Conceptual Considerations for Reducing the Computational Complexity in Software Defined Radio using Cooperative Wireless Networks

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Abstract — **This paper motivates the application of Software defined radio as the enabling technology in the implementation of future wireless terminals for 4G. It outlines the advantages and disadvantages of SDR in terms of Flexibility and reconfigurability versus computational complexity. To mitigate the expected increase in complexity leading to a decrease in energy efficiency, cooperative wireless networks are introduced. Cooperative wireless networks enables the concept of resource sharing. Resource sharing is interpreted as collaborative signal processing. This interpretation leads to the concept of a distributed signal processor. OFDM and the principle of FFT is described as an example of collaborative signal processing.**

***Keywords*:** Software Defined Radio, Cooperative Wireless Networks, Collaborative Signal Processing, Computational Complexity

1. INTRODUCTION

The mobile phone has developed from being a single standard communication device to a multi standard device supporting a variety of communication technologies. The evolution of technologies for mobile communication predicts an increasing number of technologies each aimed at providing the user with new and more advanced services. This scenario is part of the vision for the fourth generation of communication technologies, 4G, which embraces the creation of new technologies providing even higher data rates. 4G is also envisioned as a platform for access convergence putting the user in the central position [1], and enabling the merging of, cellular and ad-hoc network communication services into a single platform. The view on 4G as a platform for convergence between different and today divergent technologies lead to a view on how future wireless devices may be implemented. Implementing the wireless devices with separate hardware for each supported standard, as is done today, is not feasible considering the increased number of standards and the cost and form factor of such a terminal. Therefore this leads to the concept of Software defined radio as an enabling technology in the implementation of future wireless devices, [2].

1.1. Software defined Radio

Software defined radio (SDR), enables flexibility and reconfigurability in future wireless transceivers. Flexibility and reconfigurability is considered to be important features in the implementation of wireless transceivers required to fulfill the anticipated scenarios and requirements in 4G. The ability to reconfigure a wireless device, enables the device to match its behavior to suit various scenarios e.g cellular and short range ad-hoc scenarios and to reconfigure e.g. modulation and coding schemes according to these scenarios. But the advantages of SDR comes with inherent disadvantages in the form of increased signal processing complexity and hardware requirements in both the analog and digital domain. Furthermore the increased requirements put on flexible hardware architectures implies a potential loss of energy efficiency compared to today's dedicated hardware architectures. In choosing architectures for SDR, it is therefore nessecary to consider architectures that not only consider reconfigurability and flexibility but does so in an energy aware manner, providing the best trade-off between reconfigurability, flexibility and energy efficiency, [3].

1.2. Cooperative wireless networks

In this paper a cooperative wireless network is defined as two or more terminals interacting in a network using short range coomunication schemes, sharing resources in an ad-hoc based manner terms of energy and processing. It is assumed that cooperating terminals will have a bilateral benefit from taking part in such a cooperation and that incentives for operating in such a network do exist. The principle of sharing resources, seen from different levels of interest, is illustrated in Figure 1. From a network level of perspective, cooperation aims at improving the overall network performance. From a user point of view, allowing their terminals to integrate into a cooperating network, where the benefit is improved services with a quality and a cost that may be difficult to

