

Wireless Backhauling for 5G Small Cell Networks

Abdullah A. Al Orainy

Abstract—Small cell backhaul solutions need to be cost-effective, scalable, and easy to install. This paper presents an overview of small cell backhaul technologies. Wireless solutions including TV white space, satellite, sub-6 GHz radio wave, microwave and mmWave with their backhaul characteristics are discussed. Recent research on issues like beamforming, backhaul architecture, precoding and large antenna arrays, and energy efficiency for dense small cell backhaul with mmWave communications is reviewed. Recent trials of 5G technologies are summarized.

Keywords—Backhaul, Small Cells, Wireless, 5G.

I. INTRODUCTION

NEXT generation wireless systems will transport multi-gigabit traffic in order to support the exponential increasing demand for wireless data. The key solution to fulfill this requirement is to deploy a new network architecture, which consists of many small cells embedded in each macro layer. Small cells are installed on building walls, lampposts and payphones, which is different from macro cells located in preplanned sites. It is expected that 5G wireless networks will support very high data traffic, much more connections and latency of sub-millisecond.

Small cell backhaul networks can be established in different methods. However, the number of small cells is an order of magnitude than macrocells and backhaul takes a significant percentage of the total network cost. Thus, backhaul solutions need to be more cost-effective, scalable, and easy to install than macro backhaul technologies.

Connecting small cells to mobile network can be through copper or fiber (OF) providing high reliability and high data rates. Backhaul via wire solution is rather difficult to implement with unarranged situation and potentially increases installation costs. Wireless solution is seen to offer more cost effective solution for backhauling as the number of cells is greatly increased. Different wireless technologies have been proposed for backhaul connections. However, wireless backhauling introduces other problems such as interference, spectrum allocation. Hybrid mmWave optical backhaul networks might also be an approach for future backhaul networks.

In this paper, we discuss wireless solutions with their backhaul characteristics for small cell base stations connections. An overview of recent research going on small cell backhaul networks with emphasis on wireless technologies is presented. Recent trials of 5G technologies will then be summarized.

Abdullah AlOrainy is with the King Abdulaziz City for Science and Technology, Riyadh, S.A. (phone: 966-11-4813763; fax: 966-11-4813765; e-mail: alorainy@kacst.edu.sa).

II. SMALL CELL BACKHAUL SOLUTIONS

Data rate, infrastructure cost, interference and spectrum availability are among other factors that need to be addressed when wireless backhaul solution is selected. Various wireless backhaul technologies were considered; TV white space (TVWS) spectrum, satellite, sub-6 GHz radio wave, microwave and mmWave technologies. MmWave and sub-6 GHz have both licensed and unlicensed bands while microwave are usually of licensed bands.

TVWS: White space (WS) spectrum, which not used by TV primary broadcasters, could be freed up for small cells backhauling through a request to an online database. Light licensing WSTV links provide good propagation through and around obstacles. However, the freed up white space spectrum will not be sufficient to meet the growing traffic demand. Interference between users needs also to be lessened to insure reliable operation.

Satellite: In a satellite link, the attenuation due to weather depends on the frequency band selected. At the lower frequency C band (4–6 GHz) signal is almost unaffected by weather, while at the Ka-band band (20–30 GHz), could have up to 24 dB of rain fade.

Although satellite links can provide capacity up to 350 Mbit/s it can be only adopted for particular situations such as for remote areas when other solutions cannot reach or too expensive to implement. The high cost per capacity lower its competitiveness to other solutions in dense areas. Other use of satellite backhaul may be for mobile small cells such as on portable mobile sites, ships and planes.

Sub-6GHz: Sub-6 GHz systems can support both non-line-of-sight and line-of-sight propagation due to low loss. Sub-6 GHz frequency bands are proven as a viable solution for small-cell backhaul. However, the available bandwidth below 6 GHz is limited and aggregating sub-6 GHz band with higher frequency bands for backhauling offers more vigorous solution for small cell backhauling.

Microwave: Microwave is a cost efficient solution and widely used in macrocells backhaul as a line-of-sight (LOS) technology capable of providing gigabits/sec capacity. Since losses are high above 6 GHz, LOS propagation is usually proposed. Small cells positioned mainly below roof height and, therefore, do not have clear line of sight. Nevertheless, some recent studies on NLOS transmission above 20GHz band might outperform sub-6GHz systems [1]. In a small cell backhaul network, it was shown that with NLOS technology, 90% of the sites in a small-cell backhaul deployment with a throughput greater than 100Mbps could be reached [2]. However, Spectrum became rare at microwave frequencies. Doubling the current cellular bandwidth is thus needed.

