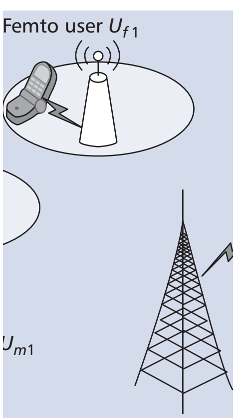
MACRO-FEMTO HETEROGENEOUS NETWORK DEPLOYMENT AND MANAGEMENT: FROM BUSINESS MODELS TO TECHNICAL SOLUTIONS

PENG LIN, JIN ZHANG, YANJIAO CHEN, AND QIAN ZHANG,
HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY



The authors discuss the business mode in macro-femto heterogeneous networks. They propose three frameworks according to the deployment types of femtocells: joint deployment, WSP deployment, and user deployment frameworks.

ABSTRACT

The femtocell technique can address the poor in-building coverage problem and increase network capacity cost efficiently. At present, some wireless service providers have launched their femtocell services, although there are still plenty of challenges unsettled. In this article we discuss the business mode in macro-femto heterogeneous networks. We propose three frameworks according to the deployment types of femtocells, which are joint deployment, WSP deployment, and user deployment frameworks. Their unique characteristics, corresponding challenges, and potential solutions are further investigated to provide deeper insight systematically. We also present two schemes for WSP revenue maximization under the WSP deployment framework. The first scheme jointly handles the interference and users' demand satisfaction via cross-tier channel allocation, and the second scheme further considers the optimal pricing selection for accessing different networks.

INTRODUCTION

Recent surveys [1] show that in-building generated phone calls and data traffic are expected to account for 50 and 70 percent of total volume, respectively, in the near future. Mobile operators should be able to support the huge indoor traffic demand to win the market share. Despite the ever growing investment in macrocell base stations (BSs), users still often suffer from low signal strength and poor service quality in indoor environments, especially under third-generation (3G) cellular networks operating in high frequency bands. The urgent task on hand for mobile operators is to provide good indoor coverage and high capacity in a cost-effective way. The femtocell technique [2] is believed to be the most promising approach to solving this problem, and has drawn great attention from manufacturers, operators, and researchers.

Femto-BSs are low-power, small-size, in-home BSs that provide wireless service to cellular users nearby. They operate in the spectrum licensed for cellular operators and connect to the local network by wired backhaul. Femto-BSs are able to provide higher capacity because their users can receive signals with higher signal-to-noise ratios due to the short transmitter-receiver distance and slight attenuation. Besides, small, densely deployed femto-BSs can create a large bundle of spectrum reuse opportunities and thus improve the overall system capacity, which is welcomed by operators. The femto-BS is similar to a WiFi access point in the sense of providing indoor coverage, but it has more advantages than WiFi. First, it does not require a dual-mode mobile device, which sells at a higher price. Second, it can provide guaranteed quality of service (QoS) using licensed band, while WiFi in the crowded unlicensed band cannot.

Because of the appealing characteristics described above, the femtocell technique has drawn great attention from many wireless service providers (WSPs). Many well-known WSPs have finished small-scale trials and formally launched their commercial femtocell services, such as Sprint's Airave, Verizon's Network Extender, and China Unicom's 3G Inn. With initial attempts emerging, there are still lots of challenges to address in both economic and technical aspects. We believe that the economic challenges, especially the business operating modes including the demands, goals, and incentives of all market participants, are the most fundamental and important. Because a perfect solution based on an unrealistic scenario will not be amenable to WSPs and users, this would contribute little to the development of the femtocell industry. Only when these issues are well defined and investigated can we further discuss the corresponding technical solutions reasonably. However, many existing works have just tried to address the detailed technical problems while spending little attention to the corresponding scenarios. As far as we know, there is no work

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that systematically analyzes the potential business frameworks of macro-femto hybrid networks.

This article discusses cross-tier (tier means the macro or femto system layer in this article) heterogeneous networks from a business mode point of view. The unique characteristics and possible solutions are discussed. We propose three frameworks for the deployment and management of macro-femto hybrid networks, which are joint deployment, WSP deployment, and user deployment, according to the ownership and operating mode of femto-BSs. Under each framework, we identify the pros and cons and the challenges from both economic and technical points of view. We also provide possible solutions to solve these challenges. Then, to give a concrete example and illustration, we propose two schemes under the WSP deployment framework, in which a WSP tries to provide better wireless access service and maximize revenue by adjusting spectrum allocation and traffic scheduling. One of the schemes adopts cross-tier channel allocation to jointly manage the interference and demand satisfaction, and the other considers the optimal pricing for accessing different networks.

