Analysis: The New Frontier in RAN Heterogeneity: Multi-Tier Drone-Cells

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SUMMARY

This paper attempts to solve the performance degradation of cellular networks due to random and hard-to-predict spatio-temporal distribution of the traffic (load, demand) which does not fully match the fixed locations of the radio access network (RAN) elements. The concept of multi-tier cells (heterogeneous networks, HetNets) has been introduced in 4G networks to alleviate this mismatch. However, as the traffic distribution deviates more and more from the long-term average, even the HetNet architecture has difficulty in coping with the erratic supply-demand mismatch, unless the RAN is grossly over-engineered (which is a financially non-viable solution). This paper evaluates the opportunistic utilization of low-altitude unmanned aerial platforms equipped with base stations (BSs), i.e., drone-BSs, in future wireless networks. In particular, it envisages a multitier drone-cell network complementing the terrestrial HetNets. The variety of equipment and non-rigid placement options allow utilizing multi-tier drone-cell networks to serve diversified demands. Hence, drone-cells bring the supply to where the demand is, which sets new frontiers for the heterogeneity in 5G networks. It investigates the advancements promised by drone cells and discusses the challenges associated with their operation and management. It proposes a drone-cell management framework (DMF) benefiting from the synergy among software-defined networking (SDN), network functions virtualization (NFV), and cloud computing. Finally it demonstrates DMF mechanisms via a case study, and numerically shows that it can reduce the cost of utilizing drone-cells in multi-tenancy cellular networks.

PROBLEM

Although discussions on utilizing drone-cells in cellular networks have flourished recently, cellular networks are not yet quite ready to employ such dynamic nodes because of the following problems.

- Drone-cells require seamless integration to the network during their activity and seamless disintegration when their service duration is over. This requires complex new applications, tools, and technologies, which are time and money consuming.
- Massive amounts of granular information about users and networks must be continuously collected and analysed by intelligent algorithms. Collecting, storing, and processing big data is challenging for existing wireless networks.
- It is not yet clear how to balance centralized (e.g., mobile cloud) and distributed (e.g., mobile edge computing) paradigms.
- Recent proposals for future wireless network architectures include cloud computing, software-defined networking (SDN), and network functions virtualization (NFV) which may decouple the roles in the business model into infrastructure providers (InPs), mobile virtual network operators (MVNOs), and service providers (SPs), which also changes the owners and sources of information.

RELATED WORK

In [1], the authors develop an algorithm that determines optimal altitude and position of a drone base-station (drone-BS) where optimality is defined as maximum number of users covered by drone-BS. A user is covered by a drone-BS if their QOS, measured by signal-to-noise ratio, is above a certain threshold. For drone-BS, the primary governing factor of signal-to-noise ratio is the path-loss incurred by the air-to-ground channel. The most complete models of air-to-ground channels are provided by the International Telecommunication Union Radio communication Sector and Al-Hourani et. al; the authors build upon these works. One of the key characteristics of the air-to-ground channels is the probability of line-of-sight (LOS) communication between drone-BS and user. If the user is within LOS then path-loss decreases, but if LOS is obstructed by objects in the environment—tall buildings—then path-loss increases and QOS decreases.

Given these considerations, the authors develop an air-to-ground channel model that first computes the probability of LOS as a function of user position (Xi,Yi) and drone position (Xd,Yd,h). Given the probability of LOS, the path-loss can be computed as a function of the probability of LOS and additional parameters that depend on whether the drone is in urban, suburban, dense urban, or high-rise urban environments. The optimization problem can be rephrased as moving the drone-BS to an area where demand is high and revenue can be maximized by covering the most amount of users. The area of highest demand is not necessarily the area that will generate maximum revenue because high demand in a high-rise urban environment where path-loss is substantial may generate the same revenue as suburban area with less demand given that revenue is correlated to number of users covered by drone cell. The authors are able to reformulate the problem into a mixed-integer nonlinear optimization problem. Under this formulation, an iterative search algorithm can be used to determine optimal parameters Xd, Yd, h that will maximize revenue for service provider. The parameters that describe environments (dense urban, suburban, high-rise urban, etc) have been precomputed by Al-Hourani et. al. in their seminal work on air-to-ground channel models. The authors use these parameters to run monte-carlo simulations to prove the optimality of their algorithm. Under a series of simulations, the algorithm output drone positions that, with 95% confidence interval, resulted in maximum revenue. The results from [1] were used a benchmark for comparing the effectiveness of the drone-cell management framework (DMF) where multi-tenancy mobile virtual network operators and an intelligent cloud-based services were able to determine the positioning of drone-BS (drone base-stations) that outperformed the projected revenue in [1].

The cellular SDN framework defined in [5] proposes an architecture employing the type of software defined networking and network virtualization functionality required to operate a multi-tiered drone-cell networks. The primary SDN component of the C-SDN is the central control plane. The control plane consists of a network operating system (NOS) that abstracts the distributed state of the network and provides global view of the network in addition to network virtualization building blocks. Among the state maintained by the control plane are the operating characteristics that can be leveraged to efficiently manage radio resources and mobility management—both particularly useful for exploiting the multi-tiered drone cells. An SDN controller also has the ability to update routing such that burst traffic from the drone-cells is carried through the network without any bottlenecks. Similarly, in case of a natural disaster that causes the network to partially malfunction, network health information in the cloud can be utilized by the SDN to route the traffic of drone-cells through undamaged parts of the network.