RF/FSO: RF/free-space optical (FSO) might also be a

hybrid cost effective solution combining FSO-backhauls features such as high rate and low latency; and RF-backhauls advantages of NLOS propagation and low cost. FSO does not require digging, which is usually the drawback for the Optical fibers deployment. However, FSO links may severely affected by fog or rain.

Recently, Dahrouj et al have proposed Hybrid RF/FSO solution which use RF or FSO only when it is required; depending on weather conditions and interference levels which make it a convenient complementary technology for upgrading the networks. [3]

MmWave: mmWave with its enormous spectrum tend to be the prominent small cell backhaul solution. At 60 GHz and 70-80 GHz mmWave provide high capacity backhaul. Small wavelengths enable large number of tiny antennas yet relies on simple configurations. The small size and low costs make mmWave the best choice for small cell dense deployment. However, there are still issues that need to be addressed before mmWave backhaul networks can be used to forward massive traffic in low cost and energy efficient way. Channel transmission, beamforming and block effects need to be studied. The design of novel backhaul architectures and protocols for ultra dense small cell implementation are also required. Whether existing network protocols can support the huge backhaul traffic and frequent handover are other challenges to mmWave backhaul solution.

Wireless backhaul scheme of mmWave MIMO-based for 5G dense Network is shown in Fig. 1. Macrocells support high-mobility users, whereas numerous small cells deliver higher rates for low mobility clients. Owing to the high number of small-cell BSs, frequency reuse could be improved, and energy efficiency may also be enhanced significantly owing to the small cells less path loss [4].

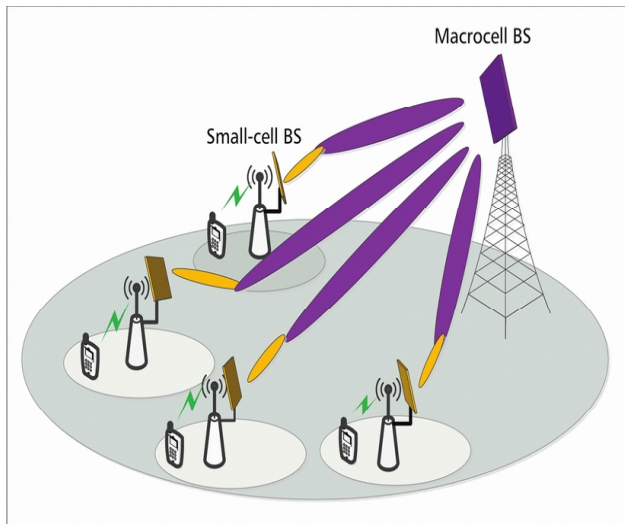


Fig. 1 A scheme of MmWave MIMO-based wireless backhaul Network [4]

Although digital mmWave array provides full capacity and flexibility it may not be a practical solution due to cost and

space constraints. A hybrid array of many analog subarrays could be an effective scheme. However, massive hybrid array for mmWave communications have their own design problems owing to the sizable degree of freedom offered by hybrid array scheme and special signal propagation [5].

The increase in carrier frequency of mmWave communication leads to higher free-space path loss. Fortunately, beamforming using large arrays offer gain needed to overcome path loss. Also, precoding multiple data streams on large arrays system can enhance spectral efficiency. Fig. 2 illustrates beamforming schematics for sub 3 GHz cellular and mmWave systems. Beamforming is performed in the baseband in traditional cellular systems while in mmWave transmission large number of antennas with hybrid beamforming architecture can be used.

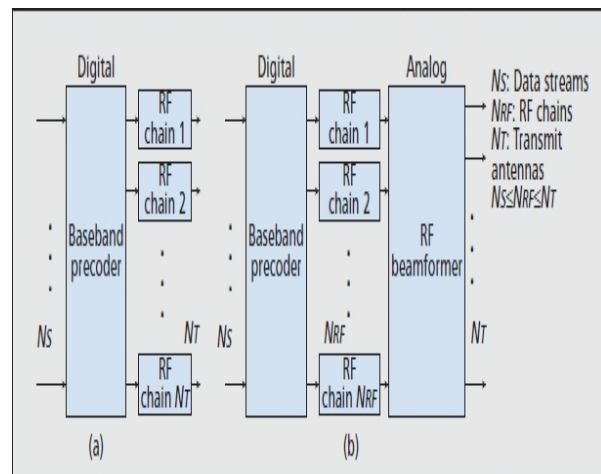


Fig. 2 Schematic of Beamforming a: 3 GHz and b: mmWave configurations [6]

Attenuation which occur due to free space transmission and atmospheric gaseous was investigated in [6]. When array antennas are used it was shown that the received power could be much more than that of the sub-6 GHz patch antenna ones. Atmospheric gaseous losses only occur at some mmWave frequencies. Beyond absorption peaks at 57–64 GHz (oxygen absorption) and 164–200 GHz (water vapor absorption) mmWave transmission will not be deteriorated by gaseous loss.