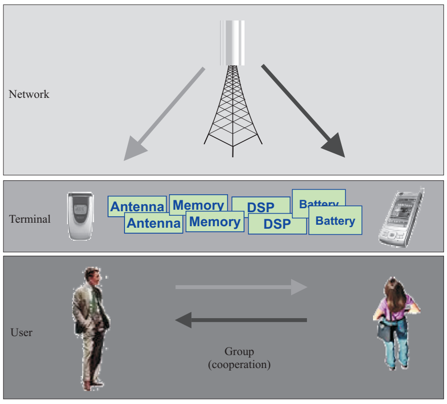

Figure 1: Concept of cooperative networks and resource sharing

achieve in a non-cooperating network. The third perspective and the focus of this paper, is resource sharing as illustrated in Figure 1. The cellular infrastructure sends different sources of information, as part of a service, to different terminals. The terminals are configured to share their processing resources, examplified as the antenna (RF), memory, DSP and battery. The potential for sharing processing resources leads to the idea of distributing processing demands for a given scenario and service. The anticipated increase of cost in terms of signal processing complexity and the potential loss in energy efficiency related to introduction of SDR technology, makes it realistic to consider the potential for reducing processing demands per terminal by utilising cooperation and distributed processing. This leads to the idea of combining the advantages of SDR with the concept of a cooperating wireless network. Cooperative networks offer the possibility of energy efficient delivery of services as well as the potential for reducing the computational complexity per terminal, which is the motivation for this work. The rest of the paper with a section 2 which further motivates the application od SDR and cooperative wireless networks, section 3 shed some light on design and computational complexit and section 4 gives a view on collaborative signal processing as a methodology for realising a cooperative wireless network. The paper ends with concluding remarks in section 5.

2. SOFTWARE DEFINED RADIO AND COOPERATIVE NETWORKS

This section further motivates the combination of Software defined Radio and the use of cooperative networks, the discussion includes a comparison against the use of state of the art technologies, which will be defined as the Software Controlled Radio, SCR. The claim being that, the cooperative wireless networks approach can be more efficiently implemented using a flexible approach as opposed to fixed implementation in an SCR.

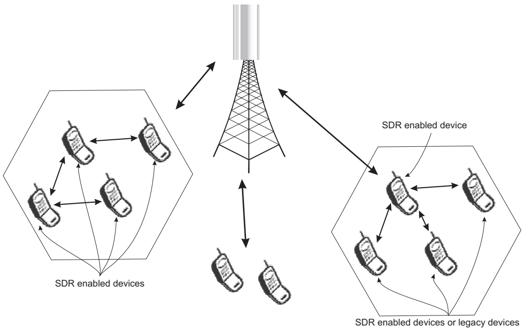

Figure 2: Cooperative scenarios illustrating the gateway and the Information and resource sharing

2.1. Scenario examples

The need for flexibility and adaptability is illustrated by a scenario where a cellular network infrastructure is mixed with multiple short range networks. A wireless device in such a scenario may be required at different time instances to participate in these different scenarious depending on the given application/service. Figure 2 illustrates such a scenario with a combination of cellular and short range networks. Looking further at the scenarios depicted;

2.1.1. Gateway

Figure 2 illustrates a gateway scenario. The SDR device acts a gateway to either other SDR devices or legacy devices at short range. This scenario exploits the capabilities of an SDR device to establish links to devices with different technologies. This enables the delivery of services to devices that do not support the technology in the cellular structure or devices that do not have the required computational capabilities. It is assumed that the device that acts as the gateway is chosen according to hardware resources, e.g. computational capabilities, memory- or battery capacity etc. From a complexity point of view, the gateway will have to deal with a high degree of complexity in order to support the cooperation, but the cooperating terminals can support services with a lower complexity and cost by benefitting from the resources in the gateway. The gateway scenario is an example of a scenario where the complexity requirements for a group of cooperating terminals for a given service can be alleviated by taking advantage of resources offered by one device, in this case the gateway. It is obvious that in the case of the gateway, proper incentives for participating in such a cooperation should be established due to the fact that the gateway is sharing all or most of its resouces with the cooperating devices.

2.1.2. Information and resouce sharing

Where the gateway scenario was an example of one device sharing its resources with a number of cooperating terminals, requiring a large amount computational capacity from the gateway, another scenario is information and ressource sharing among a number of cooperating terminals. This scenario would benefit from the same characteristics as the gateway scenario, but now all the cooperating devices can take the role of sharing resources with other devices leading to the potential for lowering the computational complexity for each of the cooperating devices. The requirement from each of the cooperating terminals is that they all posses the possibility of computational flexibility which motivates the use of SDR enabled devices. It is likely as compared to the gateway scenario, that this scenario may introduce extra overhead in signalling as the shared information need to be coordinated and communicatied between the cooperating devices.

