FemtoHaul: Using Femtocells with Relays to Increase Macrocell Backhaul Bandwidth

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***Abstract*—The ever increasing user demand for highly data-intensive applications is motivating cellular operators to provide more data services. However, the operators are suffering from the heavy budgetary burden of upgrading their infrastructure. Most macrocell Base Stations still connect to backhauls with capacities of less than 8 Mbps, much too low to be able to serve all voice and data users in the cell. This so-called macrocell backhaul bandwidth shortage problem is encumbering the growth of cellular data services. In this paper, we propose a novel solution, *FemtoHaul*, which efficiently exploits the potential of femtocells to bear the macrocell backhaul traffic by using relays, enhancing the data rates of cellular subscribers. We design a system architecture and its related signaling and scheduling strategies. Extensive simulations demonstrate that FemtoHaul can effectively serve more users and support higher data demand with the existing macrocell backhaul capacity.**

I. INTRODUCTION

Cellular services are experiencing a transition from simple traditional voice services to highly data-intensive applications. The fundamental cause of this transition lies in the ever increasing user demand for higher data rates in cellular wireless networks, for applications such as content-rich multimedia and gaming. At the same time, the average growth of revenue per user for voice is declining due to the saturated market, which is driving the cellular operators to turn their focus to data services. Moreover, the storage and computational power of a cellular phone today is approaching those of a personal computer, allowing it to support more data-based applications. All these trends are driving the design and development of new data-oriented cellular systems.

However, the lag between the development of the cellular infrastructure and the traffic demand is a major obstacle. Current 3G standards are pushing cumulative macrocell data rates to tens of Mbps or even more. For instance, with the highest modulation, Evolved High-Speed Packet Access (HSPA+) can achieve a 42.2 Mbps maximal data rate, while this parameter for WiMAX is 63 Mbps [1]. Future cellular standards, such as 3GPP Long Term Evolution (LTE), support even higher data rates. However, most of the macrocell Base Station (BS) backhauls use only a few (2 to 4) T1/E1 lines [2] which account for only about 3 to 8 Mbps of bandwidth. Although adding multiple lines to the BS backhaul, or increasing the number of BSs may seem like an obvious solution to fill this gap, high CAPEX and OPEX costs (more than $10000 per line and $50000 per site annually) [2] make this an expensive option. The macrocell backhaul has thus become a bottleneck delaying the growth of cellular data services. This problem has been attracting much attention in industry lately [3], [4]. Companies like Jupiter Networks [5] and ADC [6] are already offering their solutions to this backhaul bottleneck problem.

The introduction of the femtocell offers a cost-effective solution to this problem. A femtocell is a low-power and low-cost base station overlaid on the existing cellular network [7]. It is normally installed indoors, connected to the broadband service modem in a manner similar to WiFi access points, to provide a high-speed data connection to subscribers within a small range. Due to spatial reuse of the wireless spectrum, the usage of femtocells provides a significant gain in capacity (throughput per unit area). As a result, subscribers are able to enjoy faster speeds and longer battery lives due to the shortened distance between the wireless transmitter and the receiver. A femtocell is connected to the customer's broadband wireline network provided by their Internet Service Provider (ISP), which carries the traffic that originally went on the macrocell backhaul. This relieves the heavy burden on the operators to upgrade their infrastructure. As a result of this win-win situation, market research predicts femtocell revenue growth from $13 million in 2009 to $429 million in 2012 [8].

In this paper, we propose a novel solution to the macrocell backhaul problem, named FemtoHaul, which efficiently exploits the potential of femtocells to bear the backhaul traffic, enhancing the data rates of cellular subscribers. In our solution, we propose to use any user in the range of a femtocell as a candidate to relay traffic. When mobile outdoor users are communicating with the macrocell BS, instead of fetching data through its own backhaul, the macrocell BS uses relays to obtain the data from the broadband wireline networks connected to the femtocells, which typically have more than adequate bandwidth, as shown in Figure 1. Note that the concept of relays has been accepted in standards such as IEEE 802.16j. Through analysis and simulations, we show that this solution can accommodate high data demand and a large number of users that would otherwise overload the macrocell BS. Specifically, the contribution of this paper is two-fold:

1) We design the system architecture and devise corresponding protocols that handle the signaling between different entities, as well as efficient decision making and relay choosing strategies for the macrocell BS, while considering the interference, channel allocation and handoff issues.
2) We conduct extensive simulations. The simulations demonstrate that our solution can significantly reduce the macrocell backhaul traffic while still guaranteeing a

high data rate to the subscribers.

