to accommodate high data rate transmissions with low complexity implementations by the separation of high rate data stream into parallel low rate data rate streams.

From the point of view of a cooperative scenario, multicarrier transmission is attractive because of its inherent capabilities of flexible subcarrier allocation with respect to carrier frequency, power and bit loading schemes.

From an implementation perspective, we consider two approaches, the SCR architecture, with a fixed subcarrier allocation scheme and an SDR architecture with a flexible subcarrier allocation scheme, these two schemes are depicted in Figure 3.For both schemes it is understood that the common spectrum, or iin the case of Multicarrier transmission, the total set of subcarrier, are divided between cellular communication from basestation to terminals and short range communication between cooperating terminals.

The SCR approach is to be understood as cooperating terminals with SCR architectures. Considering the scenario shown in figure Figure 2, it is apparent that cooperating terminals are required to process a number short range

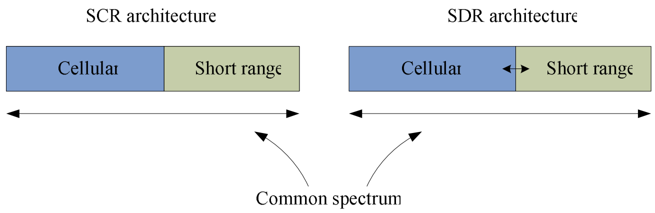


Figure 3. Spectrum allocations using an SCR implementation and an SDR implementation

communication links from other cooperating terminals. An SCR architecture would need to accommodate that number of short range communication links in its architecture design. In Figure 3 it is indicated that because of this architecture requirement, the spectrum allocation between cellular and short range subcarriers can only be done as fixed allocation. This is contrary to a scenario where the cooperating terminals are terminals with an SDR architecture. In such an architecture the spectrum allocation can be made flexible and dependent on the actual number of cooperating terminals. It should be noted that considering the common spectrum and the spectrum allocation, the number of subcarriers allocated for short range, are smaller than the spectrum allocated for cellular communication, this is due to the assumption of better link quality resulting en more spectral efficient modulation formats and henceforth a lower number of required subcarrier.

We now turn to the application of OFDM in a cooperative scenario as the one shown in Figure 1, we describe the use of FDMA with OFDM as each cooperating terminal are assigned a set of subcarriers. The use of FDMA OFDM is illustrated by examples where we argue that an SDR architecture has the potential to prove as a more efficient solution compared to an SCR architecture.

3.3 OFDM in cooperative wireless networks

Figure 4 shows a micro cooperative scenario using the principle of OFDMA with three cooperating terminals. This assumes a common air interface between basestation an terminals and between terminal cooperating. In this type of scenario, it is assumed that the subcarriers are freely allocated between cellular and short range communication links. Using the the principle of a multi-carrier transmission allows the flexible allocation of resources in terms of spectrum and the efficient use of that spectrum by proper power allocation and spectral utilization schemes, according to the prevailing channel conditions, [5]. The downlink cooperative scenario allocates only a subset of a OFDM spectrum to be processed by each cooperating terminal, this in effect decreases the processing load of FFT processing as the computational complexity of an FFT is O(N logN), with N being the length of the FFT, . It is further assumed that link quality in the short range links are higher enable the use of higher order of modulation format at a lower transmit

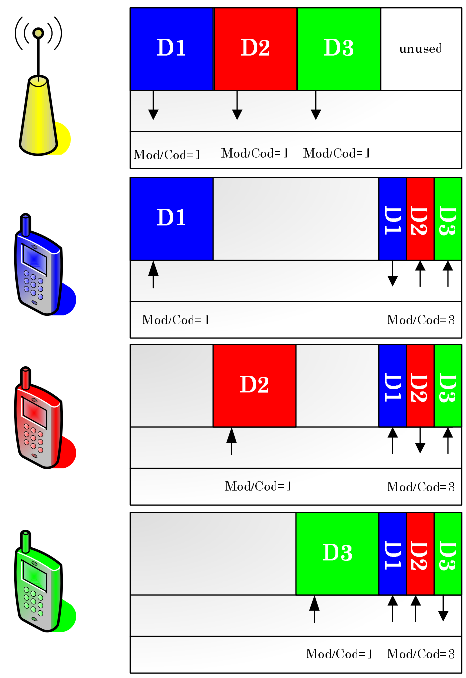


Figure 4. Downlink cooperative scenario using the principle of OFDM and FDMA

power and shorter transmit time as information distributed among cooperating terminals are transmitted using a higher order of M symbols per information bit than the cellular channel.