El Ayach et al. have considered receiver combining in large antenna arrays mmWave networks with precoding. They have developed algorithms, which estimate optimum unconstrained combiners and precoders. Even when hardware constraints are taken into account, their algorithms permit mmWave networks to obtain their unconstrained performance limits [7].

In the context of limited-feedback, a hybrid precoding has also been proposed for mmWave connections with multiple antenna arrays [8]. The feasibility of using multiple antenna arrays to get diversity/multiplexing gains in mmWave networks, where each array is capable of beamforming separately, has been investigated. With a codebook-based beamforming technique, algorithms of low complexity, by

exploiting the limited multipath nature of the mmWaves, were developed.

Interference in Heterogeneous cellular networks due to deployment of small cell backhaul within macro cellular systems is recently discussed by [9]. They have analyzed the influence of backhaul delay and the related implementation cost in heterogeneous networks (HetNets). The main result of their work is that due to delay, increasing small access point to high densities may not provide a sustainable approach to mobile data capacity crunch [9].

Synchronization between densely deployed small cells presents another important issue for the materialization small cell networks. For synchronization, macro cell base stations employ global navigation satellite system (GNSS). Due to cost limitations and some deployment constraints such as indoor applications, GNSS might not be convenient method for small cell synchronization. Alternatively, Zou, et al. have investigated another synchronization technique based on radio-interface by adopting coordinated timing detection and muting [10]. An improved design, which removes interference, has been presented.

Energy efficiency EE, measured as the number of bits transmitted per joule, has emerged as an important issue with the growing network capacity. Both EE and spectrum efficiency (SE) need to be improved under the constraint of QoS for each user [11].

Energy consumption is a crucial issue where batteries are used for wireless devices. In small cell systems, the transmitted power is likely equivalent to the circuit power [12]. However, the small cell can enhance SE significantly with frequency reuse and simultaneously. In addition, power, needed to compensate path loss, fading and noise, could be minimized by the low distance between user and BS. Hence, the EE can thus be improved [13].

X. Ge et al. have studied the energy efficiency of dense small cell backhaul with mmWave communications. It has been shown that hybrid solution containing wireless and fiber could be a good solution. Novel sleeping model and adaptive control of Small BSs were also proposed as an effective approach for energy saving [14].

Large Scale MIMO technology offers significant SE/EE improvements. MmWave can be simply combined with Large Scale MIMO for better link reliability. It is seen as a promising solution of improving the SE by using a large number of antenna elements (AE) to serve a less number of User equipment [15]. To show the tradeoff, maximizing EE and SE simultaneously in downlink massive MIMO systems is an optimization problem. However, connecting to mmWave BS with their much wider bandwidth is not always available. Hence, users may connect to the closest microwave MBS if mmWave link is not available [16].

Backhaul effect on radio resource management (RRM) is an important issue. Bandwidth allocation and interference management are different from those adopted in cellular networks. The RRM is mainly related to interference and traffic management. Challenges and design problems for RRM with backhaul concerns has been discussed recently by [17].

Through numerical results, authors have illustrated how small cell backhauling with MIMO technology affect the cell association scheme in a two-tier system. By conducting cell association and bandwidth allocation, significant gains in perceived user rates were achieved. In addition, the small cell density has been shown to have lower effect on the user rates than of the density of users.

Sharing of radio access networks due to cell densification will reduce cost and interference. Fig. 3 illustrate sharing between different operators at the small cell level.