The rest of the paper is organized as follows. Related work is described in Section II. The system architecture is introduced in Section III. System model and assumptions are presented in Section IV. Extensive simulation results are shown and discussed in Section V, followed by a discussion in Section VI. We end with conclusions in Section VII.

II. RELATED WORK

As a promising technology, the femtocell has driven several research innovations. A survey in [9] described WiMAX femtocell deployment and showed a potential 150 times capacity gain and good indoor coverage. Despite the advantages a femtocell offers, various technical challenges still remain. Interference Management is the main issue considered. Claussen [10] analyzed the feasibility of femtocells in the same frequency band as a macrocell network and showed that femtocell power control mitigates interference to other users. Choi et al. [11] studied the public access policy of the femtocell and showed that an adaptive policy which takes the instantaneous loads on the network into account can lead to improved performance. Resource management is another issue for femtocell overlay cellular network. A location-based solution for leveraging maximal spatial reuse from OFDMA-based femtocells by allowing them to reuse the macro resources is presented in [12].

None of the articles above considers the macrocell backhaul problem. To the best of our knowledge, our work offers the first solution to mitigating this problem by intelligently using femtocells to reduce the macrocell backhaul traffic load.

III. SYSTEM MODEL AND ASSUMPTIONS

In this section, we present a brief description to the channel allocation model and the access policy in this cellular overlay network, along with the assumptions we made. Note that we use the term users and cellular phones interchangeably.

A. *Channel Allocation Model*

In a cellular network with femtocells, the channel allocation policy is an open problem. Fixed allocation of channels between the macrocell BS and the femtocells leads to a waste of spectrum. On the other hand, making them share the same spectrum causes interference. In our system, we let the macrocell BS use all the frequency channels, while allowing the femtocells to reuse some of them to communicate with their associated users, as presented in [12]. This can be achieved in the future OFDMA-based standards (WiMAX, LTE), which ensure an efficient channel usage with controlled interference. Under this model, users that behave like relays can use separate channels to communicate with the macrocell BS and the femtocell.

B. *Access Policy*

Due to the low transmission power and signal penetration loss, femtocells always serve the users within only a small range, while we assume the entire region is served by the macrocell BS as shown in Figure 1. Every femtocell also has a set of registered users who can be thought of as those who own or lease the femtocell, and whose ISP is used by the femtocell as its backhaul. In our model, a femtocell gives absolute priority to traffic to/from its registered users.

In our system, we assume that each user can sense all the channels for the pilot signals sent from the macrocell BS and the femtocells, and connect to the one with the strongest pilot signal. The femtocells adopt an open access policy which allows all the users to connect to them. This avoids the "loud neighbor effect" [11], in which the strong signal from a close-by but unauthorized user of the femtocell contributes significantly to the noise environment in the neighborhood of the femtocell.

C. *Demand Model*

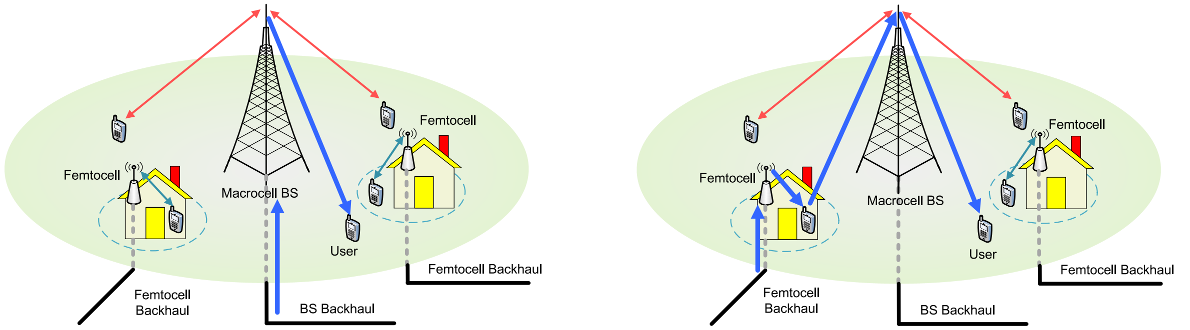
We model two typical kinds of applications in our system, voice and data services. Since voice calls are highly delay-sensitive, we let the macrocell BS serve all the voice applications, except for the registered users of the femtocells, who use femtocells for their voice applications. For data applications however, femtocells serve all demand for their associated users in their range, whether they are registered or not.

