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UWEE Technical Report
Number UWEETR-2012-0007
September 2012

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Abstract

Cellular networks are confronted with an exponential increase in capacity requirements, due to the proliferation of high-end consumer devices (smartphones, tablets, e-readers) consuming ever increasing multimedia content. Clearly, availing of new spectrum (as with 4G allocations) is a necessary part of meeting this challenge, but so are improved *network architectures* that achieve enhanced spatial spectral efficiency (bits/s/Hz/area). Network operators are increasingly moving toward a heterogeneous architecture consisting of overlaid cells of various sizes; in particular, a variety of small, low-power pico/femto base stations and relays are being deployed to increase capacity around local hotspots. OFDMA femtocells are considered a key enabler in 3GPP LTE-Advanced networks of very high data rates for indoor users. However, the unmanaged nature of femtocells implies the need for careful modeling (and ultimately, managing) of inter-cell interference especially in dense deployments. So far, co-channel interference in femtocells has been investigated using traditional, cellular resource allocation approaches that usually assume a fully loaded network where the system is insensitive to the activity of a single user. This assumption is not suitable for femtocells which are designed to serve very few users and thus lacks the presumed traffic aggregation. This article provides a fresh look at the femtocell interference problem from a multiple access perspective. It first compares the multi-channel features inherent to OFDMA with traditional multi-channel MAC designs for wireless LANs and highlights how the ability to schedule users in both *time* and *frequency* as afforded by OFDMA, can be exploited to achieve more effective (distributed) random access. A simplified MAC model that hides the complexity of LTE protocol stack is proposed to facilitate the design and analysis of random access MAC algorithms in the context of OFDMA femtocells.

1 Introduction

The explosive growth of broadband traffic driven by smart mobile devices has pushed current wireless networks to their capacity limits. Wireless operators around the world are attacking this problem on multiple fronts: via acquiring new spectrum as well as via enhanced *temporal spectral efficiencies* (measured in bits/s/Hz) resulting from new wireless technologies and *spatial spectral efficiencies* (measured in bits/s/Hz/area) due to new network architectures [1]. Improved temporal spectral efficiencies are expected to result from deployment of 4G technologies - notably Long Term Evolution (LTE) and (in future) LTE-Advanced (LTE-A), as defined by the 3G Partnership project (3GPP). LTE aims for peak data rates of 300 Mbps on the downlink and 170 Mbps on the uplink [2]. The primary radio access method in LTE is Orthogonal Frequency Division Multiple Access (OFDMA) which is built upon the efficient multi-carrier modulation technique Orthogonal Frequency Division Multiplexing (OFDM) known for its robustness against multipath interference and its low-complexity implementations. OFDMA enables high spectral efficiency from multiuser diversity and high bandwidth flexibility to support a wide range of broadband data and multimedia applications.

On the architectural side, wireless networks are moving from a homogeneous cellular topology into an overlay of different cell sizes with various backhaul options. In addition to the high power outdoor macrocells, smaller base stations are being introduced to provide localized coverage inside residential/office buildings and around public hot spots. The term *small cells* is an umbrella term for low-powered radio access nodes such as picocells, microcells and femtocells that operates in the licensed spectrum and have a range of 10 meters to several hundreds meters [3]. Picocells and microcells are compact base stations deployed by the operator to enhance coverage in densely populated

