UAV-Assisted Dynamic Coverage in a Heterogeneous Cellular System

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Abstract

The growing popularity of mobile Internet and massive MTC with special traffic characteristics and locations have imposed huge challenges to current cellular networks. Deploying new base stations, however, becomes difficult and expensive, especially for complicated urban scenarios and MTC traffic. The UAV-assisted heterogeneous cellular solution is proposed in this article. It utilizes UAV-based floating relay (FR) to deploy FR cells inside the macrocell, and thus achieves dynamic and adaptive coverage. Comprehensive analyses on FR cells' deployment including frequency reuse, interference, backhaul resource allocation, and coverage are given.

Introduction

In the past decades, wireless cellular systems have been prosperous in both urban and remote areas. The latest standards, such as Long Term Evolution (LTE) and LTE-Advanced (LTE-A), have provided high data rate services on the air interface and guaranteed the quality of service (QoS) for each user at the same time. However, due to the rapid development of mobile Internet (MI) and the Internet of Things (IoT), the volume and characteristics of traffic carried by the wireless links have changed dramatically and have led to congestion.

Exchanging multimedia information by handheld devices significantly increases the traffic volume in both the uplink and downlink, challenging the existing cellular system. The situation can be even worse with a large number of machine type communication (MTC) devices reporting data simultaneously.

According to Technical Report 36.888 of the Third Generation Partnership Project (3GPP), the locations of MTC devices are different from those of traditional handsets. They are usually deployed in basements, substation boxes, and all kinds of pipelines. The existing cellular coverage was designed for human active areas, and thus the MTC devices may experience more severe shadowing and penetration loss. The majority of MTC devices are sensing- and monitoring-based. Due to the uplink dominated traffic type, extra transmission energy needs to be consumed in these worse channel conditions. This results in less endurance of the battery, conflicting with the requirement of 5–10-year battery life for many MTC devices.

New base stations (BSs)/relays are required to mitigate the capacity shortage of existing cells and enhance the coverage for MTC devices. However, deploying new BSs has become increasingly difficult and costly, especially in complicated urban scenarios [1]. The optimal location of a new BS to cover the users in upper floors of skyscrapers may be in mid-air. Besides, people have more health concerns when deploying a new BS near them [2]. Most MTC traffic is bursty, and MTC devices tend to have synchronized behaviors. When an unusually high number of devices are triggered to report sensing data or events simultaneously, they can overload the BS in a short period, and the QoS, especially the latency requirement, cannot be guaranteed during this period. It may not be profitable to deploy new BSs to solve this problem. Given the bursty traffic, the overload situation will disappear soon, and newly deployed BSs with fixed coverage may be left idle most of the time.

The technologies of unmanned aerial vehicle (UAV) have become mature in recent years. They are light and flexible and have a longer battery life [3]. A UAV, such as a commercial-level quadcopter, has entered the daily lives of the public for years, which results in large production scale and reduced cost. In most current applications, a camera or sensor node is carried by the UAV. The urgency of the increasing volume of MI traffic and extreme channels of the MTC devices, as well as the problems of deploying traditional BSs mentioned above, motivate us to investigate the possibility of introducing the UAV-based floating relay (FR) in the cellular system.

Some existing works have already employed the UAV in wireless communication systems, mainly wireless sensor networks (WSNs) [4–6]. Some specific outcomes could be applied in the cellular network, such as the positioning problem analyzed in [7,8], the optimal multihop path obtained in [9], and the optimized topology of UAVs in [10]. But many practical issues, such as frequency reuse, inter-cell interference, backhaul, and traffic model in the cellular system, need to be further investigated. Reference [11] showed the throughput improvement of a few simple cases of using FR in the cellular system. In [12], UAV was applied for public safety communications (PSC) in the cellular system. However, the full coordination between the macro BS and the FR remains unsolved. A neural-based cost function was formulated and then minimized in [13] to find out the optimal mapping scheme from UAVs to demand areas. More comprehensive interference models other than the mutual interference between UAVs and the analyses on resource allocation for UAVs' backhauls are still open issues.

In this article, we propose the UAV-assisted base station (UABS) to solve the problems brought about by the increasing traffic volume of MI and by serving MTC devices with special traffic characteristics and locations. It enables heterogeneous deployment inside the macrocell

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and achieves dynamic and adaptive coverage. Key issues related to the deployment of FR cells including frequency reuse, interference, backhaul resource allocation, and coverage are analyzed comprehensively.