The rest of the article is structured as follows. We propose three frameworks for macro-femto deployment. We propose two schemes on the WSP's revenue maximization under the WSP-deployment framework. The last section concludes the whole article.

Frameworks for Macro-Femto Network Deployment and Management

In this section, we discuss the frameworks of macro-femto heterogeneous networks by clarifying their network scenarios driven by business cases. Under each framework, the state of the art, the economic and business challenges, as well as potential solutions are further investigated.

Joint Deployment Framework

In this framework, the femto-BSs are provided by the operator, and users pay for indoor installation, either as a one-off charge or by monthly rent. Femto-BSs take some minutes to sense radio environments, localize positions, register themselves, and auto-configure the parameters for the first time, then work stably later. The WSP can be aware of the appearance of them, and set/adjust some system parameters and strategies. As the owners, users can freely move and turn on/off the femto-BSs. Apart from the hardware and new services of the femto-BSs, users also have to pay for the landline networks and consumed electronic power. The operator saves lots of money by offloading most of the capital expenditure (CAPEX) and operational expenditure (OPEX) onto users. This may explain why this framework is now adopted by most mobile operators. It can be further divided into two categories according to whether the macro users are allowed to access the nearby femto-BSs.

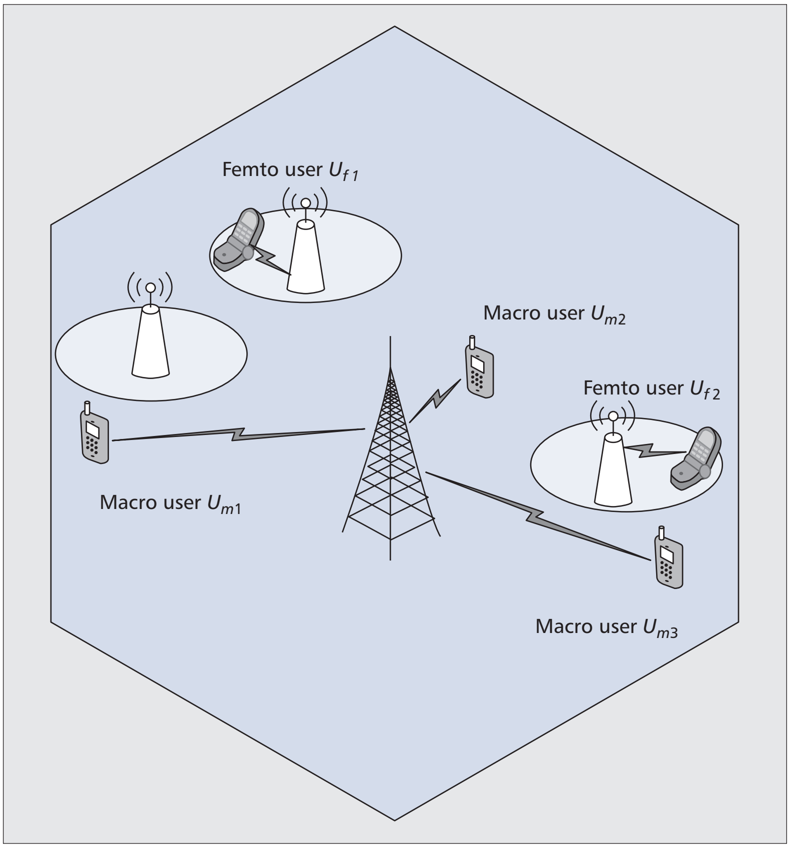

Figure 1. *Closed access mode.*

Closed Access Mode — In this mode, a femto-BS just serves its registered users, such as the owners, family members, and friends. Unregistered ones, such as U_{m1} and U_{m3} in Fig. 1, cannot access the femto-BS even if they are in close proximity. According to a survey [3], home users prefer femtocells with closed access mode. The reason is straightforward: femto users would not be pleased to share the limited capacity of femto-BSs and landline throughput with others if no incentive is provided. Most current business femtocell products support mode switch such that users can set the mode according to their wishes.