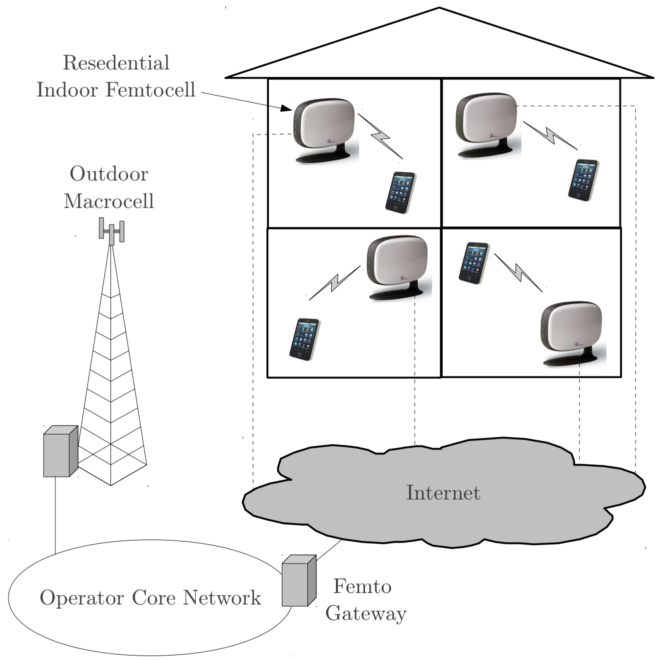

Figure 1: Femtocell Network architecture

public areas and enterprises. Femtocells are smaller base stations that employ IP-based backhaul over the Internet, as illustrated in Fig. 1. In simple terms, a femtocell is an indoor wireless access point installed by the consumer and appears as a regular macrocell base station to client devices. It operates on the same licensed spectrum as the outdoor macro cells, but utilizes the users own broadband Internet connection as a backhaul link to a Femto Gateway in the cellular network. However, beyond mere in-band range extension indoors, femtocells (that typically serve only few users at a time) can also support much higher data rates compared to macrocells. Hence, they provides a cost-effective way for offloading traffic and operational cost away from the macro network [3].

Combining advanced 4G technologies (LTE) with small cells (femtocells) can increase the overall network capacity many fold provided that inter-cell interference is handled effectively. Because the femtocell covers a small area and serves very few users, it already operates at maximum spectral efficiency, whereby additional gains from multiuser diversity and link adaptation are marginal at best. In such environments, the main performance limiter is the interference from nearby co-channel cells. The downlink interference from macrocells is predictable because they are well planned and their location and power settings are fairly static. The real challenge comes from nearby "unplanned" femtocells especially in dense deployments of femtocells.

Although LTE has been equipped with some built-in interference coordination, the challenge brought by femtocells interference is unique from multiple aspects. First, femtocells are deployed and managed by the consumer and their exact location is not known to the network, hence static frequency planning is not suitable. Second, since the backhaul link between the femtocell and the cellular network is a high-latency virtual tunnel over the Internet (see Fig. 1), real-time interference coordination between macrocells and femtocells and among adjacent femtocells is not feasible. This is a major factor that preclude centralized solutions from dynamic interference coordination in femtocells. Third, because the femtocell is designed to serve only few users, the resulting interference becomes very dependent on the user's activity and hence leads to a highly dynamic interference situation. This is in contrast to macrocells where the high traffic aggregation from many users makes the system insensitive to the activity of a single user. Finally, though "unplanned", femtocells are synchronized with the cellular network, i.e. they are not completely random as in ad-hoc IEEE 802.11 WLANs. Synchronization is needed for seamless handoff from/to the macrocellular network.

In examining the literature on femtocells, we can identify two approaches for handling the interference problem [4]. The first approach is based on distributed power control techniques which require measuring interference and adapting the transmission power accordingly. Most self-optimizing femtocells in commercial deployments today are based on power control, especially in 3G CDMA devices [5]. The second approach which is more viable for OFDMA-based networks is based on orthogonalizing time/frequency resources among adjacent femtocells. Inter-cell interference can

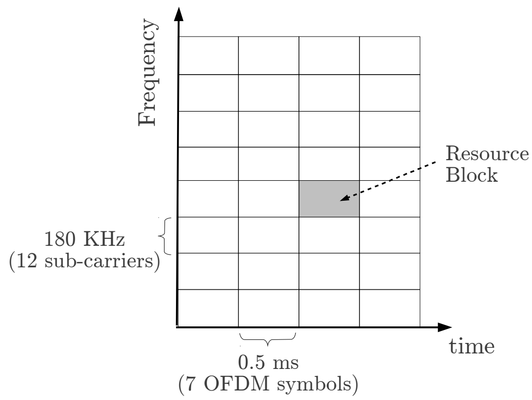

Figure 2: LTE Resource Grid (OFDMA sub-channelization)

be mitigated by controlling the sub-carrier assignment in each femtocell. This approach attempts to generalize the single-cell resource allocation problem to the multi-cell case. However, almost all the proposed solutions assume full loading in each cell and ignore the user activity factor. This assumption, though justified in macro cellular networks, is simply not valid in femtocells for the reasons explained above. *Therefore, the randomness of the user activity must be accounted for through appropriate traffic model in any proper study of femtocell interference*.