UAV-Assisted Base Station

The UABS is a BS centralized controlled system, where the coverage can be dynamically adjusted leveraging the mobility of UAV-based FR. The BS monitors the traffic within the macrocell and sends out one or more FRs when needed, as shown in Fig. 1.

The macro BS monitors the buffer status of each user and the contentions on the Physical Random Access Channel (PRACH) to determine the timing of sending out the FRs. Suggested coverages of FR cells can be made based on the real-time users' locations and the statistic history record. In addition, most of the MTC devices have predefined transmission schedules and fixed locations, so the FRs can be placed beforehand. When an FR cell is no longer needed, it will be recalled by the macro BS. There is a small garage on the BS tower for FRs to park. Their batteries will be recharged when entering the garage.

The monitoring and information collecting functions are available in current LTE/LTE-A BSs. Three additional updates are needed to deploy a UABS:

1. The algorithm for the macro BS to determine the optimal deployment of the FR cells
2. A separated control plane (CP) protocol between the macro BS and the FR, which enables the control of the FR's behavior and collects possible feedback from the FR
3. The parking garage with a recharging function for the FRs

Among the required updates above, update 3 is hardware-related. It can be implemented by non-contact recharging. It is out of the scope of this article. Updates 1 and 2 are software-related. For the new CP protocol mentioned in update 2, there are lots of existing mechanisms, such as adding a new layer on top of the radio access network (RAN) protocol stack. The control information for the FR will be piggybacked onto the radio resource control (RRC) messages, similar to the transmission of the non-access stratum (NAS) signaling in LTE/LTE-A. An alternative approach is to enhance the existing RAN protocol, such as adding new information elements (IEs) in an RRC message or medium access control (MAC) headers. The detailed contents of the control information should be related to the UAV movement and is not examined in this article.

We assume that update 2 has been implemented, and the FR can fly anywhere according to the macro BS's order. In this article, we focus on the issues related to update 1, including frequency reuse, interference, backhaul resource allocation, and coverage.

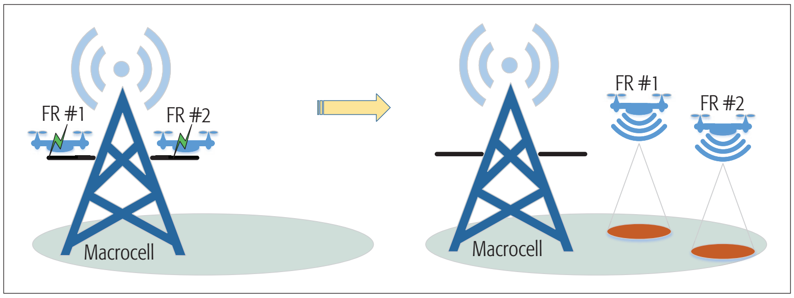

FIGURE 1. The basic concept of the UABS.

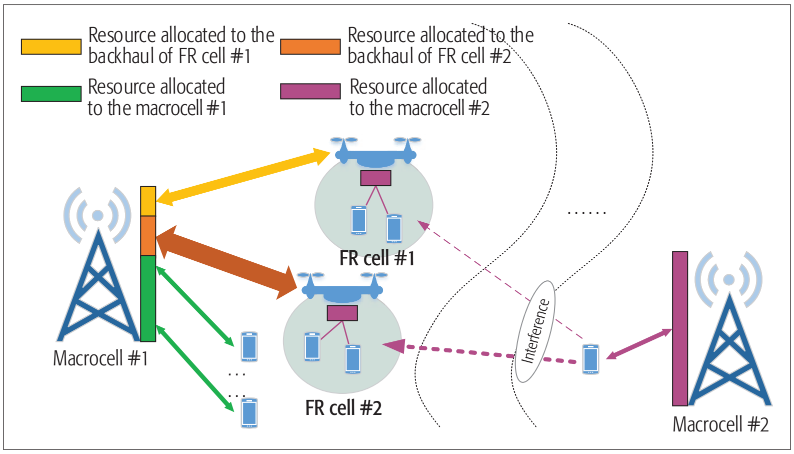

FIGURE 2. Frequency allocation for the FR cells and corresponding interference.