How to optimize the performance of heterogeneous networks is one of the key concerns under this mode. The major technical challenges are the spectrum allocation strategy and interference management, which are partially coupled together. Two frequently used spectrum schemes are orthogonal assignment and co-channel assignment. Orthogonal assignment, which assigns orthogonal spectrum to macro and femto systems, can completely eliminate cross-tier interference, but it limits the available spectrum for both macro and femto systems, and is thus not very efficient in spectrum reuse. How to optimally split the spectrum and manage the femto-femto interference has been studied by some works. On the contrary, co-channel assignment, which enables macro and femto systems to operate at the same frequency, is more efficient in spectrum use, but the interference is more serious. Both cross-tier and co-tier interference exists if using co-channel assignment, which makes it more difficult to analyze. Many works

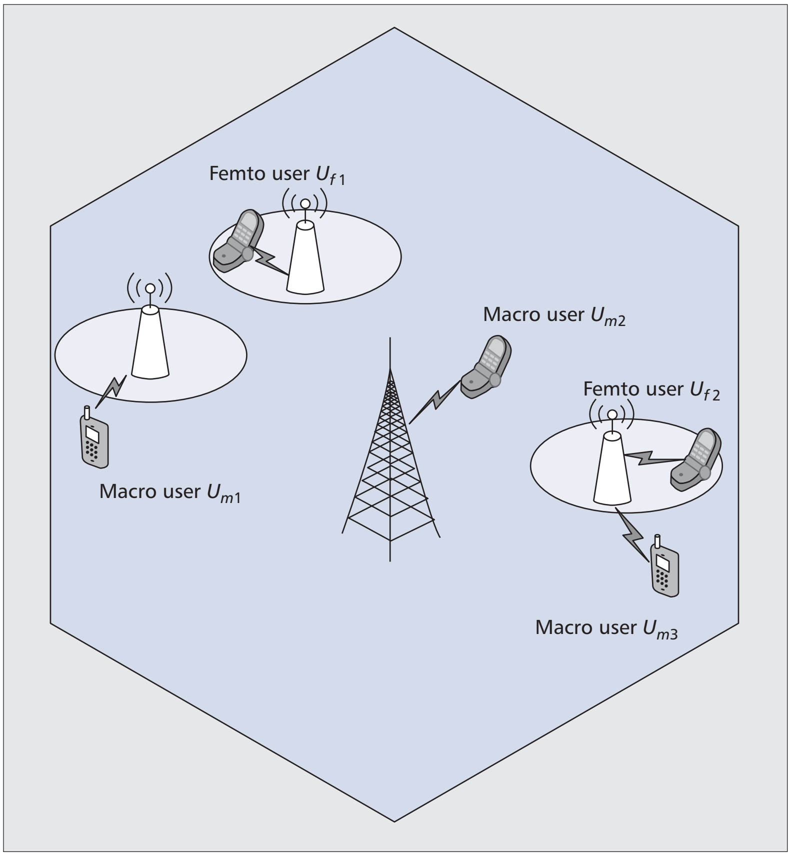

Figure 2. *Open access mode.*

have discussed the "dead zone" problem in this case. During the downlink transmission stage, macro users located at the edge of the macrocell can receive strong interference from nearby femto-BSs. During uplink transmission, the situation reverses, and femto users receive excessive interference from macro users. Users such as U_{m3} and U_{f2} in Fig. 1 will repeatedly experience poor signal-to-interference-plus-noise ratio (SINR) in the signal dead zones. There are not yet satisfying conclusions on the choice, such as the optimal performance of two assignments and the influences of different conditions.

Traditional solutions on spectrum assignment and interference management techniques can also work. The distinguishing points for macro-femto hybrid networks are the two-tier structure and the different physical characteristics, such as dense deployment, smaller power of femto-BSs, and the strong signal fading environment. These do not exist in traditional cellular networks or wireless local area networks. The WSP has to jointly consider the two tiers' performance and interactions, which adds to the difficulty.

Open Access Mode — As a potential solution to the dead zone problem, open access mode has drawn much attention. In open access mode, femto-BSs can serve nearby macro users rather than users on white lists only. As shown in Fig. 2, U_{m1} and U_{m3} are allowed to access nearby femto-BSs in this mode. Research studies reveal that the open access mode is more efficient in improving system capacity because short-distance femto transmissions take place of long-distance macro ones, which experience serious path losses. It can also ease the burden of macro-BSs and save resources for femto-BSs. The dead zone problem can also be avoided.

The first and most important challenge here is how to motivate the holders to open their femto-BSs. It is the indoor users who pay for everything: hardware, landline, monthly plan, and electronic power. They are not willing to make free offers to help the operator increase its benefit. A counter example is Verizon's Network Extender. Its femtocell service has drawn fire since the very beginning. One of the reasons is that the expensive Extender does not support closed access mode. Thus, passing Verizon users may freely access the Extenders and pay Verizon, while the owners of the Extenders get no allowance.