This article provides a fresh look at the femtocell interference problem from a multiple access perspective. We highlight the fact that at the packet level, interference coordination between femtocells is essentially a multiple access (MAC) design problem similar to MAC design in IEEE 802.11 WLANs but with the added flexibility of OFDMA and the advantage of synchronism. Specifically, we discuss the viability of OFDMA-based random multiple access and describe appropriate MAC models in the context of femtocells. Our goal is to open up new design ideas outside the traditional cellular resource allocation framework to handle the femtocell interference more efficiently. Section 2 presents a brief overview of OFDMA as a multiple access scheme in wireless networks. Then, we discuss and motivate the case for OFDMA-based random multiple access for femtocells in Section 3. In Section 4, we propose a simplified MAC model that abstracts the details of LTE protocol stack and allow us to study OFDMA-based random MAC algorithms with random packet arrivals in femtocells.

2 Overview of OFDMA Multiple Access

Multiple access policies typically attempt to provide non-interfering communication channels for each active transmit-receive pair in the network. In previous generations of cellular networks, this was achieved by allocating separate resources to each active user, e.g. frequency channels (FDMA), time slots (TDMA) or spreading codes (CDMA). Each one of these techniques has its pros and cons, but the common issue is the lack of bandwidth flexibility to accommodate different applications data rates. OFDMA combines the desirable features of both FDMA and TDMA by allowing multiple users to transmit in the same time slot over different sets of subcarriers. High bandwidth flexibility is achieved by allocating more subcarriers to users demanding higher data rates on a slot-by-slot basis. Typically, subcarriers are grouped into subchannels in order to reduce the complexity of the system. For example, the smallest unit of allocation in LTE is called a *Resource Block* (RB) comprising of 12 subcarriers (180 KHz) for the duration of 7 OFDM symbols (0.5 ms) as depicted in Fig. 2.

The fine-grained time-frequency channelization in OFDMA enables the design of flexible multiple-access policies to accommodate many users with varying applications, data rates and QoS requirements. In the context of cellular networks, multiple access design is usually treated as a dynamic resource allocation policy, that coordinates the assignment of resources (subchannels and power) among cells, to reduce interference and harness the inherent multiuser diversity gains. The general problem of interference avoidance and resource allocation in cellular networks continues to be of great research and practical interest because of the continuing need for more efficient spectrum utilization. A majority of the prior art on this subject presents centralized solutions suitable for centrally managed cellular networks. Furthermore, dynamic resource allocation has been confined, until recently, to users within a single cell; inter-cell interference is usually mitigated via careful frequency planning. However in 4G networks, all cells are allowed access to the whole spectrum (frequency reuse factor of 1) in order to maximize the utilization of the licensed spectrum. In this case, the multiple access policy must handle inter-cell interference in addition to the subchannel assignment within each cell [6, 7]. We can group OFDMA multiple access strategies into three categories: (1) centralized schemes, (2) distributed (contention-free) schemes and (3) random access (contention-based) schemes.

Centralized multiple access in OFDMA networks refers to the multi-cell subchannel assignment and scheduling problem [8]. This problem is usually formulated as a constrained optimization problem, to a) either minimize the total transmit power subject to constraints on the user data rate or b) maximize the total data rate with a constraint on total transmit power. These approaches have been investigated extensively in recent years with numerous optimal and sub-optimal algorithms in various settings. A general formulation is discussed in [9] and a survey of different subchannel assignment algorithms for OFDMA downlink and uplink is presented in [10] and [11] respectively. There imply two key assumptions in these schemes; first, there exists a controller in the network that is able to collect channel information per subchannel from all users in all cells in real time. Second, each user's traffic buffer is always full such that radio resources are not wasted when the user is scheduled for transmission. In the network architecture of femtocells, there is no central node suitably positioned to play such a centralized role other than the Femto gateway (Fig. 1). However, the high latency Internet-based backhaul (VPN tunnel) between the femtocells and the gateway cannot be used for tracking and controlling the highly dynamic interference situation in femtocells (due to user activity). In addition, the complexity of this scheme grows very quickly with the number of cells as the controller has to process large amount of information in real-time. Therefore, centralized solutions are not practical in the femtocell case.