Frequency Reuse and Interference

Within the coverage of a UABS, FR cells reuse the uplink frequency bands used by other macrocells. We assume that the adjacent macrocells use different frequency bands, and a certain reuse distance should be maintained by the topology. The transmissions inside an FR cell can reuse the mechanism of device-to-device (D2D) communication, which has been used for many purposes in heterogeneous networks, such as load balancing [14] and improving the connectivity to the Internet [15].

An example of frequency reuse and corresponding interference is illustrated in Fig. 2, where FR cells #1 and #2 are controlled by macrocell #1 and reuse the uplink frequency of macrocell #2. Three types of interference are generated in such situations, as discussed below.

The Interference from the FR Cells to the Macrocells

The signal transmitted inside an FR cell can be received by other macro BSs (e.g., macrocell #2 in Fig. 2). At the macro BS side, the uplink signal from a macro user may be interfered by the transmissions in the FR cells using the same time-frequency resource.

FR cells are similar to or even smaller than small cells. It can fly along a series of dense traffic areas and even proactively approach a specific user with very bad channel condition, rather than increase the transmission power. This strategy is especially suitable for the MTC scenario. Therefore, the transmission power used in an FR cell will be maintained at a very low level. If the topology has guaranteed sufficient reuse distance, this type of interference can be negligible in practice.

The Mutual Interference between the FR Cells

If multiple FR cells are close to each other and use the same frequency, mutual interference will be generated. One effective way to avoid this type of interference is to let different FR cells use different frequency bands. An example is illustrated in Fig. 3a, where the reuse factor equals 1/7.

In this case, one single macrocell, the one using

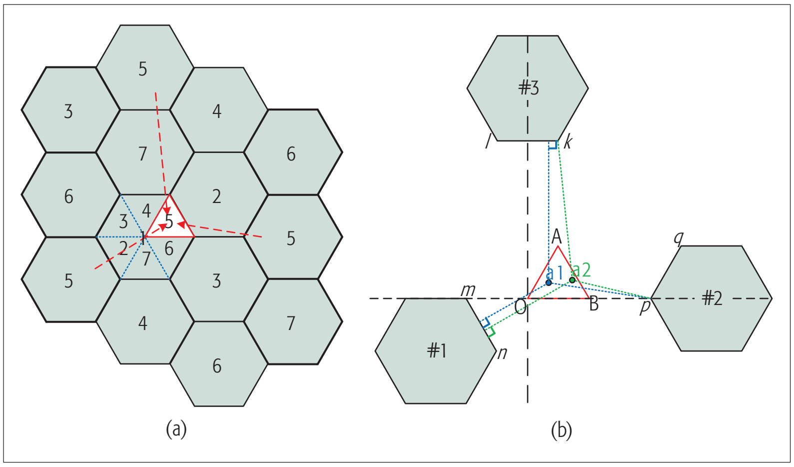

FIGURE 3. An example of the frequency allocation and the topology of interference.

frequency band #1 in Fig. 3a, is divided into six frequency-reusing areas. The six reusing areas use six different frequency bands, #2–#7, which are used by adjacent macrocells. Given that any two of the reusing areas will apply different frequencies, if at most one FR is deployed in each reusing area, the mutual interference can be largely eliminated. Alternatively, one single frequency band could be divided into several sub-bands for multiple FR cells in the same frequency-reusing area, by which their mutual interference is eliminated.

Another approach is to allow the interference within a given threshold by adjusting the transmission power of each FR cell to achieve an acceptable signal-to-interference-plus-noise ratio (SINR).

The Interference from the Macrocells to the FR Cells

As shown in Fig. 3a, the FR cells can also be interfered by uplink transmissions initiated by macro users in nearby macrocells. Most of the macro users at the cell edge apply a larger transmission power to overcome the path loss of a long transmission distance, which results in higher interference to the FR cells. Considering the relatively low transmission power inside the FR cells, the SINR will be largely degraded.

Therefore, among the three types of interference, the one from the macrocells to the FR cells is the most critical and cannot be ignored. The best time and location for FR deployment, and the arrangement of the frequency-reusing areas highly depend on the modeling of this interference. We use the topology shown in Fig. 3a to build the model.

We focus on the area reusing frequency band #5, as shown in Fig. 3b. The result can be applied to other areas. We consider the worst case in this model, where there is always a macro user transmitting at the same time-frequency resource in each of the three closest macrocells. Furthermore, given any point inside the triangle ΔOAB, the shortest distances from it to the three interfering macrocells are applied.