To motivate the openness of femto-BSs, WSPs should surrender enough profit, and users should respond based on overall consideration. In fact, a WSP can provide incentive for owners to open their femto-BSs in various forms of subsidization. It can provide plenty of choices, such as cash back or a special femto-zone tariff. By weighing the gains from improved capacity and losses from subsidization, it can achieve optimality. A femto user's considerations may include its own demand, the attractiveness of the allowance, and the demand from nearby macro users. It may have different degrees of concerns about its demand satisfaction and the allowance. It may also have to compete with other femto users for the allowance, as it may not be the only one who can help. In all, both the operator and the users have to trade off the gains and losses. Suitable game and auction models may provide some deep insight into the scenario.

WSP Deployment Framework

Another possible framework is that the WSP deploys femto-BSs without asking users to pay for femto-BSs. In this way, the WSP could control the whole system in a centralized method to optimize overall performance. The users just pay for the electronic power and at most additional landline throughput while they get enhanced indoor signal qualities and some subsidizations. As users cannot freely change the femto-BSs' setup, the dynamics due to movement and on-off of femto-BSs can be eliminated. Deployment can also be carefully planned.

This business mode is quite exciting and regarded as a successful business possibility. The advantages of this mode are achieved from both technical and economic aspects. From the technical aspect, the randomness of mobile networks is reduced. All the resources (spectrum, femto-BSs, and backhauls) are owned by the same WSP, which makes elaborate system scheduling easier. From the economic aspect, free installation of femto-BSs is quite attractive to customers and competitive against opponents. It goes without saying that the WSP should take its responsibility to provide better indoor service rather than pass the buck to home users. Japan's operator Softbank Mobile launched its 3G service in this mode. It provides a free asymmetric digital subscriber line (ADSL) plus femto-BS deal to home and small business customers. The users pay for mobile calls as usual and additional electronic fees, but the signal quality and coverage can be significantly improved.

The technical challenge in this case is how to optimize the network performance. This is distinguished from the optimization problem in the joint deployment/closed access framework in the following ways. First, its dynamic factors in hybrid networks have been reduced to some extent, including the movement and on-off of the femto-BSs. Second, under the open access assumption, users have more choices for subscribing femto-BSs. It is possible to jointly schedule the additional subscription problem with other problems to achieve better system performance. It is also different from the challenges in the joint deployment/open access framework because one has to provide incentive for opening the femto-BSs and the other does not. The overall performance of an optimization is usually considerably better than that of a game where the participants are selfish.

Some work has focused on this scenario. V. Chandrasekhar *et al.* [4] conducted an uplink capacity analysis and gave an interference avoidance strategy under the stochastic deployment assumption. However, their scheme did not guarantee optimal system performance. N. Shetty *et al.* [5] proposed an economic framework to maximize the operator's revenue. However, they considered simple cases and adopted some unrealistic assumptions such as linear distributed capacity. We look into this scenario and propose two schemes for revenue maximization of the WSP, introduced briefly later.

USER DEPLOYMENT FRAMEWORK

Under this category, home users deploy femto-BSs for their own self-interests. The femto-BSs are in closed access mode, as there is usually no incentive to share the femto-BSs. These femto-BSs are obtained without registration on the WSPs. If they work on the licensed band, they are secondary in priority as they have to avoid causing harmful interference to primary macrocell users and vacate channel resources if necessary. The femto-BSs deployed in a plug-and-play way are quite flexible but in an unplanned manner. The disorder exists in two aspects. First, the femto-BSs do not have a common interest. They compete for available spectrum resource and generate co-channel interference to others nearby. Second, they lack thorough planning and fair coordination from the methodology aspect. These two factors mean that optimality of the system performance is not achievable.

Most current works study the best strategies of the femto-BSs under this scenario. Typical cognitive techniques, such as power control, are adopted to manage interference and maximize the individual's utility. H. Jo *et al.* [6] addressed open and closed loop interference mitigation strategies for femto users. V. Chandrasekhar *et al.* [7] modeled the femto users' power control problem as a non-cooperative game and provided a distributed utility-based SINR adaptation method. The existence and uniqueness of the Nash equilibrium were derived in their model. J. Yun *et al.* [8] proposed CTRL, a distributed and self-organizing femtocell architecture to manage the femto-macro interference. CTRL was designed to be compatible with the legacy macrocell system. All their results verified the protection of the macro users' transmissions, but unsurprisingly none could guarantee the performance of femto users.

However, we argue that this framework may not be as promising as the previous two even though much work has been conducted on it. It may be adopted to complement the other modes for unguaranteed services. The major reason is that these femto-BSs do not work on their dedicated spectrum. If they work on 2G/3G licensed band, even though the cognitive functionalities are executed, interference to the primary system cannot be eliminated completely. Hence, the licensed system will not allow them to access it. Otherwise, they work on other licensed or unlicensed bands, which needs dual-mode modules in the devices and makes the femtocell not as competitive with WiFi. Furthermore, neither being secondary in the licensed band nor sharing the unlicensed band can provide guaranteed QoS.

