A Context Aware Architecture for Energy Efficient Cognitive Radio

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Abstract. Energy efficiency is a critical issue for future wireless communication. The European FP7 C2POWER project is to research, develop and demonstrate energy saving technologies for multi-standard wireless mobile devices, exploiting the combination of Cognitive Radio and co-operative strategies. The basic objective is to establish an energy optimization framework founded upon energy aware Cognitive Radio nodes which can dynamically optimize energy consumption while satisfying desired Quality of Service (QoS) for specific radio environments and applications. The context awareness for energy efficient Cognitive Radio can be seen as decision-making processes to optimize energy saving strategy based on energy related context information. The decision of a single node may have impacts on the energy consumption of other nodes and the entire Cognitive Radio network. Such decision-making processes are interactive. Game theory provides a mathematical basis for the analysis of interactive decision making processes. This paper presents a context aware architecture for energy efficient Cognitive Radio network from a game theoretical perspective.

Keywords: energy efficiency, Cognitive Radio, context awareness, game theory.

1 Introduction

Currently, 3% of the world-wide energy is consumed by the ICT (Information & Communications Technology) infrastructure that causes about 2% of the world-wide CO2 emissions, which is comparable to the world-wide CO2 emissions by airplanes or one quarter of the world-wide CO2 emissions by cars. However, these figures will rise with the expansion of the information technology. Therefore, developing energy efficient green communication systems is crucial to our environment. Economically, we can also benefit a lot from green communication since energy costs account for as much as half of a mobile operator's operating expenses. From mobile device side, battery capacity is finite and the progress of battery technology is slow with little improvement in the near future. However, the emerging 4G devices are expected to support higher data rates and multi standard radio interfaces (UMTS, LTE, WiFi, DVB-H, Bluetooth, etc) to

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provide users with a continuous multimedia communication. A considerable increase of energy demand for 4G devices is expected. Without any new approaches for energy saving, 4G mobile users may end up in so called 4G “energy trap”, where users have to relentlessly search for power outlets rather than network access, and becoming once again bound to a single location. Therefore, there is a clear need for new disruptive strategies to address all aspects of power efficiency from the user devices through to the core infrastructure of the network and how these devices and equipment interact with each other.

The European ICT C2POWER project [1] is to research, develop and demonstrate energy saving technologies for multi-standard wireless mobile devices, exploiting the combination of cognitive radio and cooperative strategies. Cognitive Radio [2] proposed by Mitola is seen as a radio which has awareness on its environment and has the capacity to adapt the transmission parameters to the changing environment. Currently, most research in Cognitive Radio focuses on the spectrum awareness which could improve the spectrum usage. However, the awareness should not be limited to only one context such as spectrum. In the C2POWER project, the energy awareness aspect of Cognitive Radio is targeted. Applying the ideas of Cognitive Radio to achieve energy efficient green communications is a growing interest [3,4,5]. The main objective is to establish an energy optimization framework founded upon energy aware Cognitive Radio nodes which can dynamically optimize energy consumption while satisfying desired Quality of Service (QoS) for specific radio environments and applications. The context awareness module, the brain of Cognitive Radio, makes decisions to adapt its operation based on context information. The decision of a single node not only changes its own behavior, but may have impacts on the energy consumption of other nodes and the entire Cognitive Radio network. Therefore, such decision-making processes can be highly interactive. This paper studies such interactive decision making processes from a game theoretical perspective and proposes a game theory based context aware architecture for energy efficient Cognitive Radio.

The paper is organized as follows. Section 2 describes scenarios defined in the C2POWER project. A context awareness architecture is proposed in Section 3 for the C2POWER system. Section 4 concludes the paper and describes the future work.

2 C2POWER Scenarios

To exploit cooperation and cognition for energy saving, typical scenarios have been defined in the C2POWER project [6]. Two different schemes have been proposed for energy saving: 1) radio nodes can form cooperative clusters using short range communication instead of connecting to a remote base station individually; 2) multistandard radio devices can select the most energy efficient radio access technology (RAT).