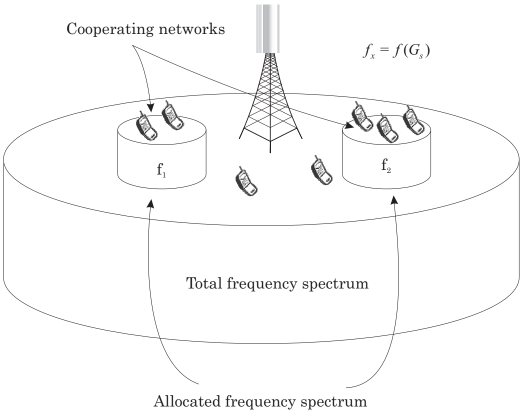

Figure 3: Frequency allocation

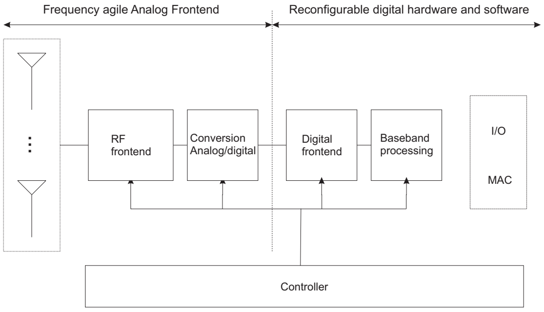

Figure 4: General receiver chain SDR block schematic

2.2. Flexible frequency allocation

Another issue motivating the use of a technology that supports flexibility and adaptability is illustrated in figure 3. This figure shows the spectrum allocation for two ad-hoc short range networks from a larger pool of frequency spectra. The larger frequency spectrum may cover licensed as well as unlicensed frequency bands. As indicated in the figure, the range of frequencies can vary with the number of participating entities in each network. The allocation of a varying frequency spectrum motivates the claim that the application of SDR provides a more efficient implementation of cooperative wireless network compared to an implementation using SCR. By efficient implementation we mean that SDR differentiates from SCR in hardware architectures that are not dedicated to support a specific standard and therefore fixed to support only predetermined frequency bands. This characteristic enables the possibility of choosing an approproiate technology and frequency band for a given scenario and choosing parameters which adapts to the actual application requirements.

3. COMPLEXITY

As the future of wireless commmunication is highly expected to provide the user with new types of services that require more bandwidth and higher datarates, the anticipated complexity of a wireless terminal in a future wireless scenario most likely will increase. Although the features of SDR makes the technology attractive for future wireless scenarios, the same features comes with an inherent increase in complexity. The following discussions shed some light on design and computational complexity related to Software Defined Radios.

3.1. Design complexity

The foreseen increase in design complexity in SDR is dominated by the fact 1) that design requirements are not necessarily known at design time and 2) that a given hardware architecture should be able to support an evolving air interface and network architecture without hardware modifications. This is in contrast to the implementation of state of the art wireless standards, where hardware is implemented using dedicated solutions in which the functionality is frozen at design time. The support of multiple standards are provided either as all-in-one hardware solutions or parallel architectures each supporting a given standard. An SDR architecture as compared to a traditional architecture, is supporting multiple standards by a single hardware architecture. Figure 4 illustrates a typical block schematic for a reconfigurable receiver chain. The point of the A/D conversion is a key point in the design complexity of an SDR transceiver. Moving the conversion closer to the antenna and putting more functionality into the digital domain thus approaching the ideal SDR. But as the conversion is moved closer to the antenna, the bandwidth and thus the rate at which A/D conversion is done increases, putting stronger requirements on the A/D converter and increases the energy consumption typically beyond feasible limits for implementation in mobile devices. Reducing the rate at which A/D conversion is done, has been the solution, using direct conversion frontends or IF/passband sampling as the alternatives. This means that instead of performing a A/D conversion of the entire frequency band of interest, conversion is done on a frequency band limited by the channel bandwidth of interest. But the channel bandwidth increases as the demand for higher datarate increases, from the relatively narrow bandwidth of 200KHz for a GSM system to above 20MHz for WLAN and future 4G systems. This again emphasises the A/D conversion as the key component togehter with RF frontends that can accomodate the widespread frequency bands used in different wireless communication standards.

