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Hybrid information and energy transfer in ultra-dense HetNets

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ABSTRACT

Wireless energy transfer is a promising technique to power sensors and mobile devices in order to perform functions beyond the constraints of their batteries. We envision that future ultra-dense heterogeneous networks (UDHetNets) are capable of realizing hybrid information and energy transfer (HIET) with an elaborated architecture design. To enable effective HIET in the designed UDHetNets with massive multiple-input multiple-output (MIMO), three features of wireless energy transfer, i.e., the known transmission signal, the helpful interference signals and the linear beamformer structure, as well as their typical applications are considered and presented in detail. Numerical results study and clearly demonstrate the advantages of the designed HIET systems over existing schemes.

1. Introduction

With the rapid development of wireless communications, their various applications have been extended from human-to-human to Internet-of-Everything (IoE). Actually the main applications of future Fifth Generation (5G) communications include three typical scenarios: enhanced Mobile Broadband (eMBB), massive Machine Type Communication (mMTC), and ultra-Reliable & Low Latency Communication (uRLLC) [1]. For each scenario, the considered performance metrics are different due to the varying service requirements. Apart from the typical metrics, such as capacity, latency, reliability and energy efficiency, the lifetime of terminal batteries is suggested as another metric for 5G communication systems. Because of the slow improvement of battery capacity and the fast growing trend for energy-hungry applications, the finite capacity of terminals' batteries becomes a significant factor impairing the quality of service (QoS) of wireless communication networks. On the other hand, to cut the "last wires" of wireless communications, namely the cables for recharging the terminals' batteries, wireless energy transfer has been recently introduced [2,3]. Therefore, hybrid information and energy transfer (HIET) appears to be essential for future wireless communications.

In order to satisfy the traditional metric requirements of 5G communications, some new techniques have been proposed [4,5]. Firstly, the ultra-dense heterogeneous networks (UDHetNets) consisting of both macro-generalized Node Bs (gNBs) and ultra-dense micro-gNBs have been proposed in order to increase geographic spectrum reusability [5]; Secondly, the available frequency bandwidth is increased by employing certain techniques, such as exploiting millimeter-wave (mmWave) band [6], carrier aggregation and cognitive radios. Another approach that can be considered is to improve the spectrum efficiency by leveraging massive multiple-input multiple-output (MIMO) [7] and non-orthogonal multiple access (NOMA) techniques. However, these techniques are substantially provided for information transmission, there is no clear roadmap on how to employ them for the defined HIET systems.

At present, wireless energy transfer techniques have been widely applied in practical systems. In particular they are capable of feeding sensor nodes, in which replacement or recharging of batteries is either impossible or inconvenient, and transferring energy to the terminals in inaccessible or hazardous regions, for the cases of batteries in the radio frequency identification (RFID) systems or people's bodies [3]. Wireless energy transfer techniques could be classified into three types, namely the near-field electromagnetic coupling based on inductive coils, the laser beaming and the long-distance transfer of radio-frequency (RF) signal energy [8,9]. The first one is capable of guaranteeing efficiency up to 70%, however only operating within distances of the order of the wavelength [3]; for the second one, there are still some technological challenges for practical applications [3]; the last one has been accepted as a promising technique capable of prolonging the working time of terminals' batteries together with cutting the "last wires" of wireless communications [2]. There are two types of RF-based energy transfer techniques. One type foresees that ambient

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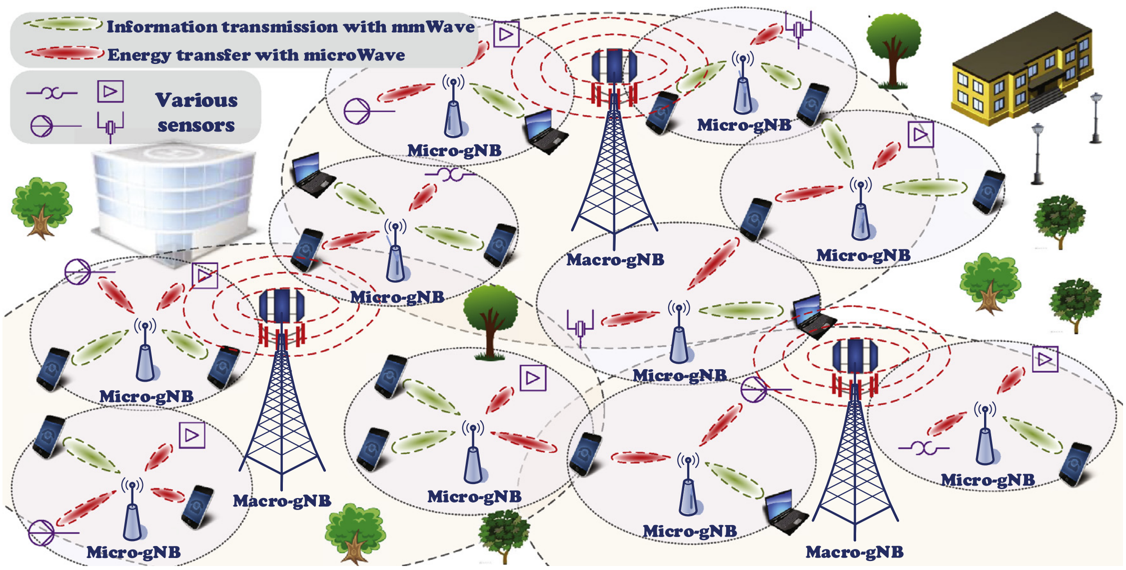