3.4 Scenarios of composable channel

This section introduces the three different scenarios of subcarrier allocations in the case of the downlink scenario describe above. It is argued that in the case of a scenario with cooperation as well as dynamic carrier allocation, and that an SCR implementation will appear to be less feasible in all terms of architecture performance factors, complexity, cost, flexibility and efficiency. This leads to the conclusion that SDR proves to be a feasible implementation alternative to the SCR in cooperative wireless network scenario.

3.4.1 Cellular with no cooperation and static channel composition

With reference to Figure 5 this scenario is similar to a traditional cellular communication between a basestation and a given terminal using the principle. No cooperation is formed meaning that terminals communicating with the base station are processing the whole bandwidth as indicated in Figure 5. Subcarriers are statically assigned, meaning that group of subcarriers are assigned for the duration of a connection and without the use of link quality information for each subcarrier. From the perspective of a terminal, the receiver architecture shall accommodate the flexibility of

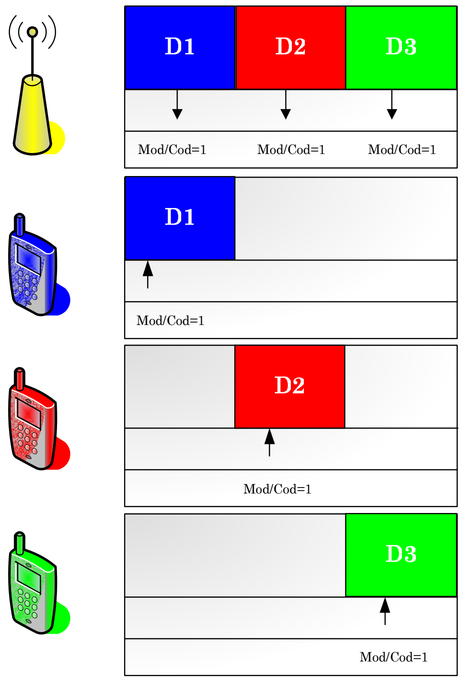


Figure 5 Carrier allocation scenario with no cooperation and static carrier assignment

adapting FFT sizes according to datarate requirements and users together with adaptive modulation and coding for each subcarrier or group of subcarrier, similar to requirements set forth in IEEE802.16 and the concept scalable OFDMA [6]. This kind of flexibility we term flexibility by adaptation. The options for adaption are limited and the degree of flexibility needed is not assumed to be high enough to justify the employment of SDR.

3.4.2 Cellular with cooperation and static channel composition

Referring to Figure 4, this scenario introduces cooperation, but similar to the previous scenario subcarriers are statically assigned. It is apparent that the use of static carrier assignment, although providing for low complexity in system implementation, pose the risk of a group of sub-carriers be positioned in a deep channel fade thereby causing a degradation in link quality and datarate for that group of subcarriers. Considering an architecture for a terminal supporting this kind of scenario reveals the first distinction between a Software Controlled Radio based architecture and an Software Defined Radio based architecture and the concept of flexibility by reconfiguration. Considering an SCR implementation, it is apparent by studying Figure 4 that the concept of cooperation involves the accommodation of a terminal having the capability of receiving and processing a number short range links according to how many terminal that are participating in the cooperation. We now define a state of the art SCR implementation as one that has a fixed functionality typically implemented in dedicated hardware, with parameters being controllable in software. Accommodating the principle of cooperation in an SCR implementation would require the implementation of short range receive chains in hardware. This achieved energy gain can be as high as 40% dependent on the number of cooperating terminals compared to a non-cooperating energy consumption [1].