Traditionally digital signal processing has been carried out by, ASIC's, Digital signal processors, DSP's and microcontrollers, each working at different processing rates in the receiver chain. The Digital front in Figure 4 are usually implemented as an ASIC due to high processing rates, similarly the baseband processing is done in a DSP, at a lower processing rate. Although the ASIC are typically capable of handling high processing rates and in an efficient manner, the ASIC has its functionality fixed at design time, this is in contrast to the DSP which by nature is programmable, but does not provide the same processing rates and energy efficiency as the ASIC. Signal processing in the digital domain for an SDR implementation should not only support the nessecary processing rates, but fulfill the requirement for reconfigurability and still be energy efficient.

3.2. Computational complexity

Computational complexity, is related to the processing requirements for the digital signal processing part of an SDR transceiver architecture. The common understanding of flexible SDR architecture is to shift the signal processing from the analog domain to the digital domain. This is requested by the need for flexibility and reconfigurability. Although methods like subband sampling enables the possibility of sampling at radio frequencies at much lower rates than dictated by the sampling theorem, together with promising converter technologies like Sigm-delta converters which reduces the problem of noise aliasing, the state of the art approach is still to shift frequency range of interest down to lower frequencies, IF or Baseband and perform sampling at these frequencies. Adding digital signal processing to compensate analog circuitry is an example of how SDR architectures and design complexity add to the computational complexity of a terminal. Adding further to the computational complexity is the requirements from state of the art and future wireless communication standards in terms of Bandwidth, mitigation of channel conditions, spectral efficiency and the fact that applications of terminal will most likely be more diverse than today. The issue of computational complexity is therefore an important topic to consider together with methods to reduce it. Defining the MOPS as a metric for the Computational complexity. The computational complexity depends on the bandwidth of interest and the complexity, in operations per unit bandwidth, of functions in the digital part of the SDR transceiver [4]. (1) defines a simplified relation between computational coomplexity, the signal bandwidth and the complexity for a given operation in a transceiver chain.

$$C_i = F(w, g) \tag{1}$$

Where (w, g) are defined as elements in the sets (2) and i indicates an index for the $i'th$ complexity measure in a given part of the transceiverchain.

$$w \in W, g \in G \tag{2}$$

Elements in the sets W, G are signal bandwidths and different places in a transceiver chain and processing complexities related functions processed at these bandwidths.

$$W = \{W_{RF}, W_{IF}, W_{channel}, \dots, W_x\} \tag{3}$$

$$R = \{G_{RF}, G_{IF}, G_{channel}, G_{baseband}, \dots, G_x\} \tag{4}$$

The above definition fascilitates a simplified view on complexity in a wireless device as a sum of complexities for different functionalities in the transceiver chain.

$$C = \sum_i C_i \tag{5}$$

4. COLLABORATIVE SIGNAL PROCESSING

The concept of collaborative signal processing has been introduced in the application of wireless sensor networks which are by nature characterized by short transmission range, low processing capabilities and limited energy resource, [5]. It is therefore interesting to investigate whether this principle can be applied as a methodology to reduce computational complexity in a scenario of SDR terminals and cooperative wireless networks. The sharing of resources in a cooperative wireless network is interpreted as having each of the cooperating terminals acting as part of a distributed signal processor. The sharing of resources now becomes, through appropriate collaborative schemes, a matter of distributing computational requirements among the cooperating terminals using a "'divide-and-conquer"' principle.