In distributed contention-free schemes, all nodes in the network coordinate the assignment of subchannels via explicit message passing over dedicated control channels. A node could be a base station coordinating with other BSs to reduce inter-cell interference in a cellular network or could be a single user coordinating with other users in an ad-hoc network. The principle of operation is the same in both cases: local channel information is exchanged by a node with its neighbors to enable subchannel assignment in a distributed manner. In 3GPP LTE femtocells, the X2 interface which is defined between adjacent cells could be realized over the air using some dedicated subchannels. A survey of some distributed interference avoidance algorithms is given in [12]. Although some of these algorithms claims good performance relative to the centralized ones, they are slow to converge and cannot cope with the high traffic dynamics and the user activity factor in femtocells. Nevertheless, they provide viable solutions in many scenarios and hence are often preferred over centralized solutions.

The third category, which is the main focus of this article, consists of pure random multiple access techniques. In a random access MAC, users contend for the channel, rather than being allocated a resource. Conflicts are then resolved using a collision resolution protocol. Random access MAC has been known for decades and has been successfully implemented in many wireless standards such as the popular IEEE 802.11 (WiFi). In the simplest random access MAC (Aloha), the user transmits packets at will without regard to other users. If the packet is not acknowledged by the receiver, the user backs off and tries again after a random duration. In Carrier Sense Multiple Access (CSMA), the user "listens" to the channel before transmitting in order to avoid collisions whenever possible. Collisions can still occur and are then resolved using some backoff algorithm. Effectively, the random access MAC schedules the users into non-interfering time slots in a distributed way without explicit coordination.

Although random access is almost always pursued in the time dimension for any given frequency channel, there is no reason that the frequency dimension could not be utilized better for more efficient access. In OFDMA, users can in principle contend for subchannels and multiple "winning" users can transmit simultaneously on different subchannels without collisions. This significant feature of OFDMA is what allows for *Random Multiple Access* as apposed to simply *Random Access*, and has generally been under-explored. In the following sections, this concept is defined and contrasted with the concept of multi-channel MAC from prior wireless MAC literature. Then, we discuss the use of OFDMA-based random multiple access for interference avoidance in femtocells and describe an appropriate MAC models for future investigation.

3 OFDMA-based Random Multiple Access

Since OFDMA is often associated with planned cellular networks, random access MAC may seem of little relevance. So far, random access MAC has only been used for initial channel request and synchronization. For example, LTE sets aside few resource blocks in each radio frame with a set of random preamble sequences to be used exclusively for the Random Access Channel (RACH). The RACH procedure is essentially a form of Reservation-Aloha in which users contend to reserve a larger bandwidth or to be admitted into the system; i.e. no actual data is transported over the RACH. Once the user is successfully admitted, all subsequent downlink and uplink transmissions are scheduled by the Base Station. At the macrocell level, the BS can be considered active most of the time because a macrocell usually serves a large number of users. This implies that the randomness of the traffic at the user level needs not be taken into account in studying the inter-cell interference in a macro-cellular network.

However, because a femtocell is designed to serve very few users with at most one or two users being active at any instant, the generated traffic load at the cell level is often bursty with low duty cycles. Furthermore, the number of femtocells operating in the same licensed spectrum in a given area is relatively small. We can view this as a cluster of interfering transmit-receive pairs (single-user femtocells) competing for channel access without a central arbitrator. In such situations, random multiple access is a viable choice if designed properly. In fact, we can exploit the flexibility of OFDMA and time synchronism to design more efficient random MAC algorithms for OFDMA-based femtocells. OFDMA provides an additional degree of freedom by allowing contention resolution over the frequency as well as over time dimension.

The time-frequency resource grid in OFDMA (Fig. 2) can be thought of as a slotted multi-channel system. The grouping of sub-carriers into Resource Blocks (RB) divides the channel bandwidth into equally-sized subchannels which can be accessed on a slot-by-slot basis. We will use the terms ”subchannel” and ”channel” interchangeably to denote one RB in the frequency domain. Because these subchannels are orthogonal, the channel access problem translates into a Multi-Channel MAC problem. Numerous contention-based algorithms have been studied for Multi-channel MAC mostly in the context of ad-hoc and mesh wireless networks [13]. In multi-channel ad-hoc networks, the user usually contends for a single channel and then transmits one packet over that channel. The advantage is that when the number of users is much greater than the number of channels, the multi-channel MAC can distribute the contention load and reduce collisions.