The SDN controller is also responsible for orchestrating and managing virtual network functions. For example, today's LTE cellular network rely on Evolved Node Base stations that connect mobile phones to the core network and manage allocation of share resources, handovers, and session management among other responsibilities. The framework in [5] replaces e-node-BS with virtual e-node-BS that are managed by the central control plane. The centralized control plane makes decisions about radio resources from a global perspective so that the control plane can effectively distribute users among base stations for load balancing. Under this scheme, the drone-BS would be abstracted away as just another v_e-node-BS so that the central control plane could migrate users onto the drone-BS when they arrive at an area of high demand--meeting the requirement for seamless integration of drone-BS into existing network.

While terrestrial base-stations rely on wired backhaul, drone cells must use a wireless backhaul. In [10], the authors enumerate several challenges of using a wireless backhaul in addition to solutions to overcome these challenges. The key wireless backhaul solutions leverage exploiting the millimeter wave (mmWave) spectrum in 60 GHz and 70–80 GHz bands, microwave spectrum between 6 GHz and 60 GHz bands, sub-6 GHz band, TV white spaces, and satellite technologies. If LOS is maintained then mmWave spectrum interference is limited; however, poor penetration of obstacles is serious challenge. This can be overcome by using large phased-array antennas can be used, but this sort of antenna is generally too massive to be mounted on a drone base-station. For both microwave and mmWave spectrum, a physically clear and unobstructed path is generally required between the base-station and backhaul gateway. A lower frequency option for wireless backhaul is using TV whitespace--it does not require LOS but has limited bandwidth at 18Mb/s compared to the 1Gb/s bandwidth of the microwave and mmWave spectrum signals.

Another challenge of wireless backhaul is backhaul delay. This type of delay occurs when interference causes transmission failure requiring the signal to be retransmitted. Wireless backhaul delay can be further classified as satellite backhauling delay characterized by lengthy signal propagation delays up to 260 ms and packetization and processing delays up to 50ms. The authors in [10] characterize the cellular region boundary beyond which the down-link transmission capacity of a user served by a given cell becomes limited due to the backhaul link capacity referred to as the "backhaul-limited region". As the distance between the cell and the backhaul gateway increases, the received signal power at the cell decreases due to path loss and this path loss limits in turn limits capacity for a user in the down-link. The authors demonstrate the usefulness of employing full-duplex transmission to increase backhaul capacity under certain interference conditions. These facts motivate the need for adaptive full-duplex in sub 6 GHz-backhaul small cells that allow cells to decide their mode of operation in an opportunistic manner.

EVALUATION METHODOLOGY

To evaluate the benefits of the Drone Management Framework (DMF), the authors first develop metrics in which to evaluate against. They chose to compare their results against those in the paper "Efficient 3-D placement of an aerial base station in next generation cellular networks" by Yaliniz, El-Keyi, and Yanikomeroglu.

The authors next develop a what they call considerations. These considerations are a way to group common network attributes in which to optimize the DMF over. Congestion is the consideration of serving as many users as possible. Multi-Tenancy is the consideration of serving as many carriers as possible. Green Wireless is the consideration of serving energy critical users, for example sensor systems, or users in dead zones. And Content is the consideration to serve high bandwidth users, for example those users streaming HD video. With these considerations, the DMF can be formulated as an optimization problem with an objective function of the form:

$$w_1 \sum \alpha + w_2 \sum \beta + w_3 \sum \gamma$$

Where α, β, γ are based on the above considerations, and w are weights. The problem is subject to a number of constraints, including the number of users, location of drone cell, drone cell capacity, altitude, and quality of service (QoS), to name a few.

To test the DMF, the authors developed a simple scenario consisting of two service providers, each with 15 users spread randomly over a three kilometer square area, and one drone base station, which can move in 3-D (x,y,z). They ran 100 monte carlo simulations across four DMF configurations: DMF on with single-tenancy, DMF on with multi-tenancy, DMF off with single-tenancy, and DMF off with multi-tenancy. In all cases, the authors found that the DMF on configurations were able to service more users and equally distribute service across carriers. They do however, make a note that there are limitations in the testing due to the limited amount of work that has been done in this area, and point at future work in aerial network optimization.

CRITIQUES

The authors present original ideas building off previous work in a relatively new area (aerial drone base stations in cellular networks). They also present a framework that can be implemented in the real world, and that could be used to solve real world problems. The authors have learned that more work needs to be done in the field for significant progress to be made and significant lessons learned. There were a number of choices made in relation to the optimization problem, namely congestions, multi-tenancy, energy, and content delivery. These seem reasonable and one would believe align well with user needs. There are a number of assumptions however, that may need to be reexamined in a real implementation. Altitude and airspace, for example, would have to comply with FAA requirements. The sample size for the simulations were also small (30 users) in comparison with real user bases (100s-1000s of users). There was a lack of previous work in the paper, which points towards this being a newer area of study. There was also a lack of experimental results, moreover, a lack of explanation of experimental results. In all this is an interesting paper covers some very basic optimization ideas in regards to the use of drones as cellular network base stations.

[1] R. I. Bor-Yaliniz, A. El-Keyi and H. Yanikomeroglu, "Efficient 3-D placement of an aerial base station in next generation cellular networks," *2016 IEEE International Conference on Communications (ICC)*, Kuala Lumpur, 2016, pp. 1-5.
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