Fig. 1. Illustration of a UDHetNets architecture for HIET systems.

signals are opportunistically harvested to charge the terminals' batteries whereas the other one operates towards a dedicated energy source transfer energy to power the terminals' batteries [2,9]. The randomness of ambient signals results in unstable energy harvesting and therefore the current work mainly focuses on the latter combined with information transmission. However, the efficiency of wireless energy transfer is low as of the long-distance path-loss of signal propagation. On the other hand, most of the techniques for HIET systems are legacy of information transmission systems, which might not be suited for wireless energy transfer. Therefore, new transmission or network techniques need to be studied for HIET systems.

In order to realize the defined HIET systems for 5G wireless communication networks, this paper mainly discusses and focuses on the network architecture and several key techniques. Firstly, an UDHetNets architecture employing both microWave and mmWave bands is designed for HIET systems based on massive MIMO and the current multiplexing techniques. According to the theory of energy harvesting and energy transfer, three features, namely the known transmission signal, the helpful interference signals and the linear beamformer structure, are described for wireless energy transfer. Taking advantage of the three given features, the solution to the challenges of the uplink pilot allocation, the coexistence between information transmission and energy transfer as well as the cooperative energy transfer in multi-cell scenarios, are proposed for the HIET system in detail. Finally, the practical performance is studied and simulation results demonstrate the advantages of the proposed solutions in contrast to existing schemes.

The rest of this paper is organized as follows. The next Section discusses the UDHetNets architecture and the corresponding challenges of HIET systems. Consequently, three features of wireless energy transfer and their applications for UDHetNets are presented to satisfy the considered challenges. Finally, the performance of the proposed HIET systems as well as our derived conclusions are given, respectively.

2. UDHetNets architecture for HIET systems

A UDHetNets architecture for HIET systems is illustrated in Fig. 1, where the micro-gNBs could connect to macro-gNB with a wired or wireless mode. The macro-gNB together with micro-gNB employing massive MIMO serve both information-required terminals (IRTs), such as mobile phones and laptops, etc., and energy-required terminals (ERTs), such as various sensors and some high energy consuming phones, etc. The micro-gNBs could provide both information transmission and energy transfer, and the terminals have both information decoding and energy harvesting circuits.

2.1. Functions of ultra-dense gNBs with massive MIMO

2.1.1. Ultra-dense gNBs

It is well-known that ultra-dense micro-gNBs could improve the geographic spectrum reusability and therefore increase the throughput of the entire communication system. On the other hand, path-loss fading is dramatically reduced due to the short distance between the ERTs and their served gNBs in ultra-dense networks. Thus, it is likely that wireless energy transfer will be possible, where the sensitivity level of ERTs is in the order of about -10 dBm in contrast to the sensitivity level of around -100 dBm for IRTs [2].

2.1.2. Frequency band allocation

Taking advantage of separation of control plane and data plane in software-defined networks (SDNs), macro-gNBs using microWave frequency bands are in charge of wide coverage of terminals and controlling signal transmission; mmWave and microWave frequency bands are employed respectively for information transmission and energy transfer by ultra-dense micro-gNBs in order to compensate for the sensitivity level difference between the IRTs and ERTs.

2.1.3. Massive MIMO

Small-scale MIMO could provide high array gain and improve the system capacity, as well as harvested energy. In order to scale up its advantages, massive MIMO is proposed and applied to the HIET systems [10]. Taking advantage of extremely narrow beams for targeted terminals, massive MIMO could further compensate for the path-loss of both microWave signal for energy transfer and mmWave signal for information transmission. On the other hand, the high degree of freedom (DoF) of massive MIMO could concurrently support massive terminals with space-division multiple access (SDMA) in UDHetNets.