Two unique features distinguish OFDMA from traditional multi-channel MAC proposed in the context of wireless ad-hoc and mesh networks. First, channel switching is instantaneous, because by definition OFDMA allows control over which subchannels are accessible and which are not on a slot-by-slot basis. This type of channelization being entirely realized in the digital processing domain marks a big leap over traditional multi-channel wireless systems where the transmitting node has to switch its radio from one frequency carrier to another incurring a significant time penalty. The second feature is the ability to transmit and receive over a variable number of subchannels simultaneously with a single radio. For example, a packet in LTE is segmented or concatenated with other packets to fit into a variable-size block that is mapped to the allocated (randomly accessed) subchannels. This enables the random MAC protocol to adapt dynamically to various network loads and traffic scenarios.

Several random access algorithms have been proposed to exploit the multi-channel nature of OFDMA. Opportunistic multi-channel Aloha (discussed in [14] among others) attempts to exploit the multi-user diversity by adapting the transmission probability in each subchannel to its corresponding channel quality. However, the first work that studied contention resolution over the frequency domain in OFDMA appeared in [15]. It proposed what we term OFDMA-Aloha - a fast retrial algorithm for frequency-domain backoff. In OFDMA-Aloha, instead of waiting for a random backoff period after a collision, the user tries another (randomly selected) subchannel immediately subject to a maximum retry limit. This basic idea was extended to OFDMA-based CSMA/CA systems in [16]. In OFDMA-CSMA/CA, the user first senses all subchannels and randomly selects one subchannel from the set of idle subchannels for transmission. Then, it backs off for a random Collision Avoidance (CA) interval whose length is proportional to the number of sensed idle subchannels in every slot.

In the above algorithms, the user is not allowed to access more than one subchannel at a time because the target is to distribute the offered load (attempt rate) over the available subchannels. The implicit assumption here is that the number of users is greater than the number of subchannels. The MAC model in this case is the traditional multi-channel MAC with *single access* where exactly one packet is transmitted over a single subchannel. This MAC model is not suitable for femtocells where the number of subchannels is significantly greater than the number of active users. Hence, an important design criteria in this case is to allow the user access to as many subchannels as possible to maximize utilization. The MAC frame in OFDMA is a single coded block of bits that is mapped to multiple subchannels. Since the user can initiate transmissions over multiple parallel subchannels, we need to define the notion of collision for such parallel transmissions. This motivates us to propose the *Bulk Access* model to facilitate the design and analysis of random multiple access in OFDMA femtocells.

4 Bulk Access Model for Femtocells

The term "Bulk Access" is derived from *bulk service* queuing models where a group of customers are served together in bulks or "batches" by a single server [17]. The distinction from multi-server model is that the service time of each customer in the bulk is not independent, i.e. they are served together as one unit. This is precisely how OFDMA handles packet transmission over multiple subchannels. The information bits which are transmitted over multiple subchannels are actually treated as a single code block in the physical processing chain. To understand this better, it is necessary to examine the downlink protocol stack in LTE and the relevant functionalities.

4.1 LTE Protocol Stack

In LTE, IP packets travel through four layers before they are transmitted over the air as shown in Fig. 3. The Radio Link Control (RLC) layer receives packets (or PDUs) from the the Packet Data Convergence Protocol (PDCP) which is responsible for IP header compression and ciphering. The RLC layer is responsible for the segmentation and concatenation of packets into RLC PDUs, whose sizes vary from one slot to another depending on the resource allocation offered by the MAC layer. The main function of the MAC layer is resource allocation and scheduling in addition to implementing the Hybrid-ARQ (H-ARQ) process. The PHY layer performs coding, modulation and resource mapping as dictated by the MAC scheduler.