2.1 Energy Saving Using Cooperative Communication

Mobile devices located in the proximity could form a cooperative cluster by pooling their resources such as antennas together. Mobile devices within the same cluster can communicate directly with each other using short range technology. A cluster acts as one entity for long-haul transmission outside of the cluster. Such a cluster has a potential for energy efficient transmission by utilizing multiple antennas of its cluster members. This technique is known as cooperative MIMO [7] or virtual MIMO [8]. In [7], Cui et al. have compared the total energy and delay between cooperative MIMO and SISO communications. The results suggested that the cooperative MIMO scheme can lead to considerable energy saving, in particular for a long-distance transmission. A similar work in [8] has extended the results in [7] by taking into account the training overhead required in MIMO systems. The result in [8] showed even with an extra energy overhead required for MIMO training, the virtual MIMO still can offer substantial energy savings. However, the authors in [7] and [8] focused on the total energy saving of multiple nodes and did not consider the energy saving for each individual node. There could be cases where individual nodes will not have energy savings by joining the cooperative cluster. Clearly, a conflict between social benefits and self interests may discourage the cooperation. Hence, how to promote social beneficial cooperation while satisfying individual nodes' self interests is a open research topic.

2.2 Energy Saving Exploiting Heterogeneous RATs

The mobile devices with multiple RATs will be a common feature in future wireless communication. The devices are capable to switch from one RAT to another to maintain connectivity, data rate and QoS. The individual devices take decisions to select the best networks based on metrics such as QoS. This is known as vertical handover in heterogeneous network [9]. C2POWER will investigate strategies and algorithms that enable a device to select the most energy efficient RAT based on the energy metrics, while satisfying QoS requirements. However, we may discover potential conflicts in this network selection process. In a network environment, multiple nodes may discover the same network for energy saving. A competition among these nodes to access the same network resource may offset the expected energy saving gains. Apparently, nodes' decisions on network selection are highly interactive.

3 Context Aware Architecture

Context awareness is a key feature of Cognitive Radio. The context awareness for energy efficient Cognitive Radio can be seen as decision-making processes to output energy saving strategies based on related context information. By analyzing the scenarios in Section 2, we can reasonably expect the decisions of single Cognitive Radio nodes will impact the outcomes relevant to others. Game theory provides a mathematical basis for the analysis of interactive decision-making processes. It provides a set of modeling tools for predicting what might happen when agents with conflicting interests interact. Therefore, we propose a game theory based context aware architecture for energy efficient Cognitive Radio network in the C2POWER scenarios in Section 2.

3.1 Context Information

First, a common understanding about what context means in C2POWER needs to be established. Context, in general, can be seen as an aggregate of information or modes of parameters describing the operational environment including information such as time, geographical location etc. For Cognitive Radio, context may include information on mobile device, network and user applications. The context information can be put into two basic categories: information on the device itself (RATs, battery life, battery consumption rate, processing power etc) and information on the current state of the network (cell load, cell capacity, QoS availability etc).

For the C2POWER system, particular interest is on those context information related to energy use and consumption, such information affect many parts of the communication system. To give an example, a list of energy related context information fragments is presented below:

- Access system availability
- Transmit power
- Energy per bit
- SNR
- Interference power
- Battery life
- Current state of battery consumption
- Processor's energy profile
- Power emission requirements based on regulations

Above parameters mainly characterize the energy use and consumption within a single terminal, however, the energy consumption has also to be considered in the wider context. A context engine for energy efficiency will need to consider also the situation and availability of neighboring terminals and the entire network. For example, context information to be considered in such cases may includes:

- Availability of neighboring nodes
- Energy status (remaining power levels)
- Access technologies availability

In addition to these, a node should also have an understanding about the context of its neighboring nodes, meaning it may have aforementioned energy information of its neighboring nodes available.

The context awareness process starts from collecting context information from various sources with different ways. A context manager processes and refines the collected context information. Finally, the refined context information is presented to decision engine which outputs the energy saving strategies.

3.2 Interactive Decision Making Based on Game Theory

Before discussing the specific game models for the C2POWER, some basic terms and concepts on game theory are introduced. A basic game consists of three elements:

- **Player.** A game is played by a finite set of players $\mathcal{N} = \{1, 2, ..., i, ..., N\}$.
- **Strategy.** Each player $i \in \mathcal{N}$ can choose a strategy s_i from his strategy set S_i.
- **Utility.** The objective of player i is to maximize his utility u_i.

The players are assumed to be rational in the sense that they choose their strategies to maximize their own utilities. A strategy profile $s = (s_1, s_2, ..., s_i, ..., s_N)$ is a vector containing the strategies of all players. s_{-i} is used to denote the collective strategies of all players except player i.