Provided with the definition of computational complexity given in (5), the concept of collaborative signal processing, CSP, in this work is to reduce the complexity by distributing the processing between terminals participating in a cooperative network.

Considering the distribution of processing between the terminals, this means the communication of processing tasks and the return communication back to the orginal sender. It is apparent that the cost of this communication should be considered togehter with the cost of processing at each terminal. The objective of employing cooperation should be too reduce the computational complexity per terminal and thereby reducing energy consumption. But the energy consumption related to processing demands at each terminal should be weigted against the energy consumption related to the communication between cooperating terminals. The cost of this communication is dominated by the transmit power. The most immediate parameters that affect the transmit power are distance, modulation and channel coding scheme in the sense that the two last mentioned affects the transmit power needed to acquire a needed signal to noise ratio, for a given distance and propagation conditions . Each cooperating terminal will in principle be engaged in cellular and short-range transmissions, service and cooperating transmissions respectively. The total cost of communication from terminal i to terminal j can formulated as (6).

$$p_{i,j} = f(d_{i,j}, m_{i,j}, c_{i,j}) \tag{6}$$

Where $d_{i,j}$, $m_{i,j}$ and $c_{i,j}$ are the distance between terminals, the modulation scheme and the channel coding scheme respectively. For a cooperating terminal wich communicating with a number of terminals, the total cost of communication can be formulated as the summation of $p_{i,j}$ over the number of terminals cooperating with a given terminal.

$$P_i = \alpha \sum_j p_{i,j} \tag{7}$$

Where α represents a weigthing factor to symbolise that the total cost of communication will also depend on the chosen access scheme employed for cooperation.

Figure 5 illustrates a simple model of a cooperating network with three nodes representing coopRating terminals $\mathrm{T}_1, \dots, \mathrm{T}_2$. The nodes communicates either with each other or with the nodes outside of the cooperating network, e.g a cellular network, the communication is depicted by t_{12},t_{21} and dl and ul for intra cell communication and intercell communication respectively. Each node in the model represents processing resources as well as other characteristica like energy resources. From a software radio point of view, the nodes represents configurable RF and baseband pocessing. From an application point of view, the nodes cooperate by sharing of exchanging information as depicted in 1. From a processing point of view, nodes cooperate by sharing processing or resources. It is important to realise the inherent tradeof distributing the processing between nodes, the communication that is used for distributing and equally important the processing for receiving the processing results from other nodes in the node that initialised the cooperation.

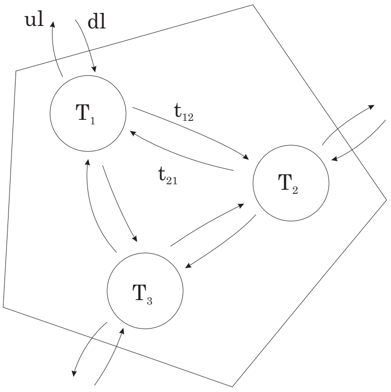

Figure 5: Model of a cooperating wireless network

4.1. Cooperation and OFDM

This part consider the employment of OFDM based transceivers in cooperative networks. OFDM is interesting to consider because it is one of the technologies considered for future 4G networks. The high spectral efficiency and resilience towards multipath fading makes it a suitable technology for wireless networks with high datarates. The IFFT and the FFT are key functionalities in the implementation of OFDM. In the transmitter of an OFDM implementation, IFFT maps a group of information symbols onto a set of orthogonal subcarriers and generates a time domain signal. In the receiver the opposite function is performed by an FFT. The FFT, [6], are an efficient implementation of the DFT, obtained by employing a divide-and-conquer approach to solving the DFT algorithm which makes it interesting to consider togehter with a cooperative network. The IFFT and the IDFT are both calculated using the respective FFT and DFT algorithms. Considering the computational complexity of the DFT,