A sample data flow is shown in Fig. 4. The MAC scheduler decides what resource blocks (subchannels) will be available for next transmission slot and what modulation and coding scheme (MCS) should be used. This information is signaled to the receiver over a dedicated control channel. The size of the Transport Block (MAC frame) is computed from the number of assigned resource blocks (RBs) and the MCS. Then, the RLC layer segments/concatenates IP packets into multiple RLC PDUs whose combined size is equal to the Transport Block (TB) size plus the MAC header. The MAC layer combines the RLC PDUs, adds a header and creates the TB for the H-ARQ process. After coding and modulating the TB with the selected MCS, the PHY layer maps the modulation symbols over the subcarriers (resource blocks) assigned by the MAC scheduler. If the TB is decoded correctly at the receiver, the RLC PDUs are reassembled and IP packets are delivered up the stack. Otherwise, the H-ARQ entity tries to retransmit the TB again (either the same soft bits or additional redundant bits) for a limited number of trials before it gives up. Although the H-ARQ provides fast error recovery from most channel errors, it is not designed to handle errors resulting from strong interference or collisions which are left to the MAC.

4.2 Simplified MAC Model

From Fig. 4, we see that the Transport Block (TB) is physically mapped into multiple small resource blocks (RBs), one per subchannel. These RBs however, are only a physical layer realization and cannot be processed independently. If one RB is corrupted due to strong interference in the corresponding subchannel, the entire TB is deemed lost and must be retransmitted. If the H-ARQ fails to transmit the TB successfully, it deletes it from its buffer and notifies the upper layers. In RLC Acknowledged Mode (AM), RLC PDUs must be delivered reliably using RLC-level ARQ. In the next available transmission opportunity, lost RLC PDUs go through the same segmentation/concatenation process, possibly with a different TB size due to the varying allocation size provided by the MAC scheduler. This sophisticated cross-layer interaction does not lend itself to easy analysis of the multiple access protocol with existing tools. This is where the Bulk Access model offers a suitable theoretical framework.

Looking at Fig. 4 in the bottom-up direction, each Resource Block (RB) may be conceived as a packet because essentially it contains coded information bits. Then assuming a link with maximum spectral efficiency (as often the case in femtocells), consider a fixed RB size and ignore any MCS link adaptation. We can also match the packet size to that of the traffic model to abstract out the RLC segmentation/concatenation functionality. Therefore, we have a multi-channel MAC with Bulk Access where packets are served in bulks. Any collision in one packet renders the whole bulk corrupted and all packets must be retransmitted, possibly with other packets depending on the MAC decision. This model matches the bulk-service queuing system where a single server takes a number of customers, depending on available capacity, and serves them as a bulk [17]. The simplified Bulk Access model is illustrated in Fig. 5.

Note that this model does not impose any restriction on the choice of the actual MAC algorithm itself. It is the function of the MAC algorithm to specify the rule for how many and what subchannels are accessed in each time slot. The purpose of the proposed model is to allow the researcher to study different random MAC options under unsaturated traffic scenarios in which random packet arrivals is a necessary assumption. The model hides most of the

