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Uplink resource allocation in SC-FDMA wireless networks: A survey and taxonomy

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ABSTRACT

SC-FDMA has been selected by the Third Generation Partnership Project (3GPP) Long Term Evolution (LTE) and LTE Advanced (LTE-A), as the primary multiple access scheme for the uplink of the 4 G wireless communication systems. This article surveys the different state-of-the-art resource allocation algorithms developed to allocate system's subcarriers and users' transmission powers in the uplink of SC-FDMA wireless networks. An objective-driven classification approach is followed where the various resource allocation algorithms are categorized into four major classes based on the ultimate goal/objective of the resource allocation process, as follows: (i) throughput optimization, (ii) fairness, (iii) satisfaction of users' QoS requirements, and (iv) joint power and subcarriers allocation. The article summarizes the activities and recent advances on this work-in-progress area, highlights the key features, advantages and disadvantages of each algorithm, and provides a detailed qualitative comparative evaluation of their attributes and characteristics according to several distinct features. Furthermore, it provides some indicative numerical results that better present and quantify the objective and achieved performance of the various algorithms. Finally the problem of resource allocation is discussed, when multicell environment is considered, where issues such as intercell interference mitigation and backhaul rate constraints pose additional challenges.

1. Introduction

WITH the growing and overwhelming demand for high data rates, support of large number of users and of multiple services with various Quality of Service (QoS) requirements, significant research efforts have concentrated over the last decades on the design and management of wireless communication systems. Towards meeting these requirements in current and future wireless networks, Single-Carrier Frequency Division Multiple Access (SC-FDMA) has been selected by the Third Generation Partnership Project (3GPP) Long Term Evolution (LTE) and LTE Advanced, as the multiple access schemes for the uplink of the 4 G wireless networks.

In SC-FDMA wireless networks, the necessity for providing a multiple access scheme that efficiently allocates the subcarriers and the uplink transmission power to the users arises as a crucial research and practical task. This task becomes even more complicated as the number of users increases and new challenges emerge. Such challenges mainly concentrate on the dynamic subcarrier allocation, adaptive power allocation, system's capacity planning, fair resource allocation, satisfaction of users' QoS requirements, etc. These issues are collectively handled under the umbrella of radio resource allocation, and are treated via appropriately formulated optimization problems and the design of corresponding optimal or heuristic algorithms.

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The main goal of this survey article is to present a concrete, concise and insightful presentation of the state-of-the-art resource allocation algorithms in SC-FDMA wireless networks, where a plethora of literature exists. Specifically, we provide an overview of different adaptive resource allocation algorithms and classify them in terms of their objectives, while highlighting their key features, advantages and drawbacks.

The algorithms discussed in this article are classified in four basic categories, according to the primary goal they attempt to satisfy throughout the resource allocation process. In a nutshell, the first group of algorithms aims primarily at allocating the subcarriers to the users towards maximizing the total transmission rate of the system. The second class considers fairness criteria, such as Max-map scheduling and proportional fairness, towards allocating the resource blocks to the users, while the goal of the third group is to satisfy the demanding users' QoS requirements, via efficiently allocating to them the resource blocks. Finally, the fourth group of algorithms, where less research effort has been invested so far due to its inherent difficulty and complexity, aims at allocating jointly the subcarriers and the uplink transmission powers to the users, towards maximizing their perceived satisfaction commonly reflected by an appropriately formulated utility function.

Based on this categorization, we do not claim absolute completeness of presentation of resource allocation algorithms in SC-FDMA wireless networks, which is an ongoing research field, but we try to provide an extensive and well organized analysis along with a comprehensive, qualitative and quantitative evaluation and comparison, when applicable.

The rest of the paper is organized as follows. An overview of SC-FDMA wireless systems is presented in Section 2 for completeness purposes. In Section 3, the four groups of the surveyed resource allocation algorithms are presented, where each class of algorithms is discussed in a separate subsection. At the end of each subsection, a comprehensive comparative table is introduced, highlighting the advantages and drawbacks of all the algorithms belonging to each class – essentially sharing the same goal, as well as their computational complexity. Indicative numerical results are also presented for some representative algorithms that better present and quantify the achieved performance of the various algorithms for different number of users. Section 4 discusses the problem of resource allocation when multicell environment is considered, where issues such as intercell interference mitigation and backhaul rate constraints pose additional challenges. In Section 5 we provide some open research directions considering the resource allocation in SC-FDMA wireless networks. Finally Section 6 concludes the paper.

2. An overview of SC-FDMA and subcarrier mapping

Single carrier frequency division multiple access (SC-FDMA) is a single carrier technique, which utilizes single carrier modulation and frequency domain equalization and has lately received significant attention, as a variant of the orthogonal frequency division multiple access (OFDMA) for 4 G systems and technology [1]. Third Generation Partnership Project (3GPP) Long Term Evolution (LTE) and LTE Advanced standards, have already adopted SC-FDMA for the uplink of wireless networks, as the most promising multiple access technique. Specifically, Release 8 of the 3GPP standard, which was finalized at the end of 2008, adopted OFDMA for the downlink and SC-FDMA for the uplink [2–5]. The choice of SC-FDMA for the uplink was basically motivated by the limited peak to average power ratio (PAPR) of this technique compared to OFDMA, which is a crucial parameter due to the fact that it results in low mobile terminal power consumption and low manufacturing power amplifier cost [5–9].

SC-FDMA is a multiple access scheme based on the single-carrier frequency domain equalization (SC-FDE) technique and is alternatively known as DFT-Spread OFDMA, which is a variant of OFDMA, due to the addition of Discrete Fourier Transform (DFT) – spread block, which transforms the time domain data symbols to the frequency domain prior to modulating the data symbols using OFDMA modulation [10,11].

A block diagram of a SC-FDMA system, i.e. the transmitter and the receiver structure, is shown in Fig. 1. Considering the transmitter part, a baseband modulator (encoder) transforms the binary input to a multilevel sequence of complex numbers, adopting one of the several possible modulation formats, which can either be the binary phase shift keying (BPSK), or the quaternary PSK (QPSK), or the 16 level quadrature amplitude modulation (16-QAM) or the 64-QAM. The system dynamically adapts the modulation technique and thereby the transmission bit rate to match the channel quality of each terminal. Afterwards, the SC-FDMA system groups the modulation signals into blocks each containing N symbols and performs a N point DFT operation to produce a frequency domain representation of the input time domain signals. Then, the N DFT outputs are mapped to one of the $M > N$ orthogonal subcarriers that can be transmitted [65].

After the subcarrier mapping procedure (analytically discussed in Section 2.1), the M subcarrier amplitudes are transformed to complex time domain signals via an Inverse DFT (IDFT) transform and each of the signals is modulated to a single frequency carrier and all the modulated symbols are transmitted sequentially. Moreover, at the transmitter part two additional signal processing operations are performed prior to the transmission. First, a set of symbols referred to as a cyclic prefix (CP) is inserted to the signal, in order to provide a guard time to prevent inter-block interference (IBI) due to multipath propagation. Moreover, a linear filtering operation is performed at the transmitter part, referred to as pulse shaping in order to reduce out of band signal energy. Finally, at the receiver part, the inverse procedure of the one followed at the transmitter part, is performed.

2.1. Subcarrier mapping methods and technical limitations in SC-FDMA

Two fundamental subcarrier mapping schemes are available for resource scheduling in real SC-FDMA networks: distributed (DFDMA) and localized (LFDMA) [12–14]. In the case of LFDMA, the N DFT outputs are