So far we have proposed and discussed three frameworks for macro-femto heterogeneous networks. Some works have discussed the potential problems within the three frameworks, most focused on the third. We elaborate on the second framework and propose two revenue maximization schemes in the next section.

To motivate the openness of femto-BSs, the WSP should surrender enough profit and the users should respond based on overall consideration. In fact, the WSP can provide incentive for the owners to open their femto-BSs in various forms of subsidizations.

REVENUE MAXIMIZATION WITH WSP-DEPLOYED FEMTO-BSS

In this section, we propose two schemes to maximize a WSP's revenue under the WSP deployment framework. In the first scheme, we adopt cross-tier channel allocation to jointly manage the interference and provide service, and then achieve the optimal revenue. We give a centralized algorithm for a small system to approach optimality and a distributed algorithm for a large system to obtain a near-optimal result with constant gap. In the second scheme, optimal pricing and spectrum scheduling are combined to maximize revenue.

ON CROSS-TIER CHANNEL ALLOCATION

Network Scenario and System Model —Consider a single macrocellular orthogonal frequency-division multple access (OFDMA) network with a central macro-BS, N_f femto-BSs, and N_u subscribing users. Let P_m and P_f be fixed macro and femto access prices per throughput unit. The WSP does channel allocation of the time-frequency blocks such that its aggregate revenue from macro and femto access is maximized. We assume the femto-BSs are open access. The users choose to access the femto-BS or macro-BS that provides the highest received SINR. All femto-BSs operate on their own licensed bands with fixed power levels such that external noise can be avoided.

We adopt the continuous time usage interference graph to model the potential contention of the nodes. The interference constraints eliminate cross-tier interference and alleviate co-channel femto-femto interference. The service provision constraints guarantee that the total resources consumed by users subscribing to the same BS do not exceed the amount allocated to the BS.

The WSP aims to maximize its revenue achieved from macrocell and femtocell service under the above-mentioned constraints. Assume that user U_i requires a throughput demand of d_i. It will only pay for the demand within d_i, without paying for additional throughput that exceeds d_i. The WSP can charge it $P \min\{t_i, d_i\}$, where t_i is provided throughput and P is P_f or P_m, depending on its subscribing BS. The objective function that needs to be maximized under the two types of constraints is $P_m \Sigma_{macro\ U_i} \min\{t_i, d_i\} + P_f \Sigma_{femto\ U_i} \min\{t_i, d_i\}$.

Centralized and Distributed Algorithms — The above problem is convex optimization and thus can be solved by existing optimization technique. We refer to this algorithm as the centralized method (CM). In this way, the nodes should pass their parameters to a central node where the computation is executed. The results are then returned to the nodes. The CM algorithm can efficiently find the optimal results at low communication and computational cost when the system scale is not very large. When there are a great many users in the macrocell, it can be impractical as the computational cost increases rapidly.

The Lagrangian decomposition based distributed algorithm, LD, generates a sub-problem for each BS; thus, the computational cost is divided among all nodes, and there is no need for a central node. First, we have to transform the original objective function to be strictly concave by adding auxiliary terms. Then we put the interference constraints into its Lagrangian formation. Next, decouple the problem such that the terms with variables on the same BS are collected together. Each node can optimize its sub-problem in parallel and keep the coupling Lagrange multipliers consistent with the neighbors. The algorithm is given here (Algorithm 1).