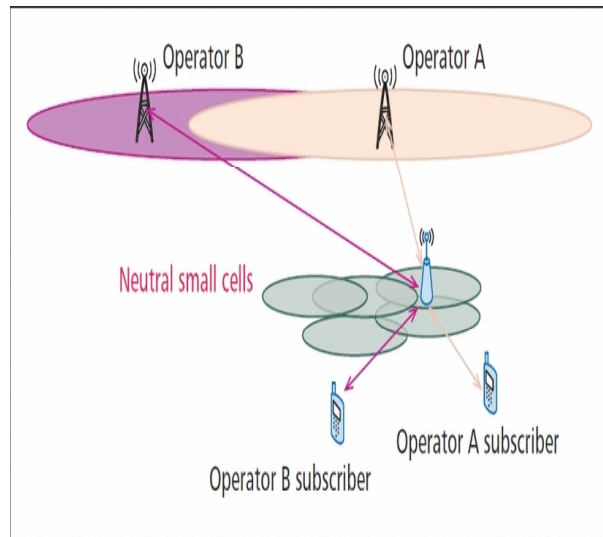


Fig. 3 Radio-Access Network sharing [18]

A resource management scheme for small cell backhaul system retaining the needed data rates at the backhaul was proposed while the total cost is minimized [19]. It has been shown that by exploiting mmWave band significant gains compared to other resource management systems can be achieved. Delay, cost, and interference management in dense small cells networks, while considering the SE and EE target, still needs further investigations.

III. 5G TRIALS

Although 5G standards have not been defined yet, vendors have conducted a number of field trials. During the past year, 5G enabling technologies were tested which lay the groundwork toward commercialization.

An in-door trial by NTT DOCOMO with Nokia Networks achieved a data transmission of 2Gbps using mmWave at 70GHz to verify beamforming and beam tracking. In a separate trial NTT with Samsung Electronics achieved a maximum data of 2.5Gbps at 28GHz signal with a mobility speed of 60km/h. Beamforming with a high number of antenna elements and beam tracking were used in this experiment [20].

A 5G outdoor test by DOCOMO and Ericsson achieved a transmission of 4.5Gbps using Ericsson 5G radio type at 15GHz verifying the feasibility of massive MIMO technology.

DOCOMO and Fujitsu have achieved a speed of 11Gbps with multi-base station and four mobile devices at 4.6GHz [21].

ZTE have developed a three dimensional outdoor massive MIMO base stations with 64 ports and 128 antennas. In a field test, such base stations reached peak value three times more than eight antenna base stations. Huawei with NTT DoCoMo have also conducted an outdoor trial in Chengdu. It was the first massive MIMO trial and able to achieve a peak speed of 3.6Gbps with 24 user devices at sub 6 GHz frequency band.

Deutsche Telekom recently completed their field trial of self-interference cancellation (SIC) technology evaluating the capabilities of SIC under realistic conditions. The trial demonstrated the potential of SIC technology to increase spectral efficiency for 5G networks.

Orange has been authenticated to 5G mmWave trials in France during 2016. Their project will test conditions of use for frequency bands between 6GHz and 100GHz for next generation 5G networks. Some other companies such as Verizon, Alcatel-Lucent, Cisco, Qualcomm and Samsung are working for their first field trials in 2016.

IV. CONCLUSIONS

In this paper, an overview of wireless small cell backhaul technologies is presented. Backhauling via wire solution is rather difficult to implement and increases installation costs. Wireless solution is more cost effective solution for backhauling as the number of cells is greatly increased.

Different wireless technologies have been proposed for backhaul connections. WS spectrum could be used for small cells backhauling but the freed up white space spectrum is not sufficient to meet the growing traffic demand. Although satellite links can provide capacity up to 350 Mbit/s it can only be adopted for particular situations such as for remote areas. Sub-6 GHz systems can support both non-line-of-site and line-of-site propagation due to low loss. However, the available bandwidth below 6 GHz is limited and aggregating sub-6 GHz band with higher frequency bands for backhauling might offer more effective solution for small cell backhauling.

MmWave with its enormous spectrum tend to be the prominent small cell backhaul solution. The small size and low costs make mmWave the best choice for small cell dense deployment. However, there are still issues need to be addressed before mmWave backhaul networks can be used to forward massive traffic in low cost and energy efficient way.

Channel characteristics, beamforming due to path loss and block effects need to be studied further. Design of novel backhaul architectures and protocols for ultra dense small cell implementation are also required. Whether existing network protocols can support the huge backhaul traffic and frequent handover are other challenges to mmWave backhaul solution. Recent research on these issue and other one have been discussed in this paper. Hybrid mmWave optical backhaul networks might also be an approach for some cases in future backhaul networks.

5G standards are expected by 2020. Nevertheless, vendors are conducting a number of field trials of 5G enabling

technologies. Some of indoor and outdoor 5G test are summarized.