Initial studies have shown that the achieved energy gain can be as high as 40% dependent on the number of cooperating terminals compared to a noncooperating energy consumption [1], this energy is achieved as the number of cooperating terminal increases. But as the number of cooperating terminals increases so does the need for receive chains. Implementing these receive chains in hardware will likely compromise the most important reasons for SCR implementations known today, namely cost, efficiency and complexity. Furthermore having terminals supporting only a limited number of cooperating entities, to limit the hardware complexity will limit the application and thereby the advantages gained by cooperation. Finally considering that sub-carriers might be assigned not statically but dynamically to achieve the best link quality for each cooperating terminal will impose further complexity requirements on a SCR implementation. These considerations lead to the argument that an SDR implementation offer the possibility of accommodating a flexible number of cooperating terminals by employing what we define as flexibility by reconfiguration. Flexibility by reconfiguration is to be understood as the ability of an SDR architecture to configure the number of short range links necessary in a given scenario.

3.4.3 Cellular with cooperation and dynamic channel composition

This section introduces the scenario of cooperation with dynamic assignment of sub-carriers. Dynamic sub-carrier allocation is to be understood as carrier allocation based on knowledge about the channel quality between the basestation and a given terminal as well as channel quality between cooperating terminals. Two possible carrier assignments are shown in figure 4. The partitioning of sub-carriers can in principle be as indicated in Figure 6 i.e carrier assignment need not be contiguous in the sense that Cellular and short range allocations should be adjacent to each other and the part of the channel spectrum can be freely distributed among cellular and short range carriers. Again the principle motivation is gain in energy efficiency, this involve, for each cooperating terminal, choosing carriers with the best link quality, enabling the minimization of transmit power and use of higher order modulation format and less coding overhead

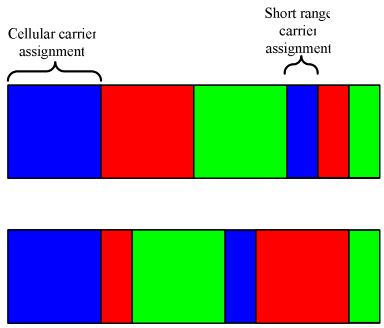


Figure 6 Example of non-contiguous carrier assignment

on the short range links. From an architecture point of view, the flexibility requirements for this scenario would make again an SCR implementation too complex and costly, giving reason to consider an SDR implementation as an alternative.

4. SDR AND MICRO COOPERATION

In the previous sections we have argued that as the requirements for flexibility increased, the advantages of an SCR implementation would decrease to the point where it is likely that an SDR implementation will be more feasible. When we are considering the feasibility of an SCR implementation versus an SDR implementation, we are considering the following parameters: Cost, Efficiency, Complexity and Flexibility

4.1 SCR Implementation Versus SDR Implementation

The SCR has traditionally been known for its advantages in the first three parameters due to the fact that SCR implementation are usually made up by dedicated hardware optimized for a given communication standard and application. The visions surrounding the SDR has been to implement flexibility, this has been at the expense of cost, due to the requirement for broadband or frequency agile RF frontend and reconfigurable baseband processing, Efficiency as the ideal SDR strives to move the A/D and D/A operations as close a possible to the antenna and finally complexity as digital signal processing are used to been employed to support traditionally RF or analog implemented functionality. With the introduction of the concept of cooperative wireless networks, it therefore seems feasible to to argue a tradeoff between the above parameters making SDR more advantageous than the SCR. The following section gives a short introduction to the parameters and the reasoning behind them.

4.2 Design space and design metrics

The parameters defined in table I make up the design space within a feasible architecture have to be chosen. Flexibility is the main requirement, but an implementation has to be chosen that is still efficient, low cost and feasible in complexity. In the following section we propose an architecture for an SDR receiver supporting the characteristics of cooperative wireless network scenario with flexibility requirements as described in the above sections.

Table 1 Parameters used for comparing SCR and SDR architectures

Cost	Cost is can be related to cost in development, implementation and production and also the cost related use of energy resources.
Efficiency	Energy; Does it make efficient use of energy resources, processing; Does it make efficient use of processing resources, can resources be reused, or does it require replicaton
Complexity	• Design complexity, i.e the Hardware implementation complexity. • Computational complexity requirements
Flexibility	In this paper we define flexibility by the ability to adapt and reconfigure functionality.