Point O is put on the origin of a rectangular coordinate system, and the edge $\overline{OB}$ is on the x axis. For a point $\boldsymbol{a}$ inside ΔOAB, the shortest distances to macrocells #1 and #2 are always equal to the perpendicular distance to edge $\overline{mn}$ and the distance to point p, respectively. The shortest distance to macrocell #3 can be either the distance to $\overline{lk}$ or that to k, depending on the location of point $\boldsymbol{a}$, as illustrated by $\boldsymbol{a1}$ and $\boldsymbol{a2}$ in Fig. 3b. These distances are easy to calculate based on geometry.

We assume that the received power is only determined by the path loss, which is a function of the distance. Given the transmission power of the macro users, the interference from one macrocell can be obtained. The interference power from the three nearest macrocells accumulate on the air interface, and thus we can have the total interference I.

In practice, this model of the worst case can be applied when there is no information on the interference available at the macro BS side. After sending out the FRs several times, the interference level at a specific time and place can be measured by the FRs and reported to the BS, according to which a statistical interference map can be built and maintained. Then more precise deployment of the FR cells is feasible. Furthermore, if the resource scheduling decisions can be shared among adjacent macrocells, the interference will be significantly reduced by utilizing the unoccupied time-frequency resources of the neighbor macrocells for FR cells.

The unlicensed bands can be used for FR cells. In that case, the mutual interference between the macrocells and the FR cells is simplified. The QoS in unlicensed bands cannot be guaranteed, so the cellular system can utilize the unlicensed bands as a complementary solution but cannot fully rely on them for serving users.

Backhaul

A certain amount of time-frequency resources should be assigned for the FRs' wireless backhauls (FR backhauls) by the macro BS, as illustrated in Fig. 2. The macro BS needs to make a trade-off between the service quality of the FR cells and that of other macro users. Several candidate methods of resource allocation for FR backhauls are analyzed as follows.

Minimum Fixed Bandwidth for the FR Backhaul

Allocating a fixed bandwidth for the FR backhaul is the simplest way and easy for management. The bandwidth can be predefined or broadcasted to all the FR cells, and the position of each FR backhaul in the frequency domain can be inferred by an FR cell's identity or other unique information. Once an FR backhaul is established, it will be maintained and kept unchanged until the FR is called back. The semi-persistent scheduling (SPS) in LTE can be further applied in the FR backhauls where resource block (RB) assignments and the modulation and coding scheme (MCS) remain fixed for a certain period. The control signaling overhead is minimized in this method.

The disadvantage of this method is also obvious. To avoid the potential waste of the resource and guarantee the QoS of macro users, the FR backhaul has to be allocated with a minimum bandwidth, which results in capacity limitation of the FR cell. The QoS of many types of traffic, especially ultra-reliable low latency communications (URLLC), cannot be guaranteed. For MTC devices with low-priority and delay-tolerant traffic, this method is the best thanks to its simplicity and low overhead.

Always-Satisfied Bandwidth for the FR Backhaul

In this scheme, the macro BS considers each FR as a macro user but with the highest priority, and the LTE dynamic scheduling is used. Thus, the traditional scheduling grant, frequent channel state information (CSI) feedback, and other necessary control messages such as scheduling request (SR) and buffer status report (BSR) will be transmitted. The control overhead is increased compared to the method of fixed bandwidth. However, the overall amount of control overhead is still reduced compared to the case without FR cells where the macro BS should consume control overhead for each user.

Assigning the highest priority to the FR backhauls is easy for the scheduler. But the QoS of macro users will be greatly affected if the traffic volume carried by the FR backhauls is too large. Also, the fairness between macro users and the users in FR cells cannot be guaranteed. The always-satisfied bandwidth should be considered only if the traffic volume in the FR cell is small and the highest scheduling priority is necessary, such as in the URLLC scenario.

Traffic-Aware Adaptive Bandwidth for the FR Backhaul

The traffic-aware adaptive bandwidth allocation method combines the above two schemes and is suitable for the mixture of low-priority MTC traffic and URLLC traffic.

The macro BS allocates a minimum fixed bandwidth to each FR backhaul to ensure the services to low-priority MTC devices while reducing the impact on other macro users as much as possible. Once packets with high priority are received, it will switch to the dynamic scheduling with always-satisfied bandwidth. The dynamic scheduling for the FR backhaul is based on the BSR of high-priority traffic, and low-priority traffic stored in the FR still needs to wait for the predefined SPS.