$$X(\omega_k) = \sum_{n=0}^{N-1} x(n) e^{-j\omega_k n} \tag{8}$$

The computational complexity for the DFT is $O(N^2)$, this complexity is calculated by considering the number of operations per frequency multiplied by the total amout of frequencies to be calculated. Having a real valued time sequence of N samples, and calculating an the N DFT, requires $2N$ multiplications and $2(N-1)$ additions. Summing the required operations gives

$$C_{DFT} = 2N + 2(N-1) \tag{9}$$

operations per frequency. Having N frequencies the total number of operations is

$$N(4N-1) \tag{10}$$

To verify that this evaluates to $O(N^2)$ we consider the case where N is increased, then (10) approaches $4N^2$ and disregarding the multiplicative factor the computational complexity is proportional to $O(N^2)$.

The principle of an FFT algorithm relies on the input sequence to have a length equal to the power of 2 and the possibility of dividing the calculation of an N point DFT into the calculation of $N/2$ length DFT's. Given a sequence og length N, the N point DFT can be written as

$$X(\omega_k) = \sum_{n=0}^{L-1} W_N^{kn} x(n), k = 0, 1, \ldots, N-1 \tag{11}$$

Collecting even and odd terms gives

$$X(\omega_k) = \sum_{n=0}^{\frac{N}{2}-1} W_N^{k(2n)} x(2n) + \sum_{n=0}^{\frac{N}{2}-1} W_N^{k(2n+1)} x(2n+1) \tag{12}$$

Considering the computational complexity in (12), the number of operations is equal to $2(N/2)^2 + N/2$, where the term $N/2$ comes from the merging of the two $N/2$ calculations. The complexity is now proportional to $N^2/2$ which is a reduction 50 percent compared to complexity of direct calculation. It is interesting to observe that the principle of the FFT, that is dividing calculation of an DFT into the calculations of sub-DFT's can be applied to a cooperative scenario, as illustrated in figure 6 Where each node now calculates the $N/2$ using an FFT algorithm. The illustrated scenario emphasises some of the requirements put on nodes in a cooperative network and some of the tradeoffs that need to be considered. The cooperating nodes calculates an variable size DFT, this requires the nodes to be implemented with technology that is able to adapt its processing acccording to DFT sizes. Furthermore, the sequences to be used for calculation need to be communicated to the respective nodes and results need to be comunicated back to the originating node.

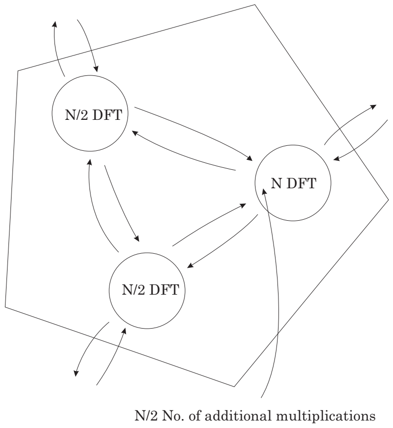

Figure 6: Cooperation scenario with sharing of DFT processing

5. CONCLUDING REMARKS

This paper motivated the application of SDR as an enabling technology for a scenario of cooperative wireless networks. The paper argued that although the concept of Cooperation can be implemented using state of the art technology, SDR provides a flexible and in that sense more efficient solution. This was examplified through two scenarios and flexible spectrum allocation. Though SDR suggests a more efficient implementation of cooperation, the drawback is the loss of energy efficiency due to an expected increase in computational complexity. Resource sharing were suggested as an idea for reducing the computational complexity in an SDR transceiver. The concept collaborative signal processing was suggested as a methodology to realise resource sharing. The principle of FFT algorithm was described as an example resource sharing and collaborative signal processing. This example highligthed the need for technology capable of handling different FFT sizes and it highlighted the tradeoff between cost of communication and the gain of resource sharing.

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