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Energy-aware relay selection in cooperative wireless networks: An assignment game approach

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ABSTRACT

In the future connected societies, everyone and everything will be inter-connected, under the umbrella of the Internet of Things, where tens to hundreds of devices will be serving every single citizen. However, connecting this massive number of energy-constrained devices pose a serious challenge on the wireless networking paradigm; energy efficiency still represents a major challenge within the design of the future generation of wireless networking (5G). In this paper, we address reducing energy consumption of energy-constrained wireless devices, through energy-aware cooperative relaying in future heterogeneous networks (HetNets). Using game theory concepts, we formulate the problem as an *assignment game*. In the first stage of the game, the optimal relay selection is formulated as a linear programming problem, whose solution assigns suitable relays to their perspective sources. In the final stage, the *core* solution is derived, which guarantees fair distribution of the payoff among players, to keep them satisfied and discourage them from quitting the coalition. Our solution also proposes a credit based system to reward cooperative players; hence possibly excluding selfish users from cooperative coalitions. The proposed relay selection algorithm is evaluated using extensive NS2 simulations. The simulation results show significant energy savings using cooperative relaying, reaching up to 22%, with extensive increase in battery lifetime.

1. Introduction

Despite recent advancements in communications technologies, wireless industry is increasingly being challenged by the current surge in mobile data traffic and the increasing number of machines going online day by day. According to a recent survey conducted by Cisco [1], mobile data traffic grew 74% in 2015, expanding 4000-fold over the past 10 years and 400-million-fold over the past 15 years. It also estimates that by 2020, mobile traffic will rise to 30.6 Exabyte per month, an eightfold increase over its volume in 2015. On the other hand, by 2020, the number of online *things* (e.g., vehicles, wearable devices, appliances, etc.) is projected to reach or exceed 50 billion [2]; for instance, connected vehicles will account for 250 million objects.

Researchers all around the world along with different stakeholders (e.g., telecommunications equipment manufacturers, network operators, standardisation organizations as well as automobile manufacturers) are now speculating the specifications of the upcoming Fifth-Generation (5G) mobile networks [3,4]. A notable outcome of these efforts is the European research project METIS (Mobile and wireless communications Enablers for Twenty-twenty (2020) Information Society), according to the findings of which [5], 5G will support 10–100 times higher data rates, relative to the incumbent 4G technologies. Furthermore, despite these improvements in the data rate, the battery of a 5G User Equipment (UE) will last 10 times more than the one of a 4G device does; this implies a 1000-fold energy efficiency improvement in 5G air interfaces, relative to their predecessors, a mission also pursued by the global research initiative GreenTouch [6].

As mobile services proliferate (e.g., with the enrichment of multimedia, gaming, and social networking applications), mobile users are increasingly being faced with a real dilemma. Although many of them may wish to constantly consume these services, they might still feel reluctant because of worrying about using up their limited battery energy. We refer to this incident as *battery dilemma*. Indeed, it arises primarily because of the fact that the pace of progress in the battery technology is continuously lagging behind the Moore's law, creating a growing gap between the power consumption of mobile devices and the power available in their battery [7]. This entails revisiting the design of the wireless networks to implement viable energy saving strategies to curb the power consumption of mobile devices, and cooperation is a

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promising approach that can take a considerable step in this direction.

In this paper, we go beyond the state-of-the-art by reinterpreting the notion of cooperation as a strategic action where mobile users are the game players that could have conflicting interests. We consider them forming a coalition that in general can encompass multiple relays and multiple sources. They pool their resources (e.g., battery, antenna, etc.) and relay each other in order to minimise their combined energy spending. We cast the problem as an *assignment game* and address the optimal way of assigning the relays (to the sources). We derive the *core* solution of the game and discuss how to use it to resolve potential conflicts that can arise between the players. We define the characteristic function of the game along with a *utility function* to assess the energy saving gain of exploiting a relay node. For the purpose of exposition, in this paper, we focus on two-hop relaying, yet the approach is generic and can suit other cooperation scenarios as well. Finally, this study is an extension of our previous work in [8–10], presenting a comprehensive mathematical explanation of the proposed game, provided with new simulation results in NS2 to weight the signalling cost of negotiation between the nodes (to form a coalition) against the potential energy saving gain.

The rest of this paper is structured as follows. Section 2 reviews the related work. Section 3 introduces the coalitional game theory concepts behind the model. Section 4 describes the system model, and Section 5 formulates the relay selection problem as an *assignment game*, defining its characteristic function and obtaining its *core* solution. This section also introduces an energy credit function and elaborates on its application to isolate selfish players from cooperative ones. Section 6 presents the simulation setup and discusses the results. Finally, Section 7 concludes, summarising the main findings and drawing some guidelines for the future work.