In this way, the macro users will be affected only if there is high-priority traffic in the FR cells, which is typically infrequent and has small volume. Without FR cells, the service for the high-priority traffic may cause even higher resource consumption due to a longer transmission distance than that in the FR cell.

Optimized Fixed Bandwidth for the FR Backhaul

In practice, the minimum fixed bandwidth should be determined based on the QoS requirements of the MTC traffic (i.e., how much delay they can tolerate). However, to serve other types of traffic with more stringent QoS requirements but not as high as that of the URLLC traffic, such as streaming media, the limited FR backhauls will become the bottleneck and affect the QoS. The optimized bandwidth solution is proposed to enable these services in the FR cells.

In this case, minimizing the usage of the resources in a macrocell is no longer the objective of the FR backhaul's design. Instead, we aim to improve the overall spectrum efficiency and achieve the maximum throughput. We take the uplink transmission as an example to further explain it. Assuming that there are totally N FR cells, allocating the optimal bandwidth for FR-backhuals, $\mathbf{B}$, can be formulated as the following optimization problem,

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$$\max_{\mathbf{B}} \left[W - \sum_{i=1}^{N} B_i\right]\eta_M + \sum_{i=1}^{N} B_i \log_2\left[1 + \frac{P_{bh} g_{bh\_i}}{n_0 B_i}\right],$$
$$\text{subject to} \sum_{i=1}^{N} B_i \le \Gamma,$$
$$0 \le B_i \le C_i, \forall i = 1\ldots, N, \quad (1)$$

where W is the bandwidth of a macrocell and B_i is the bandwidth allocated to the ith FR backhaul, P_{bh} is the transmission power of the FR on the backhaul, g_{bh_i} denotes the channel gain of the ith FR backhaul, and n_0 denotes the noise spectral density.

In the objective function, η_M is the average spectrum efficiency of the macrocell given a certain scheduling algorithm, and is assumed a constant for simplicity. When the number of users in the macrocell is relatively large compared to that covered by the FR cells, the multi-user diversity gain achieved by the macrocell will not be substantially reduced by offloading traffic to FR cells. Also, η_M will not change much with the changing of the macro bandwidth. Although the gain that comes from scheduling over frequency selective fading channels may be shrunk if the bandwidth is reduced, a threshold of the total bandwidth used by the FR backhauls, Γ, can be set to ensure a large enough bandwidth left to the macrocell. Furthermore, when the users with bad channels are covered by the FR cells and no longer scheduled by the macro scheduler, the overall spectrum efficiency of the macrocell will be increased.

In this problem, the first constraint is the threshold of the total bandwidth used by the FR backhauls. The second ensures that the bandwidth allocated to an FR backhaul will not exceed the average capacity of this FR cell, so as not to waste the resource. As described above, the D2D-based transmission mechanism is used inside an FR cell, and thus the transmission for different users should be performed in a time-division multiplex (TDM) manner. The average capacity of the ith FR cell can be simply modeled as $C_i = W'\int_0^\infty \log_2[1 + P_{fr}x/(I_i + n_0W')]f_{gi}(x)dx$, where W' is the bandwidth reused by one FR cell. It may not equal the whole bandwidth of a macrocell, W, because it may be shared by multiple FR cells in the same frequency-reusing area. P_{fr} denotes the transmission power inside an FR cell. The channel gain g_i is a random variable whose probability distribution function (PDF) is denoted by $f_{gi}(x)$. In practice, when the PDF is not available, an average value can be used to obtain the approximation. I_i is the interference received by the ith FR cell. Either the interference we derived previously considering the extreme case, or the statistical interference map can be applied, so I_i is assumed a constant for a specific location of the FR cell. Therefore, given a certain location and the channel information of the ith FR cell, C_i, can be calculated.

Taking the second derivative of the Lagrangian function w.r.t. B_i, we find that the second deriva-

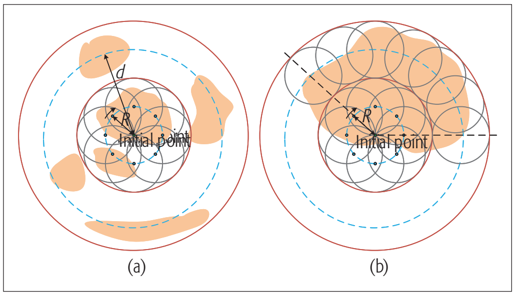

FIGURE 4. Examples of the extended coverage of the FR cell.