4.3 Software Defined Radio Architecture

In the previous sections it has been argued that a SDR implementation in a dynamic cooperative wireless network scenario is likely to be a more feasible way to implement a terminal capable of supporting the requirements for flexibility. An SDR architecture would need to support the following requirements:

- Dynamic changing number of cooperating terminals
  - The ability to reconfigure itself for supporting dynamic number of short range receive chains.
- Supporting scalable size FFT processing
- Supporting processing subbands of OFDM spectrum, an important prerequisite for lowering the computational complexity.
- Supporting adaptive modulation coding over short range links, this requirement is closely linked to the number of cooperating terminals.

4.4 Conceptual Software defined radio receiver architecture

Figure 7 gives a conceptual schematic for a proposed receiver architecture that can accommodate the principle requirements in the downlink cooperative scenario as outlined above. The following gives a short description of the functionality shown in the schematic.

1. *Subchannel filter*: The front filters select the band of sub-carriers allocated for cellular reception and short-range reception respectively. They are flexible in center frequency and bandwidth according to requirements from upper layers. From an implementation point of view low complexity implementation is essential as the complexity related to the filtering of subbands reduces the gain in complexity achieved by reducing the processed FFT size at each terminal.
2. *FFT Cellular/short range*: Flexible size FFT's processing of sub-carriers.
3. *Demodulation and decoding*: Support for adaptive modulation and coding, AMC, employed in the cooperative scenario. The use of higher order modulation formats are an essential assumption in the achieved benefits indicated in system studies.
4. *Flexibility by adaptation and reconfiguration*: Figure 7 indicates that flexibility is introduced through parameters controlling the receive chains. Furthermore reconfiguration is introduced through the dynamic instantiation of of short range receive chains according the number of terminals participating in a cooperation.
5. *Vertical configuration*: This entails the dynamic creation and closing of receiver chains according to scenario requirements. This means that the system should be able to instantiate receive chains at baseband level according to the number of cooperating entities.
6. *Horizontal configuration*: Horizontal configuration entails the configuration of the functional blocks in both the receive and transmit chains as in Figure 7 and For the receive chain the horizontal configuration include the filter bandwidth and centerfrequency for extracting a group of subcarriers. Similarly the FFT size is subject to dynamic configuration. As an important prerequisite for the performance feasibility, horizontal configuration naturally includes the support adaptive modulation and coding. It should be noted that the parameters for horizontal configuration is dependent on the vertical configuration.

5. CONCLUDING REMARKS

We introduced the novel concept of a cooperative wireless network, with the primary motivation being the potential for achieving a gain in energy efficiency while preserving performance requirements. The concept was exemplified with a downlink scenario utilizing the principle of OFDMA.

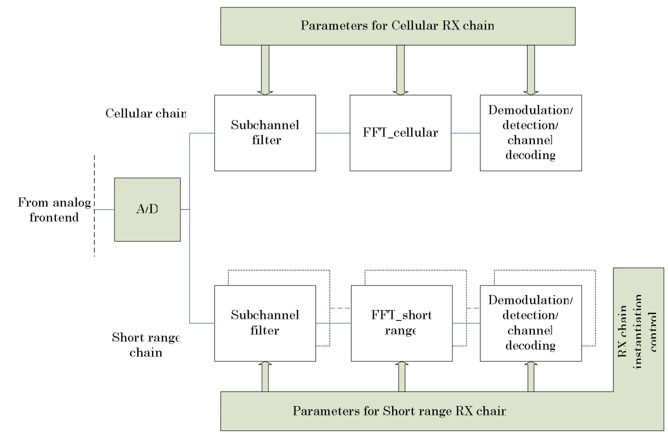


Figure 7 SDR receiver concept

With OFDMA we introduced the concept of a composable channel. Three different scenarios were introduced and with the introduction of cooperation and dynamic subcarrier assignment we argued the need for a Software defined radio implementation over the the traditional Software controlled radio. This was motivated by the increased complexity considering as the number of cooperating terminals increases. We proposed a concept for an SDR enabled receiver with capability of supporting the degree of flexibility needed in a cooperating wireless network. Future work will include proving this architecture in terms of complexity and methodologies for implementing the flexible reconfiguration of short range receive chains.

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