D. *System Architecture*

We consider a system that includes three kinds of entities, namely, cellular phone users, femtocells and a macrocell BS. In a normal scenario, when the users demand data, the BS serves them by fetching data using its backhaul. The principal idea we propose is to relieve the BS backhaul by redirecting traffic to femtocell backhauls using other users as relays. For example, as shown in Figure 1(b), when a user requests a file download, the BS, instead of directly fetching it from its own backhaul as in Figure 1(a), may forward the request to a femtocell through a relay user, who is associated with the femtocell. The femtocell, upon receipt of the request, fetches the requested file from its own backhaul, and sends it back through the path of the request. The process would be symmetric when the user requests a file upload instead. This way, the request from the user is served without using the BS backhaul. Note that though a normal system may use only a downlink channel from BS to download data, our scheme uses both downlink and uplink channels of the BS. This may appear wasteful, but note that we assume the system capacity to be bottlenecked by the backhaul capacity of the BS, and thus the wireless channel capacity is available to handle this additional load.

E. *Macrocell Base Station Decision Making*

The BS always maintains user association information with femtocells. All voice requests of registered users are forwarded to the femtocell whereas those of others go to the BS. During a voice call, voice packets are transmitted in both directions. When the BS receives a data request, it makes a decision whether to serve the request from its own backhaul or from the backhaul of a femtocell using an associated user as a relay.



(a) Traditional System: traffic comes from macrocell backhaul for all users outside of any femtocell range.

(b) FemtoHaul: traffic comes from femtocell backhaul, reaches the user through a relay.

Fig. 1. System Architecture: saving the macrocell backhaul bandwidth

The BS makes this decision based on its average backhaul utilization in the near past, θ and a given utilization threshold θ_0. When $\theta < \theta_0$, the BS uses its own backhaul to serve any arriving data demand. In other words, when the backhaul of the BS is sufficiently under-utilized, it fetches the data packets for the new data application request from its backhaul. On the other hand, when $\theta > \theta_0$, the BS chooses a user who is associated with a femtocell as the relay and forwards the data request through it to the femtocell. When the femtocell responds with the data packets through the relay, the BS forwards them to the requesting user. In either case, how the BS fetches the data packets it transmits to the requesting user remains transparent to the requesting user.

In order to choose a relay node, the BS maintains a list of candidate relay users ordered according to decreasing values of their fairness index f_i given by

$$f_i = u_i / r_i \tag{1}$$

for each user i. It is the ratio of a user's available uplink data rate to the BS, u_i, to its average uplink data rate usage in recent past, r_i [13]. Thus, the node with the highest fairness index $f_{max} = \max_i\{f_i\}$ sits at the top of the list. The BS chooses relays according to their order in the list as requests arrive. The intent is to choose those users who have a good uplink bandwidth to the BS, and have not been transmitting much on this link in recent past.

Whenever a relay moves out of the range of its femtocell during forwarding of data, the BS restarts the process of choosing a new substitute relay. When a new relay is found, the BS requests the corresponding femtocell only for the part of the file left to download. This way, the mobility of relay nodes does not result in any significant wastage of resources.

IV. PERFORMANCE EVALUATION

For the performance evaluation of FemtoHaul, we simulated it using the C programming language, which better allows for a flexible implementation of the relay choosing and traffic routing algorithms, compared to other simulation platforms. We simulated the generation of demand, and the transmission and reception of packets through queues maintained by various entities in the network. For performance evaluation, the BS and femtocell *backhaul supply rate* and the *average download rate* are measured and compared in various scenarios. We analyze these statistics at the end of this section.

A. Simulation Settings

1) Network Settings: In our simulation, there is only one macrocell covering the entire region, as shown in Figure 2. The macrocell is considered to be a circle with a radius of 1000 meters, with a BS located at the center. Femtocells and users are deployed randomly within the coverage area following a uniform distribution. The macrocell contains 500 users (including registered users). The macrocell downlink transmission power is set such that the received SNR at the cell edge is 6.0 dB, which is the minimum requirement for decoding data in IEEE 802.16e [14]. The femtocell transmission power is controlled as in [10], achieving a consistent femtocell range of 50 meters. Two users are registered with each femtocell, which are fixed and located within the corresponding range.

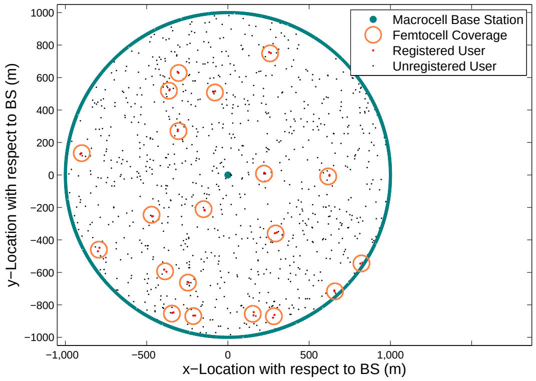


Fig. 2. The simulation area map with 20 femtocells deployed in a macrocell.