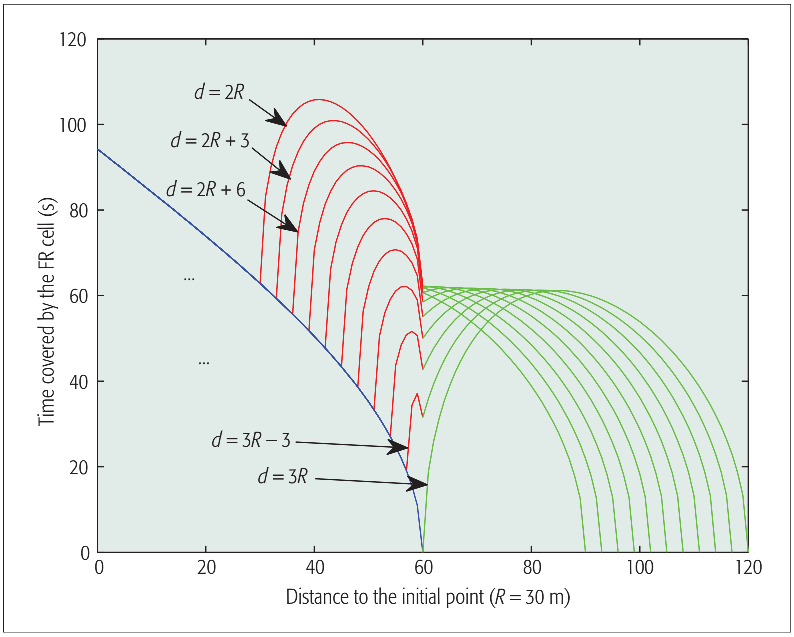

FIGURE 5. FR connection time vs. distance to the initial point.

tive is negative and the Hessian matrix is negative definite. Therefore, this problem can be proved to be a convex optimization problem, and lots of existing tools, such as CVX and fmincon, can be utilized to find out the optimal numerical results.

Coverage

The macro BS determines the suggested coverage based on the historical statistical data or the real-time distribution of the traffic volume. However, the estimation based on the historical data may not be precise. Updating the suggested coverage location to the FR in real time will significantly increase the control overhead not only on the FR backhaul but also for the macro users because the precise locations need to be collected frequently. The FRs are sent out to mitigate the overload or congestion for the macrocell; imposing extra burdens on the macro users may compromise the performance gain achieved by the FR cells.

Therefore, we propose the BS semi-controlled coverage extension methods to improve the utilization of the FR cells and reduce the control overhead. When the macro BS activates or updates an FR cell service, the initial point, as well as the cruising mode, should be included in the control message. The options of the cruising mode may include, but are not limited to:

1. No coverage extension
2. (L, $\boldsymbol{d}$) extension
3. Adaptive (L, $\boldsymbol{d}$) extension

Using option 1, the FR stays at the initial point given by the macro BS. It is suitable for the scenario of stationary MTC devices whose locations are known and close to each other. When the traffic is dynamic, or it is difficult to obtain the precise real-time locations of users, the following two options should be used.

In option 2, the FR will first cruise along a circle centered at the initial point with a radius of R, which is the radius of the original coverage of the FR cell, and thus form a new serving area where the coverage is extended from R to $2R$, as shown in Fig. 4a. This area is denoted as the first layer coverage in this article. After that, the FR extends the radius of the cruising circle from R to d, which forms the second layer coverage. Assuming R = 30 m and the flying speed of the FR is fixed to 1 m/s, given any user inside either the first or second layer coverage, the time covered by the FR cell according to different d is given in Fig. 5, which is a function of the distance to the initial point. This time is counted within the period in which the FR finishes both the first and second layer cruising once.

In Fig. 5, the blue and green curves denote the first and second layer coverage, respectively, and the red curves present the overlapped area. Seamless coverage can be guaranteed when $d < 3R$. With the increasing of d, the FR connection time (time covered by the FR cell) in the overlapped area decreases while the total coverage is increased. The selection of d should be constrained by the acceptable minimum FR connection time, which is valuable for the MTC traffic where a certain amount of data are waiting for transmission.

For other types of traffic with continuous arrivals, such as streaming media, the FR connection probability (probability of being covered by the FR cell) is more important than connection time, which is shown in Fig. 6. Compared to the single-layer extension, the average FR connection probability decreases in the two-layer extension, but the coverage is extended. The different settings of d result in different performance, as shown in the figure, which is the guildline for the macro BS to make the trade-off between the coverage and the single user's enhancement.

