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Context-aware opportunistic networking in multi-hop cellular networks

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ABSTRACT

5G networks will be required to efficiently support the growth in mobile data traffic. One approach to do so is by exploiting Device-to-Device (D2D) communications and Multi-Hop Cellular Networks (MCNs) in order to enhance the spectrum re-use and offload traffic over underlay networks. This study proposes to further improve the efficiency of transmitting mobile data traffic by integrating opportunistic networking principles into MCNs. Opportunistic networking can exploit the delay tolerance characteristic of relevant data traffic services in order to search for the most efficient transmission conditions in MCNs. The study first presents an analytical framework for two-hop opportunistic MCNs designed to identify their optimum configuration in terms of energy efficiency. Using this reference configuration, the paper then proposes a set of opportunistic forwarding policies that exploit context information provided by the cellular network. Numerical and simulation results demonstrate that opportunistic networking can significantly contribute towards achieving the capacity and energy efficiency gains sought for 5G networks. Under the evaluated conditions, the obtained results show that the proposed schemes can reduce the energy consumption compared to traditional cellular communications by up to 98% for delay tolerant services. In addition, the proposed schemes can increase the cellular capacity by up to 79% compared to traditional cellular communications.

1. Introduction

5G networks will face significant challenges to support the expected growth (by a factor of 500–1000) in mobile traffic in the next decade [1]. Such growth levels are expected to come from a 10 times increase in broadband mobile subscribers, and 50–100 times higher traffic per user. Leading international organizations also expect that 5G networks should support, compared to current 4G networks, 10–100 times more connected devices, 10–100 times higher user data rates, and 5 times smaller end-to-end latency. All this should be achieved while saving up to 90% of energy per provided service [1]. These expectations and forecasts have launched the race towards the definition and design of efficient future 5G networks. Relevant efforts currently focus on the use of higher frequency bands, the dense deployment of small cells and the design of advanced transmission technologies [2]. These approaches can be deemed as an evolution from the traditional cell-centric architectures. There is also a significant belief in the community [3] that future wireless networks need to explore and evolve from current cell-centric architectures to device-centric architectures that exploit the intelligence, communications and computing resources of smart mobile devices. This trend has been lately fostered by the identified benefits of Device to Device (D2D) communications that facilitate new value added services (including proximity based services), support critical

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public safety applications, help offload cellular traffic from the base stations, and increase the spatial frequency reuse and therefore the overall capacity of cellular networks [4–7]. In future device-centric wireless networks, smart mobile devices will provide wireless connectivity to other devices and will hence act as a bridge with the cellular infrastructure. The integration of cellular and ad-hoc or D2D communications is referred to as Multi-hop Cellular Networks (MCNs). MCNs will transform mobile devices into prosumers of wireless connectivity in an underlay network that if efficiently coordinated with the cellular network has the potential for significant capacity, energy efficiency and Quality of Service (QoS) benefits [8].

MCNs exploit the communications, computing and networking capabilities of smart devices. MCNs can also benefit from the mobility and storing capacity of mobile devices to implement opportunistic networking schemes that exploit the store, carry and forward paradigm. Traditionally, opportunistic networking has been proposed for disconnected networks that cannot always reliably ensure real-time end-to-end connections [9]. However, the authors believe that opportunistic networking can also be exploited in networks without disconnections (for example, in urban environments) in order to enhance the efficiency of device-centric wireless transmissions (whether D2D or MCN). In this case, two devices might not initiate a transmission (or even establish a connection) if such transmission is not sufficiently efficient, e.g. because of a low received signal level that would result in a high number of retransmissions and the use of low data rate transmission modes. Devices could hence benefit from waiting for more efficient transmission conditions to start their transmission. In this case, devices will reduce their energy consumption, while also improving the capacity of the network since less wireless resources will be needed to transmit a given amount of data. This opportunistic networking approach could result in some transmission delays, although it is not always the case as demonstrated in [10]. In any case, and according to Cisco estimates [11], delay tolerant services (including mobile video, social networking services, emails, and cloud services, among others) will represent a non-negligible portion of the expected mobile data traffic volume in the years to come. For example, Cisco estimates that mobile video will represent 69% of the mobile data traffic by 2018 [11]. In this context, efficiency-driven opportunistic networking principles could be designed for delay tolerant mobile data traffic, and integrated into device-centric wireless networks in order to enhance the efficiency and capacity of future 5G wireless networks. This is actually the objective of this study that focuses on device-centric wireless networks based on MCNs using mobile relays and D2D communications.

This study proposes novel opportunistic forwarding policies for MCNs and mobile delay tolerant services, and investigates their capacity and energy efficiency gains. The study focuses on two-hop uplink MCN communications where mobile devices with store, carry and forward capabilities relay the transmission between the source node and the base station. The emphasis is placed on two-hop wireless relaying due to the diminishing benefits when considering more than two hops for store, carry and forward relaying with the additional complexities and overhead to orchestrate the transmissions. The paper first presents an analytical framework that identifies the optimum mobile relay location, and the location at which the mobile relay needs to start forwarding the information to the cellular base station in order to minimize the total transmission energy consumption without degrading the end-user QoS. It might not always be feasible to implement the optimum configuration, for example, if there are no devices available at the optimum mobile relay location when needed. The study proposes then a set of opportunistic forwarding strategies that build from the optimum configuration and exploit context information obtained from the cellular network to facilitate their implementation. The strategies focus on relaxing the need to find a mobile relay located at the identified optimum location and time instant. In the first strategy, if no mobile relay is available at the identified optimum location and time instant, the source node waits for a mobile relay to reach the optimum location and then initiates the D2D transmission towards the mobile relay. In the second strategy, the source node increases the search area around the identified optimum location to find potential mobile relays. The proposed opportunistic forwarding strategies exploit context information already available in cellular systems (density and distribution of mobile nodes within the cell) to estimate the search area radius or the maximum time the source node should wait to guarantee with certain probability the presence of at least one mobile relay at the required location. The paper also evaluates the conditions under which each of these two strategies should be employed. The proposed opportunistic forwarding strategies have been designed with the initial objective to minimize the energy consumption. However, the study demonstrates that in addition to their significant energy benefits, the proposed strategies also increase the capacity compared to other forwarding schemes and traditional single-hop cellular communications where the information is directly transmitted from the source node to the cellular base station.

The rest of this paper is organized as follows. Section 2 reviews related studies. Section 3 introduces the concept of energy efficient opportunistic forwarding in MCNs using mobile relays and D2D communications, and formulates the analytical framework for deriving the optimum configuration that minimizes the energy consumption. Section 4 presents the two context-aware opportunistic forwarding proposals that relax the need to find mobile relays at the identified optimum location and time instant. These strategies are then evaluated in Section 5. Finally, Section 6 summarizes the main outcome of this study and concludes the paper.

2. Related work

Opportunistic networking was initially proposed for disconnected wireless networks. In the absence of forwarding opportunities, mobile nodes could store the message and carry it until they can forward it to other nodes. Opportunistic networking can reduce the energy consumption [12] at the cost of possible higher transmission delays [13,14]. For example, the study reported in [15] investigates the problem of optimal opportunistic forwarding for Delay/Disruption-Tolerant Networks (DTN) under energy constraints (the study considers that the energy for transmitting a message is limited). To maximize the delivery probability while satisfying