The distributed algorithm LD reduces the computational overhead on a signal BS while possibly increasing the communication cost. In making a detailed comparison, we find that LD is preferable when there are numerous femto-accessing users as the communication cost may not increase too much and the computational cost on signal BS is significantly reduced. The CM is suitable for small systems.

```
t ← 0
repeat
    Femto-BSs and macro-BS compute the results by solving its sub-problem.
    Every femto-BS sends its current channel usage and estimated utility to
      all nearby femto-BSs and macro-BS. They receive the neighbors' messages.
    The macro-BS gathers the information to compute the new auxiliary
      terms. It sends its channel usage and auxiliary terms to all femto-BSs.
    Each BS updates its Lagrange multipliers.
    t ← t + 1
until the optimal results of all BSs are changed by no more than predefined
  threshold.
The BSs unify the channel usage to strictly obey the interference
  constraints. The correction of the optimal value by auxiliary terms is
  conducted.
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Algorithm 1. *Distributed algorithm based on Lagrangian decomposition.*

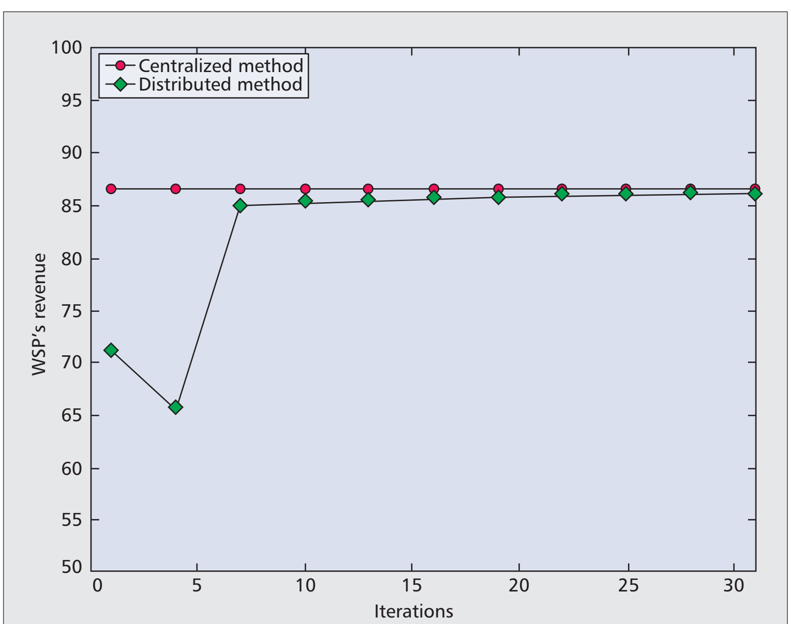

Figure 3. *Convergence of the distributed algorithms.*

Evaluation — We conduct simulations to verify the performance of the two algorithms and the advantages of hybrid macro-femto networks. We assume each femto BS has to serve an indoor user. All other users are randomly located in the macrocell.

Figure 3 verifies that the distributed algorithm works well. The convergence is fast, and the gap to optimal value can be limited by less than 1 percent.

We compare our scheme with some baseline schemes, which include fixed allocation and no femto-BSs scheduling. In the fixed allocation, the macro-accessing and femto-accessing are pre-allocated ω and $1 - \omega$ portion of spectrum respectively. The intra-macro and intra-femto allocations adopt the similar optimization method. In the traditional scenario without femto- BSs, macro-BS uses all the spectrum to serve users. Figure 4 shows our scheme always achieves the highest system revenue. If there are enough femto-BSs and indoor users, the allocations involving femto-BSs are definitely better than macro-allocation only. It also reveals that some of the fixed allocation schemes may perform as better as our scheme if the WSP happens to guess the optimal division of spectrum for the two services.

On Optimal Pricing and Spectrum Partition

Network Scenario and System Model — Consider the same two-tier networks. The WSP offers macrocell and femtocell services with prices P_m and P_f per unit of capacity, respectively. The WSP sets its ultimate goal as maximizing its profit M via price selection and spectrum allocation.

Once the prices and spectrum distribution are determined, users make their decision in order to optimize their utility. Users always prefer high capacity and low price. Therefore, the utility of each user can be defined as achievable benefit from capacity minus the payment for the service. Given the capacity and price, users compare the utility they can obtain from femtocell and macrocell service, and choose the one that generates the higher utility if the utility exceeds a certain threshold.