Based on the C2POWER scenarios, three case studies on interactive decision making are presented using different game models.

1. *Cooperative energy saving in repeated game*
   We assume a simple cooperative scenario where two nodes T_1 and T_2 can form a cooperative cluster to communicate with a remote destination node R. Each player i has the same strategy set $S_i = \{\text{C}, \text{N}\}$, where C and N denote cooperate and noncooperate respectively. The utility matrix for the game is given in Table 1, where the utility pair (u_1, u_2) indicates the utility for user T_1 and T_2 respectively. The utility u_i in this example is assumed to be the energy saving with respect to the direct communication to the destination for the user i. If both nodes act on their owns to communicate directly to the destination, no energy savings are achieved for both nodes. Thus, the both utilities are zeros. If the two nodes decide to cooperate, the utility for the user i is expressed as $u_i = g_i - c_i$. We denote the energy gain of user i from the cooperation scheme as g_i and the cost of cooperation as c_i. The actual values of g_i and c_i depends on the specific physical layer cooperative scheme that is applied. In case where T_1 cheats in the cooperation while T_2 always helps him, the free rider T_1 get a gain of g_1 without any cost and T_2 will gain nothing but bear the cost of c_2. Thus, the strategy set $(s_1 = \text{N}, s_2 = \text{C})$ results in the utility pair $(u_1 = g_1, u_2 = g_i - c_i)$ It is vice versa for the case where T_2 is the free rider.

   In a one stage game, a rational player should always choose "noncooperate" (N) and take advantage of the other. If both players T_1 and T_2 play their best responses N, the game will end up in a Nash Equilibrium (NE) which leads to no cooperation and no energy savings. The Nash Equilibrium is an important concept in game theory which has the following definition.

Table 1. Utility matrix of two nodes cooperation

	Noncooperate	Cooperate
Noncooperate	$(0, 0)$	$(g_1, -c_2)$
Cooperate	$(-c_1, g_2)$	$(g_1 - c_1, g_2 - c_2)$

Definition 1. An NE is a set of strategies $s \in S$ if $u_i(s) \geq u_i(\hat{s_i}, s_{-i})$ $\forall$ $\hat{s_i} \in S_i$, $\forall$ $i \in N$.

The interpretation is that a NE is a set of strategies such that no individual player can improve its own utility by unilaterally changing its strategy. In a NE, every player plays its best response strategy.

Such a analysis seems disappointed for the cooperative energy saving. However, if we consider the energy saving as a repeated game the cooperation among selfish nodes may become possible. In a repeated game, players do not know the game will end thus players have to consider long-term interests. In energy saving case, repeated game is a valid assumption since energy saving is in fact a long-term interest. For instance, if forwarding one packet is considered as one stage game we can reasonable expect that nodes will be interested in saving energy for forwarding the next packet and so on. Therefore, each player is not only interested in the utility in the current stage but also utilities in future stages. A player wants to maximize the total discounted utility U_i expressed as

$$U_i = \sum_{n=0}^{\infty} \delta^n u_i(s(n)) \tag{1}$$

where $0 < \delta < 1$ is the discount factor and $u_i(s(n))$ is the ith player's payoff given the strategy profile in the nth stage game. The discount factor δ controls the expected gain from future interactions. If δ is bigger, the player is more patient in the sense that more gains are expected in the future. In such a repeated game, a NE which leads to cooperation is possible if a punishment is imposed on the player who cheats in the cooperation. In [10], a trigger strategy is defined in a two-player packet forwarding game such that the cheater will not be helped by others in all future stage games. This trigger strategy can lead to a Pareto-optimal NE where two players will naturally cooperate without extrinsic incentives. A set of strategies s is Pareto-optimal if there exists no other set of strategies for which one or more players can improve their utilities without reducing the others' utilities. The discussions in [10] suggest that either extrinsic or intrinsic incentive mechanisms are necessary to promote the cooperation. For implementing the cooperative energy saving in the C2POWER system, such incentive mechanisms to promote cooperation are an interesting topic to explore.