In addition to the two-layer extension discussed here, extensions of more layers can be configured by the parameters (L, $\boldsymbol{d}$), where L represents the number of layers, $\boldsymbol{d} = [d_1, d_2, ..., d_{L-1}]$, and d_i denotes the radius of the $(i + 1)$th layer's cruising circle. The optimizations on (L, $\boldsymbol{d}$) given certain objectives are still open issues and beckon future investigation.

Option 2 is suitable for the scenario where the users are scattered randomly, such as people in a shopping mall, and it is difficult for the macro BS to obtain their precise locations, as shown in Fig. 4a. However, when the users are clustered but their locations may change over time, blindly extending the coverage may lead to very low utilization of the FR cell. For example, in some activities such as weddings and conferences, all the guests are moving from one place to another simultaneously.

Therefore, we further propose option 3. In this option, the FR will finish the first layer cruising as option 2 and monitor the traffic density along the circle. For the second layer, the FR only extends the coverage within the sector where the first-layer traffic density is higher than a threshold, as shown in Fig. 4b. In the following layers, the FR applies the same method until either the *L*th layer is reached or there is no place with a traffic density that exceeds the threshold found in the current layer.

Summary

In this article, we propose the UABS to solve the problems brought by the increasing traffic volume of MI and by serving MTC devices with special traffic characteristics and locations. It utilizes UAV-based FR to enable heterogeneous deployment of additional FR cells inside the macrocell, and achieves dynamic and adaptive coverage. We focused on how to deploy the FR cells and the associated issues. Comprehensive analyses on FR cells' deployment including frequency reuse, interference, backhaul resource allocation, and coverage were given.

Future Research Directions

There are many open issues in need of further investigation. Instead of using the interference model of the extreme case, given a certain distribution of the macro users' locations, the average interference coming from the whole macro area can be considered for an alternative solution, which may result in a more precise performance gain. A constant spectrum efficiency of the macrocell is assumed in the procedure of finding the optimal bandwidth for each FR backhaul. When the number of the macro users is not large enough, or the deduction of the FR cell covered users greatly affects the distribution of the macro users' locations, the spectrum efficiency of the macrocell will be changed. How to model this change and solve the optimization problem needs further investigation. Besides the two-layer coverage extension method in the 2D plane, 3D coverage extension, which is applicable for the case of skyscrapers, needs more in-depth analyses. When the FR extends the coverage, an optimized non-constant cruising speed and the energy consumption model can be applied to further increase the average FR connection probability while optimizing the FR's battery life.

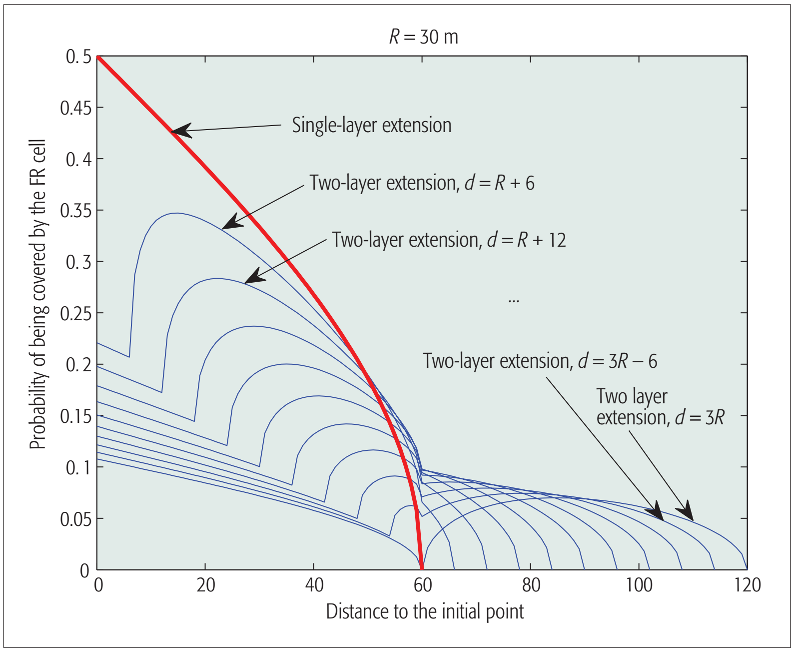

Figure 6. FR connection Prob. vs. distance to the initial point.

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