2. Related work

2.1. Game theory

Game theory is a fascinating tool to analyse strategic interactions between a set of rational and independent decision makers (players) pursuing either a conflicting or a common objective. A game is particularly an incident where the *payoff* achieved by each player depends not only on her own actions but also on those taken by the other players involved in the game (i.e., her *opponents*). Bacci et al., in [11], provide a comprehensive tutorial on game theory and its applications for solving different networking and signal processing problems. Moreover, [12] illustrates the application of strategic-form games on wireless networks, focusing on the power control problem. Game-theoretic approaches, especially those based on coalitional games [13], have recently gained considerable interest to enhance the performance of the cellular systems supporting Device-to-Device (D2D) communications through either interference-aware resource allocation [14–17] or communication mode selection (i.e., cellular/D2D) [18] in these networks. Besides this stream of applications, coalitional games have also been exploited for relay node selection in Vehicular Ad hoc Networks (VANET) [19].

2.2. Cooperative communications

Cooperative communications have been proven as an effective means to improve the efficiency of wireless networks [20–22]. In general, we may divide the techniques based on cooperative communications into two distinct categories: multihop communications and *cooperative relaying*. The former have long been advocated for cellular networks to improve the coverage and/or the Quality of Service (QoS). The resulting network from the integration of multihop communications with cellular systems is generally referred to as Multihop Cellular Network (MCN) or Hybrid Ad hoc Network (HANET) [23–25]. Opportunity Driven Multiple Access (ODMA) protocol [26] is an initial attempt on realizing MCN, proposed by the 3rd Generation Partnership Project (3GPP) for Universal Mobile Telecommunications System (UMTS)-Time-Division Duplexing (TDD): (i) to increase the high data rate coverage; (ii) to increase the network capacity; and (iii) to provide spot coverage and traffic hotspots. As another attempt in the pursuit of MCN, in [27], the authors propose the integration of mobile ad hoc network and Global System for Mobile Communications (GSM) to permit relaying for mobile phone calls. An overview of several other contributions to the Working Group 4 of the Wireless World Research Forum (WWRF) on cooperative communications can also be found in [28].

In contrast, the other form of cooperation (cooperative relaying) has been widely incorporated to exploit the spatial diversity of the relay channel to alleviate the fading impairments in wireless networks [29–39]. This stream of works is built on the groundbreaking work of Cover & El Gamal in [40] on characterising the channel capacity of the relay channel for the case where the channel is contaminated by Additive White Gaussian Noise (AWGN), which in turn builds upon a three-node channel model (one source node, one destination node, and one relay node) introduced by Van der Meulen [41]. Laneman et al., in [29], examine a four-node network (two source nodes communicating with two other destination nodes), studying the outage probabilities of different cooperation techniques such as Amplify-and-Forward (AF), Decode-and-Forward (DF), *selection relaying*, and *incremental relaying*, in a scenario where the relay nodes operate in the half-duplex mode and the Time Division Multiple Access (TDMA) scheme is used for the medium access. Similarly, Sendonaris et al. study the cooperation of two mobile users where both of them have data to transmit and address practical implementation issues within a Code Division Multiple Access (CDMA) framework [31,32]. Brown et al., [42], address a cooperative network with two source and two destination nodes, modelling the problem as an extensive form game played between the sources. They first apply bargaining technique and show that the game has a unique equilibrium in which both players defect; then, they resort to a repeated game model and analyse the conditions under which "natural" cooperation can emerge between the players. Zhang et al., [43], address a cooperative scenario with a single source and multiple relay nodes, employing auction games to find the most energy efficient partner relay for the source. Spatial diversity of the relay channel has also been exploited to improve the Spectral Efficiency (SE) through distributed space-time multiplexing techniques [30,44]. In this regard, the cooperating nodes share their antennas and transceivers to form virtual Multiple-Input Multiple-Output (MIMO) channels. In contrast to transmit or receive diversity, this form of spatial diversity is referred to as *cooperative diversity* [39].

2.3. Energy efficiency

Energy consumption of UEs is of great concern to mobile users as mobile phones tend to be equipped with several radio interfaces (e.g., Bluetooth, WiFi, LTE, etc.). There have been some research efforts to harness the energy consumption of these devices. In [45], the authors propose a technique where a Bluetooth link is exploited to wake up the Wireless Local Area Network (WLAN) interface whenever there is a pending packet, avoiding unnecessary periodic wake-ups of the WLAN interface. CoolSpots [46] exploits Bluetooth links not only as a wake-up channel for WLAN interfaces, but also as a data link when the application requires narrow bandwidth; WLAN interface is powered up only when the