2. *Cooperative energy saving in coalitional game*
The cooperative energy saving could also be analyzed in the coalitional game model. The basic concept of coalitional game is that a set of players $\mathcal{N} = \{1, 2, ..., i, ..., N\}$ seek to strengthen their positions by forming cooperative groups. Such a cooperative group is a coalition denoted by S. The coalition value denoted by v quantifies the worth of a coalition in a game. The basis of forming coalitions is that the players can gain more benefit than acting alone. Questions such like how to form an appropriate coalition structure and how to fairly distribute the coalitional gain among its members will arise.
Paper [11] gives a comprehensive survey on the application of coalitional game theory for communication networks. The coalitional games are grouped

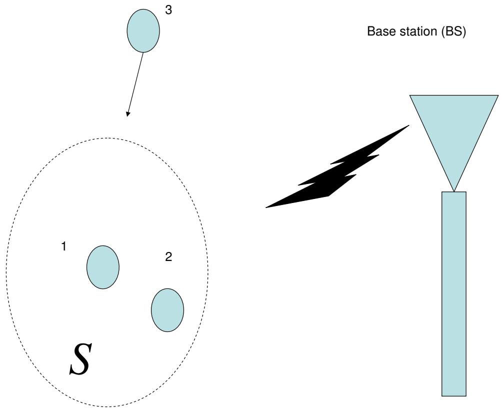

Fig. 1. An example of coalition game in C2POWER

into three distinct classes: canonical games, coalition formation games and coalitional graph games. In the C2POWER scenarios, the formation of energy saving clusters is our particular interest and could be analyzed as a coalition formation game. Let us study the following example in the coalition formation game model, shown in Figure 1. Suppose node 1 and node 2 benefit from an energy saving strategy by forming a coalition S which communicates with a remote base station. Node 3 is moving towards the proximity of node 1 and node 2. It may gain energy saving by joining the coalition S. Meanwhile, the entry of node 3 to S should not weaken the benefits of others in the coalition. Then the new coalition of three nodes is formed. If node 3 is moving away from node 1 and node 2, the cost of forming a three-node coalition may rise due to the long distance communication between node 3 and the others. In this case, forming a grand coalition is no one's interest. The coalition formation rule for a general case can be defined as follows:

$$\{S_1, ..., S_k\} \longrightarrow \cup_{j=1}^{k} S_j$$
$$if\ v(\cup_{j=1}^{k} S_j) > \sum_{j=1}^{k} v(S_j) \tag{2}$$

where $\{S_1, ..., S_k\}$ denotes k mutually disjoint coalitions and $\cup_{j=1}^{k} S_j$ is a grand coalition of k mutually disjoint coalitions. The rule indicates that a group of coalitions or users will merge into a grand coalition if the grand coalition has a larger total utility than the utility sum of all small coalitions. Similarly, a grand coalition will dissolve if the opposite condition satisfies. The rule is formulated as

$$\cup_{j=1}^{k} S_j \longrightarrow \{S_1, ..., S_k\}$$
$$if \sum_{j=1}^{k} v(S_j) > v(\cup_{j=1}^{k} S_j) \quad (3)$$

If we define the collective gain G as $G = v(\cup_{j=1}^{k} S_j) - \sum_{j=1}^{k} v(S_j)$, the only incentive for users to form a cooperative cluster is $G > 0$. The next issue to be resolved is how to fairly distribute the collective gain among users. The distribution should consider the user's self interests and promote good cooperations in the future. This example shows promise to apply coalition formation game model to study optimal coalition structures that maximize the utilities while considering cooperation costs for the C2POWER system.

3. *Network selection in evolutionary game*
   One scenario defined in the C2POWER project is that a device with multi-standard RATs is able to select the most energy efficient radio access network. However, there might be a potential conflict in this scenario.
   Suppose that a group of C2POWER nodes in a proximity are all in a cellular network. Then they discover that it is more energy efficient to connect a local WLAN access point (AP). If without the concern of other nodes' decision, all the nodes will connect to this WLAN AP. As a result, these nodes will compete for resources in the same network. Contention and Congestion may lead to communication failure or packet retransmissions. The actual loss may outweigh the expected energy saving gain. In this case, staying in the cellular network might be a better choice. We can see from the example that the decision for network selection is interactive in the sense that one's selection will have impact on the outcomes of the others. Therefore, game theory is a suitable tool to analyze the network selection decision process. In [12], the network selection process is formulated as a dynamic evolutionary game. The users in different service areas compete for bandwidth from different networks. The network selection for a user is based on its utility which is described as a function of allocated bandwidth and price per connection. The evolutionary equilibrium has been considered as the stable solution for which all users receive identical net utility from accessing different networks. If we consider energy saving as the utility, the similar game theoretical approach could be applied to solve the potential conflicts of network selection among C2POWER nodes.