For the purposes of simulation, WiMAX (IEEE 802.16e) is adopted as the cellular standard. We simulate four channels (Ch1∼Ch4) for transmissions throughout the network, each representing a group of channels in a WiMAX OFDMA system. Ch1 and Ch3 are reserved for downlink to the users

TABLE I
SIMULATION PARAMETERS

Network Parameters
Outdoor path loss: $28 + 35\log_{10}(d)$ dB; indoor path loss: $38.5 + 20\log_{10}(d)$ dB. d is the distance from the BS in meters; Wall loss: 5 dB; Noise Power: -114.13 dB
Mobility Parameters
Random Walk Model with reflection; Users' speed: 0 to 2 m/s (random, uniform); Direction Change Periodicity: 0 to 100 sec.
Demand Generation Parameters
Packet Size: 8000 bits; Voice Call Frequency: 1 call per hour; Voice Call Duration: 3 min; Voice Data Rate: 10 kbps each way ; Average File Size: 23.6 kB; Minimum File Size: 3.6 kB (as measured from W95 traces in [15]).
Transmission Parameters
Macrocell BS backhaul bandwidth: 6 Mbps; Broadband Service Bandwidth (for femtocell connection): 10 Mbps; BS Utilization Threshold (θ_0): 80%.

whereas Ch2 and Ch4 are for uplink from the users. The BS uses all the four channels and the femtocells reuse Ch3 and Ch4. Throughput statistics are obtained by calculating the SINR of each channel for the receiver, then mapping it to the corresponding modulation/coding technique supported by WiMAX system, which gives the data rate. All user transceivers are considered half-duplex and hence cannot transmit and receive at the same time. The key simulation parameters are listed in Table I.

2) Demand Generation: We assume that the requests for data download and the voice calls arrive according to i.i.d. Poisson processes for each user and the file sizes for data download are Pareto distributed.

3) Transmission/Reception Scheduling: It is assumed that the transmissions to multiple users are scheduled in a TDMA fashion with time slot lengths of 2 ms each. For each time slot, each station (the BS and all the femtocells) schedules a user for a given channel based on the proportional fairness criterion [13], as described in Section III-E. The user with the highest ratio of available link data rate on the channel to average link data rate usage in recent past is chosen for the channel. The window size for computing the average data rate is 1 sec.

4) Packet Transmission: Every voice/data stream is implemented as a packet queue. For the backhaul transmission, a packet is transmitted only if there is sufficient bandwidth for its complete transmission in the time slot. Moreover, we suppose femtocells share the bandwidth of the broadband service they connect to, with other services like WiFi. Thus the backhaul bandwidth of the femtocell is the leftover bandwidth.

For transmission, the available bandwidth is distributed equally among the voice streams. Data streams are considered in a similar manner for the remaining bandwidth. For packet transmission on the air, since the standards allow fragmentation of packets into smaller blocks before transmission [13], in our simulation, partial transmission of a packet may occur in a time slot. The total bandwidth available for each channel in every time slot is the throughput computed as stated in Section IV-A1.

B. Simulation Results

In this section, we simulated scenarios from 0 to 35 femtocells. In stationary scenarios, all nodes are fixed. In mobile scenarios, all unregistered users are mobile and registered users are fixed. We apply the random walk mobility model with reflection at the boundary [16] to drive user movement in the simulation. The parameters for the same are shown in Table I. In order to find the capacity of the network, we set the data demand rates of the users high enough to saturate the entire system. The exception to this are registered users who have absolute priority over other users; we let them have normal demand, otherwise they will block traffic from any other user. Thus, registered users's demand data rates are set at 100 requests per hour. Every scenario is run three times and the results are their average.

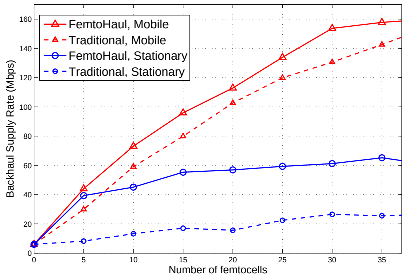
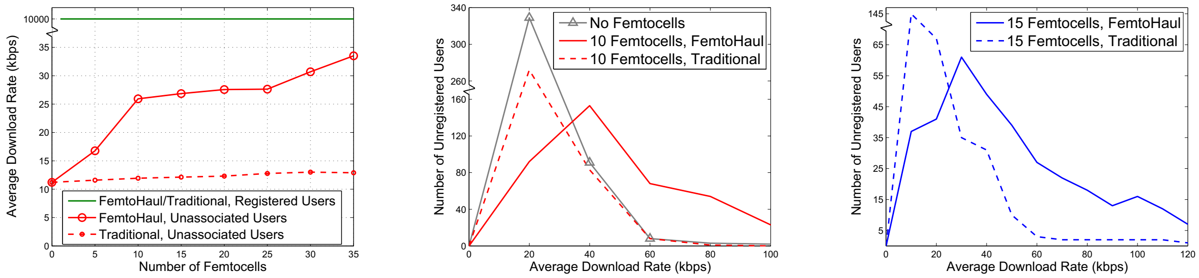