Apart from price, spectrum allocation also exerts an influence on users' determination through capacity. The WSP owns a fixed amount of spectrum resource to distribute between macrocell and femtocell. We presume that the WSP acquires an orthogonal spectrum scheme. All the femto-BSs share the same frequency, utilizing integrated channel allocation to avoid femto-femto interference. We assume that a femtocell acquires fixed channel allocation by partitioning the total spectrum into several equivalent sub-spectra for exclusive usage in each cell so that any femto-BSs that reuse the same sub-spectrum are far enough apart to be prevented from femto-femto interference.

Here we define capacity as the information rate that can be achieved. Users adopt time-division multiple access (TDMA) to transmit information. We restrict our attention to downlink transmission analysis only. A similar analysis for the uplink may be performed.

Revenue Maximization — The revenue of a WSP can be derived as the sum of money it collects from macrocell and femtocell services. We assume that macro and femto capacity independently follow exponential distribution, and the expectation of the capacity is proportional to the employed spectrum and inversely proportional to the user density. Assume the femtocell capacity is also proportional to the number of femto-BSs but inversely proportional to the spectrum reuse factor.

The expected gross capacity for each service is obtained by adding together the capacity of every user who acquires that service. In case of a certain spectrum allocation, it is the adjustment of prices that leads to different choices of service, the expectation of total capacity, and the revenue M. Calculate the first order partial derivative of M in respect to the price and assign it to be 0; we can get optimal prices for macrocell and femtocell services Then, we can obtain the maximum revenue with reference to spectrum allocation. By running through all the possible values of spectrum allocation ratio from 0.01 to 0.99, the optimal one that delivers the maximum revenue can be revealed.

Evaluation — We compare our Joint Price and Spectrum Allocation (JPSA) scheme with the Fixed Spectrum Allocation (FSA) scheme. Figure 5 shows that when the number of femto-BSs is around 33, JPSA outperforms FSA by approximately 1.25–13 times under different fixed spectrum distribution ratios. In JPSA, the maximum revenue keeps augmenting with the increase of femto-BSs. One of the reasons is that the potential of spectrum spatial reuse is well exploited by femtocells. In consequence, there is a strong economic incentive for the WSP to promote femtocell service.

Figure 6 displays the optimal prices for macrocell and femtocell service, respectively. On one hand, the price of macrocell service keeps going up because it can render higher capacity thanks to more spectrum being assigned to macrocell service. On the other hand, although there are more and more femto-BSs, the spectrum distributed to femtocells keeps diminishing. So the price of femtocell service is rather stable. Figure 6 also implies that femtocell service tends to charge lower prices than macrocell service in all situations, which strongly motivates users to acquire femtocell service and contributes to the femtocell technology boom.

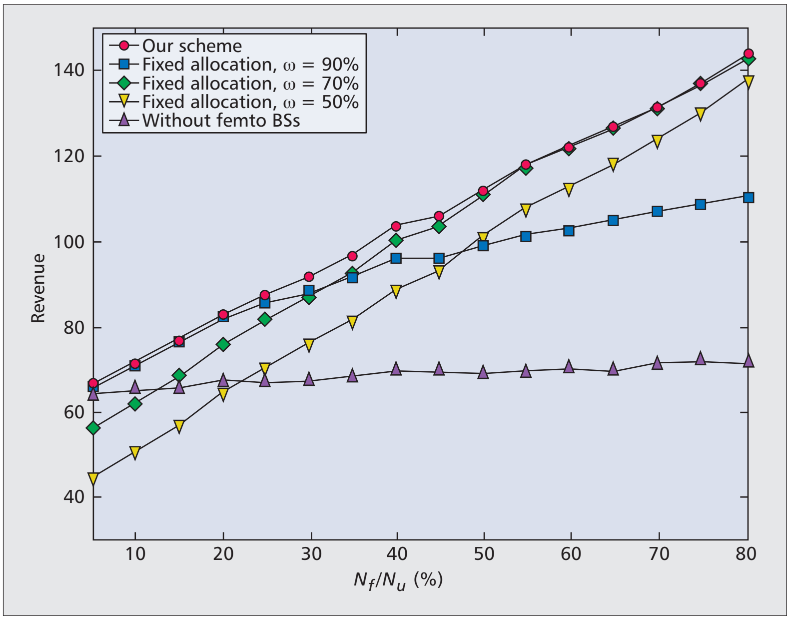

Figure 4. *Performance comparison with other schemes.*

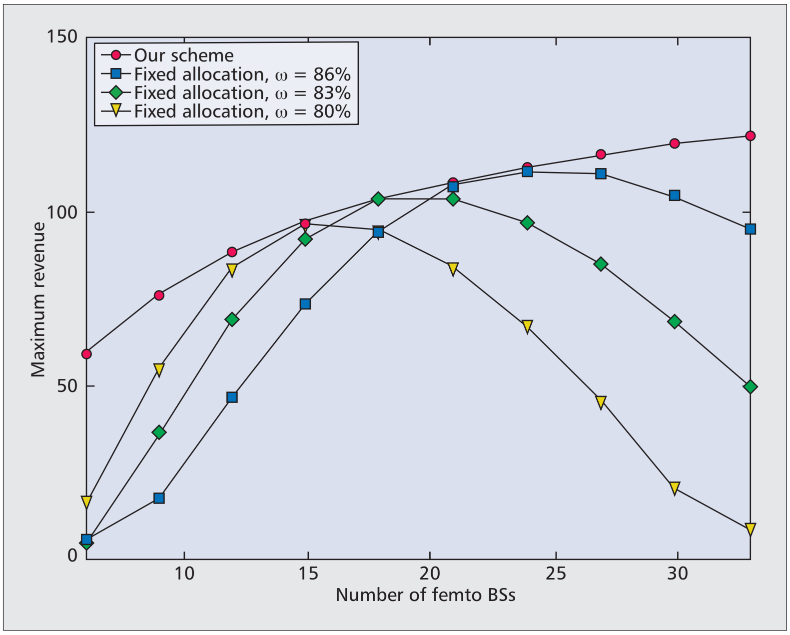