Game theory provide rich models for analyzing interactive decision making processes. Application of game theory in the context of the C2POWER project is not limited by the given examples. There could be more game models suitable for analyzing different settings in the C2POWER.

3.3 Functional Architecture

Based on the game theoretical approach, a functional architecture of context awareness for interactive C2POWER nodes is described in Figure 2. Assume that C2POWER nodes are interconnected through a network. A node (e.g. node A) can collect the context information from the network and the terminal itself. The context information from the network conveys the information of other nodes' impacts on the entire network. For example in the coalition formation game, the formation of a cooperative cluster depends on the collective gain which has to be derived from a collection of information from all potentially cooperative nodes. An extra entity in the network may be needed to aggregate the context information from individual nodes. The context information will be further processed and filtered. The most relevant context information will be used for decision making. Based on the context information outputted by the context manager, the decision engine will calculate the utility and select a strategy which maximizes the utility. This strategy will be implemented and the results will have impacts on both the node itself and the entire network. The impacts on the entire network will be observed by other nodes (e.g. node B) as context information from the network. Other nodes with the same context awareness entities may adapt their strategies according to the observation. The new strategies may again have consequences on others' outcome. This adaptation can be an iterative process. Ideally, an optimal equilibrium will be achieved in the end that all nodes can have balanced energy savings.

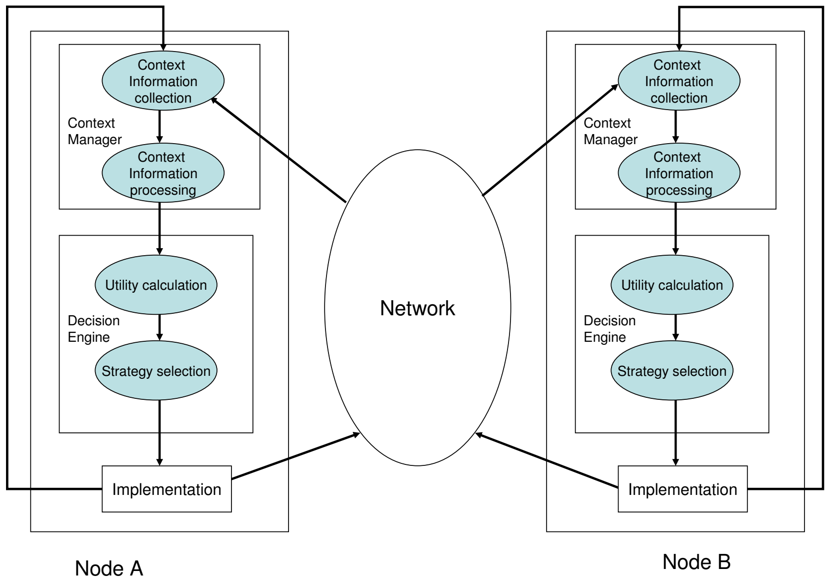

Fig. 2. Functional architecture of context awareness in C2POWER nodes

4 Conclusion and Future Work

This paper proposes a context awareness architecture for energy efficient Cognitive Radio network based on interactive decision making. As the core of the context awareness architecture, the interactive decision making process has been studied with a game theoretical approach. Different game models have been showcased to analyze the energy saving scenarios defined in the C2POWER project. The game theoretical approach provides tools to potentially solve the problem on how nodes with conflicting interests interact with each other. A optimal Nash equilibrium can lead to balanced energy savings among the C2POWER nodes.

As an initial context awareness architecture, it needs to be refined with more details in future work. First of all, the scope of context information needs to be define. Secondly, a mechanism for context information collection, aggregation and distribution has to be designed. Thirdly, an efficient context processing framework needs to be established. Finally, the architecture could be extended by adding extra entities such as learning and knowledge build-up.

As the heart of the context aware architecture for energy efficient Cognitive Radio, the interactive decision making process is the focus of our study. The interactive decision making process will be analyzed in appropriate game models. We aim to find optimal equilibrium solutions to solve conflicting interests among the C2POWER nodes such that balanced energy savings can be achieved.

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