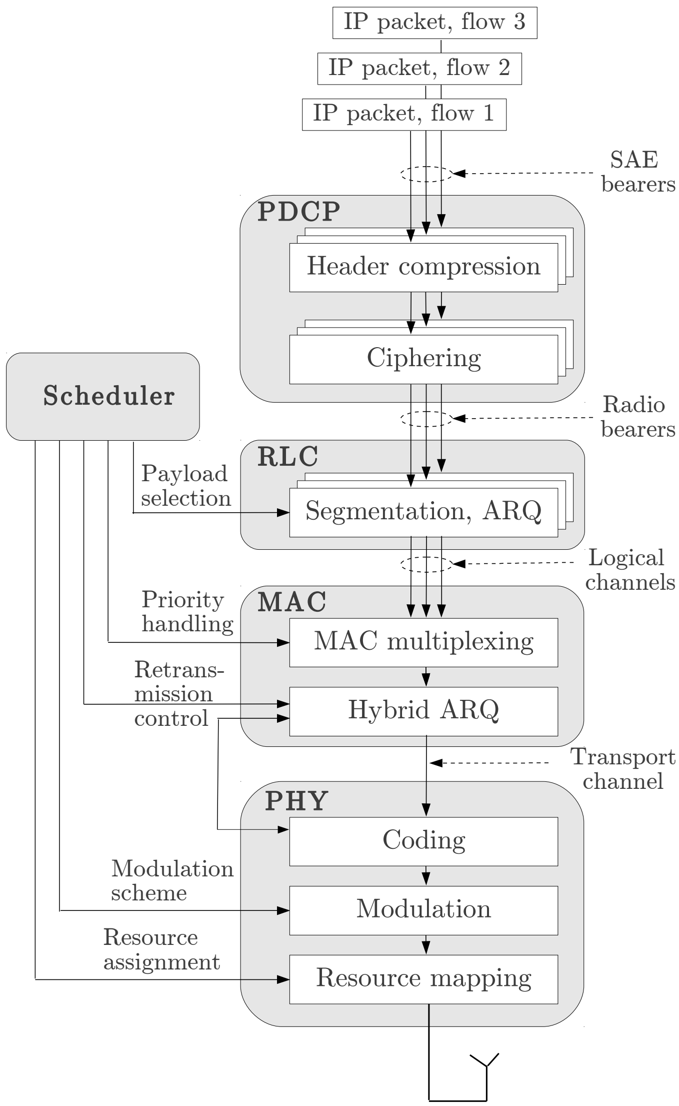

Figure 3: LTE Protocol Stack, edited from [18]

complexity of the LTE protocol stack but capture the important MAC interactions at the packet level. To this end, we present a case study for applying this model in evaluating two simple OFDMA-based random MAC algorithms.

4.3 Case Study: K-Aloha vs. Aloha

For illustration purposes, we apply the Bulk Access model to compare two simple random access schemes in a small network of OFDMA femtocells with low traffic load. Consider a slotted OFDMA system with K subchannels and N femtocells, each serving exactly one user. Assume also that all femtocells are within a single collision domain so that only one packet can be successfully transmitted in each subchannel. Packets arrive to each user's queue according to a Bernoulli arrival process with probability α in every slot. According to our bulk access model, a group of packets is transmitted as a bulk where each packet occupy one subchannel for exactly one time slot. The bulk size M is a random variable that depends on the current queue length Q and is upper-bounded by K.

In low traffic scenarios, it is common that the user does not have enough packets to occupy all K subchannels in every slot, i.e. $M \ll K$. Looking at Fig. 5, we see that we have some freedom in selecting M out of K subchannels to transmit the bulk of packets. In a random access network, the most natural choice is to select the M subchannels randomly with the hope for reducing collisions. For example, suppose we have two users each having exactly one