Fig. 3. Backhaul Supply Rate Comparison

1) Backhaul Supply Rate: In Figure 3, we compare the backhaul supply rates, defined as the average rate at which data is pulled from all of the backhauls in the system, in FemtoHaul and the traditional scheme.

We can see that when femtocells are first introduced in the network, there is a surge in the backhaul supply rate. For example, in the stationary scenario, when there are no femtocells in the system, the total data coming from the backhauls is only 6 Mbps. However, introduction of 5 femtocells in the system increases the backhaul supply rate to 8.2 Mbps. This results from the users associated with femtocells downloading files from the femtocell backhaul, rather than the BS. Moreover, FemtoHaul exploits the potential of femtocells further by using relays, which direct more traffic to the cheaper femtocell backhauls. In the same scenario with 5 femtocells, the backhaul supply rate increases from 8.2 Mbps to 39.3 Mbps due to usage of relays. The macrocell backhaul bandwidth shortage is thus relieved to a large extent. The same phenomenon can be observed in the mobile scenario. For instance, the backhaul supply rate increases from 130.6 Mbps to 153.7 Mbps in a 30 femtocells scenario, when FemtoHaul is applied. Note that the additional backhaul supply rate is delivered to the users that are otherwise underserved in the traditional system, i.e. those cannot connect to a femtocell directly.

2) Download Rate: Figure 4(a) shows the average download rates of the users who are not associated with any femtocell for stationary scenarios. In a traditional scheme,



(a) (b) (c)

Fig. 4. (a) Average download rates in stationary scenarios; (b) & (c) Download rate distributions in mobile scenarios for unregistered users

these users can only download files from the macrocell BS. Since the demand rates are high enough to saturate the system, congestion occurs and every user experiences a low download rate of less than 14 kbps. FemtoHaul enables such users to download files from femtocells through relays. From the figure we can see that FemtoHaul leads to higher download rates of up to 33.5 kbps for similar saturating demands. Note that because we set relatively large number of users and a high demand rate in the network, our resulting average download rates are lower than those in a typical system. However, similar benefits can be expected when FemtoHaul is applied to a typical system. Finally, as shown in Figure 4(a), the registered users always get a rate of almost 10 Mbps as they are close to the femtocell and their traffic always has absolute priority.

We now analyze the effect of FemtoHaul on download rates of users in mobile scenarios. Figures 4(b) and 4(c) show the distribution of download rates of users in systems with 0, 10 and 15 femtocells comparing the traditional system with FemtoHaul. The users in the low rate domain (0 to 100 kbps) are essentially those unregistered users who rarely associate with a femtocell during their move. As can be seen, such users in a traditional system suffer from low download rates. FemtoHaul, as is evident from the figures, benefits them by managing a much more fair rate distribution.

V. DISCUSSION

It is evident that FemtoHaul leads to substantial benefits both to the user and to the service provider. However, it is important to note that this is only a simplified version of the real systems in use. It is thus possible that allowing certain changes in the design of the system can enhance the benefits. For example, if femtocells can be designed so that they can directly transmit data to the BS, then it would no longer be necessary to use a user to relay data coming from the femtocell backhaul. This would save wireless bandwidth, avoid loss of packets due to handoffs resulting from mobile relays and consequently make the system much more robust. This would also alleviate the issue of relay users draining their batteries trying to help others.

VI. CONCLUSION

In this paper we present FemtoHaul, a novel solution that efficiently solves the macrocell backhaul bandwidth shortage problem by utilizing femtocells with user relays. We design the system architecture with open femtocell access, which takes channel allocation and interference into consideration. The user transmission scheduling and relay choosing strategies are devised. Extensive packet-level simulations demonstrate that FemtoHaul is able to accommodate high data demand and a large number of users that would otherwise saturate the macrocell BS. Moreover, the download rates for the unregistered users are improved due to the use of traffic relays, while the registered users still experience broadband data rates.

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