Figure 5. *WSP's revenue vs. number of femto-BSs.*

CONCLUSION

In this article, we have discussed the deployment and management issues of femtocells in two-tier macro-femto networks. We have proposed three potential frameworks from the business mode point of view: joint deployment, WSP deployment, and user deployment. The corresponding unique-

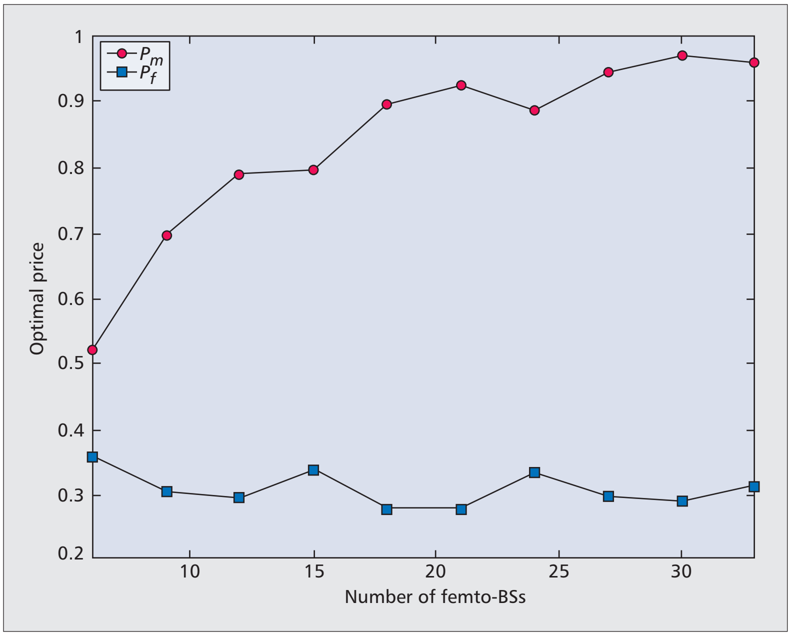

Figure 6. *Optimal price vs. number of femto-BSs.*

ness, challenges, and possible solutions have been analyzed. Furthermore, we present two schemes under the WSP deployment framework. The two schemes focus on how to maximize the WSP's total revenue in the macro-femto networks. One adopts the cross-tier channel allocation to jointly handle interference and demand satisfaction. The other further considers the optimal pricing for accessing different tier networks. While most of the existing work focuses on the technical perspective of macro-femto networks, we believe that paying more attention to the business model, combining both economical and technical perspectives, will be more valuable to operators and users.

Acknowledgment

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Biographies

Peng Lin received his B.E. degree of computer science and technology at Tsinghua University in 2008. He is currently a Ph.D. student at Hong Kong University of Science and Technology. His research interests include dynamic spectrum management and the spectrum market.

Jin Zhang [M'09] is currently a research assistant professor in the Department of Computer Science and Engineering at Hong Kong University of Science and Technology. She received her Ph.D. degree in computer science and engineering from Hong Kong University of Science and Technology in 2009. Before her Ph.D. career, she received B.S. and M.S. degrees from the Department of Electronic Engineering at Tsinghua University, Beijing, China, in 2004 and 2006, respectively. Her research interests include cooperative communication and networks, network coding, cognitive radio networking, and heterogeneous networks.

Yanjiao Chen received her B.E. degree in electronic engineering from Tsinghua University in 2010. She is currently a Ph.D. student at Hong Kong University of Science and Technology. Her research interests include spectrum management for cognitive-radio-based femtocell networks.

Qian Zhang [M'00, SM'04] joined Hong Kong University of Science and Technology in September 2005 as an associate professor. Before that, she was with Microsoft Research Asia, Beijing, from July 1999, where she was research manager of the Wireless and Networking Group. She has published about 200 refereed papers in international leading journals and key conferences in the areas of wireless/Internet multimedia networking, wireless communications and networking, wireless sensor networks, and overlay networking. She has received the TR 100 world's top young innovator award. She also received the Best Asia Pacific Young Researcher Award from the IEEE Communications Society in 2004. She received the Best Paper Award from the Multimedia Technical Committee (MMTC) of IEEE ComSoc in 2005, and Best Paper Awards at QShine 2006, IEEE GLOBECOM 2007, IEEE ICDCS 2008, and IEEE ICC 2010. She received her B.S., M.S., and Ph.D. degrees from Wuhan University, China, in 1994, 1996, and 1999, respectively, all in computer science.