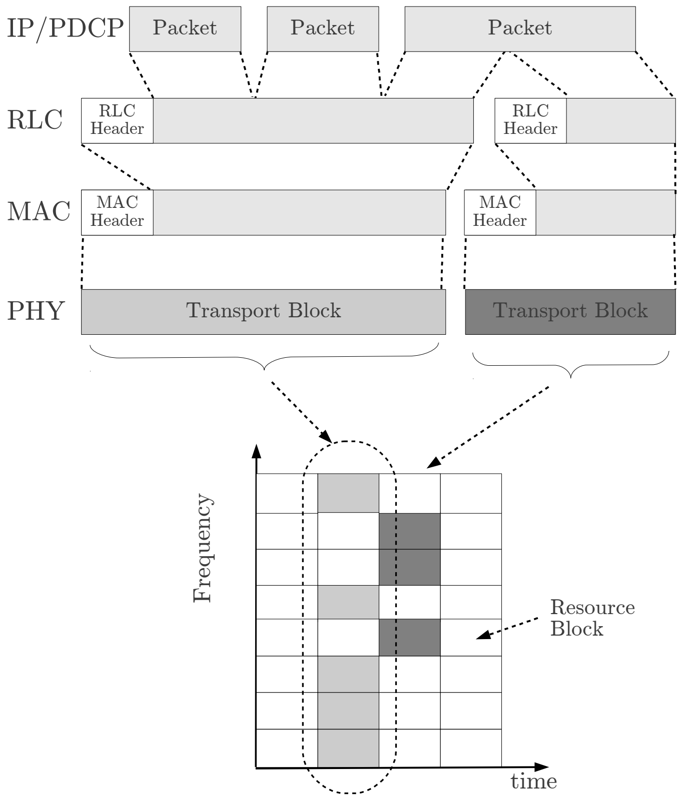

Figure 4: LTE data flow and resource mapping

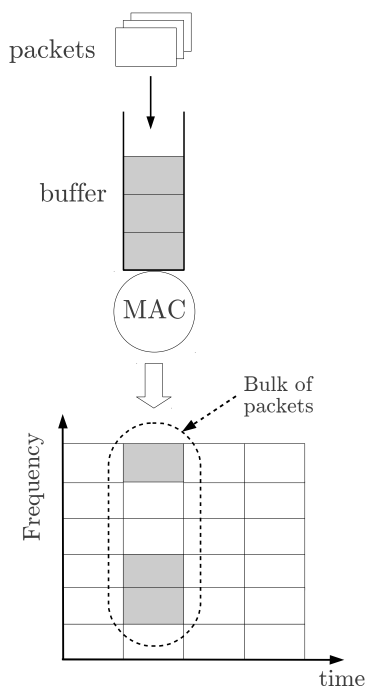

Figure 5: Multi-channel Bulk Access model for OFDMA femtocells

packet in its queue ($Q = 1$) and employing slotted Aloha MAC with transmission probability p. In this case, both users will create a bulk of size $M = 1$. If both users map their bulk starting at subchannel 1 (i.e. sequentially in order of channel index), then the collision probability is simply p. However, if the bulk is randomized over the K subchannels, the collision probability is reduced to $p \times 1/K$ (for $M = 1$). Clearly, as the bulk size M increases the collision probability increases until the gain from subchannel randomization diminishes at $M = K$.

We simulated the first scheme (Simple-Aloha) and the second randomized version (K-Aloha) in a network of $N = 12$ single-user femtocells with $K = 32$ subchannels and Aloha transmission probability $p = 1/N$. In both schemes, the user transmits a bulk of size $M = \min\{Q, K\}$ with probability p in every slot. In Simple-Aloha, the bulk is always mapped to subchannels indexed 1 through M. In K-Aloha, M subchannels are selected randomly out of the K subchannels. The input traffic load is increased by increasing α of the Bernoulli arrival process. Fig. 6 shows the packet service time which is the time needed to successfully transmit the Head of the Line packet (access delay). Clearly, in high traffic load with high queue levels ($Q \geq K$) the difference between the two schemes diminishes as indicated by the results. However, significant reduction in the service time can be achieved in the low load region if we randomize the selection of channels, i.e. spreading the bulk over the frequency domain as in K-Aloha. Clearly, this kind of randomization is not the best option to utilize the frequency dimension, but it helps illustrate the bulk access model and opens up new ideas for random multiple access in OFDMA femtocells.

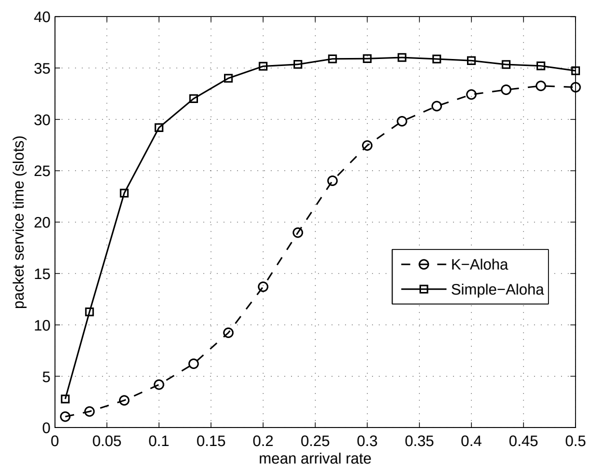

Figure 6: Packet service time (access delay) of K-Aloha vs. Simple-Aloha, $K = 32$, $N = 12$, $p = 1/N$

5 Conclusions

The distributed ad-hoc nature of femtocells renders centralized interference mitigation solutions impractical. OFDMA provides a high degree of bandwidth flexibility that can be exploited in a new way to address the interference problem in femtocells. This article discussed this problem from a fundamental multiple access perspective. In contrast to traditional multi-channel MAC in wireless LANs, OFDMA-based random multiple access MAC algorithms can utilize the frequency dimension for contention resolution more effectively. Multiple packets from multiple sources can be transmitted over multiple subchannels with a low collision rate if the MAC algorithm is designed properly. The Bulk Access model is proposed to describe the notion of collision during the transmission of multiple packets from the same source. It helps abstract the complexity of the LTE protocol stack and facilitate the design and analysis of new random access MAC protocols for OFDMA femtocells.

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