REFERENCES

- [1] "Non-line-of-sight microwave backhaul for small cells", Ericson Review, Feb. 2013.
- [2] Coldrey, M.; Koorapaty, H.; Berg, J.-E.; Ghebretensae, Z.; Hansryd, J.; Derneryd, A.; Falahati, S., "Small-cell wireless backhauling: a non-line-of-sight approach for point-to-point microwave links", Vehicular Technology Conf. (VTC 2012)
- [3] Dahrouji H., Douik A., Rayal F., Al-Naffouri T., AlOuni M., "Cost-effective Hybrid RF/FSO Backhaul solution for next generation wireless Systems" IEEE Wireless Communications, Oct. 2015, pp. 98-104.
- [4] Geo Z., Dai L., Mi D., Wang Z., Imanan M., Shakir M., "Mmwave Massive MIMO-based Wireless Backhaul for the 5G Ultra-dense Network", IEEE Wireless Communications, Oct. 2015, pp. 13-21.
- [5] J. Zhang, X. Huang, V. Dyadyuk and Y. Guo, "Massive Hybrid Antenna Array for millimeter-wave cellular communications", IEEE Wireless Communications, Vo. 22, no. 1, 2015, pp. 79-87
- [6] L. Wei, R. Hu, Y. Qian, and G. Wu, "Key Elements to enable mmWave for 5G Wireless Systems", IEEE Wireless Communications, V. 21, N. 6, Jan 2015, pp. 136-143.
- [7] O. El Ayach, S. Rajagopal, S. Abu-Surra, Z. Pi, and R. Heath, "Spatially Sparse Precoding in Millimeter Wave MIMO Systems", IEEE Trans. On Wireless Communications, V. 13, n. 3, March 2014, 1499-1513
- [8] J. Singh and S. Ramakrishna, "On the Feasibility of Codebook-Based Beamforming in Millimeter Wave Systems With Multiple Antenna Arrays" IEEE Trans. On Wireless Communications, V. 14, n. 5, May 2015, pp. 260-2683.
- [9] D. Chen, T. Quek, and M. Kountouris, "Backhauling in Heterogeneous Cellular Networks: Modeling and Tradeoffs", IEEE Trans. On Wireless Communications, V. 14, n. 6, JUNE 2015, pp. 3194-3206
- [10] K. Zou, K. Yang, M. Wang, B. Ren, J. Hu, J. Zhang, M. Hua, And X. You "Network Synchronization for Dense Small Cell Networks", IEEE Wireless Communications, April 2015, pp. 108-117.
- [11] R. Q. Hu and Y. Qian, "An Energy Efficient and Spectrum Efficient Wireless Heterogeneous Network Framework for 5G Systems", IEEE Communications Mag., V. 52, n. 5, May 2014, pp. 94-101.
- [12] G. Wu, C. Yang, S. Li, And G. Li. "Recent advances in energy-efficient networks and their applications in 5G systems" IEEE Wireless Communications, April 2015, pp. 145-151.
- [13] A. Prasad *et al.*, "Energy-Efficient Inter-Frequency Small Cell Discovery Techniques for LTE-Advanced Heterogeneous Network Deployments," IEEE Communications Mag., V. 51, n. 5, May 2013, pp. 72-81.
- [14] X. Ge, H. Cheng, M. Guizani, and T. Han "5G Wireless Backhaul Networks: Challenges and Research Advances" IEEE Network, V. 28, n. 6, Nov. 2014, pp. 6-11.
- [15] Z. Zhang., X. Wang, K. Long, A. Vazilakos and L. Hanzo "Large Scale MIMO-Based Wireless Backhaul in 5G Networks" IEEE Wireless Communications, Oct. 2015, pp. 58-66.
- [16] J. Choi, "Energy efficiency of a Heterogeneous Network using mmWave small cell base stations", IEEE PIMRC, 2015, pp. 293-295.
- [17] N. Wang, E. Hossain and V. Bhargava, "Backhauling 5G Small Cells: A radio Resource Management Perspective", IEEE Wireless Communications, Oct. 2015, pp. 41-49.
- [18] J. Guey, P. Liao, Y. Chen, A. Hsu, C. Hwang and G. Lin, "On 5G Radio Access Architecture and Technology", IEEE Wireless Communications, Oct. 2015, pp. 2-5.
- [19] O. Semiari, W. Saad, Z. Dawy, M. Bennis, "Matching Theory for Backhaul Management in Small Cell Networks with mmWave Capabilities" ICC Conference, June 2015, pp. 3460-3465.
- [20] Obara, et al., "Indoor and outdoor experimental trials in 28-GHz band for 5G wireless communications systems", IEEE PIMRC, 26th Symposium, Hong Kong, 2015, pp. 846-850.
- [21] J. Gozalves, "5G Tests and Demonstrations (Mobile Radio)", IEEE Vehicular Technology Magazine, June 2015, pp. 16-25