BACKHAUL NEED FOR SPEED: 60 GHZ IS THE SOLUTION

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ABSTRACT

The availability of 7–9 GHz of unlicensed spectrum at 60 GHz, advances in low-cost silicon technology, and high interference rejection due to atmospheric loss make 60 GHz an ideal solution for future 4G/5G small-cell backhaul links, where multi-gigabit rates are required. In this article, we review the 60 GHz propagation properties, the practical technology limits, and the regulatory and regional environmental impacts to present a framework for the 60 GHz backhaul link design that translates the link requirements to the essential transmitter and receiver system parameters. This approach includes a preliminary design that generates the input data set for an optimization problem. Two physical front-end architectures are discussed in this work: single-input single-output antenna for point-to-point applications and phased arrays for the future 4G/5G self-organizing backhaul networks. It is shown that selecting the proper channel bandwidth can increase the interference rejection. Furthermore, we calculate the physical data rates for the proposed modulation and coding schemes. When phased array is used, the backhaul link design can be defined as an optimization problem to find the optimum number of antennas and the gain per antenna.

INTRODUCTION

Faced with higher data traffic per cell, cellular network operators need to find ways to minimize the operating costs to transfer data to the core network. This is where backhaul links, which are composed of point-to-point (PTP) and/or point-to-multipoint (PTM) links interconnecting the base stations and the core network, come into picture. Figure 1 depicts the small-cell network layout in Long Term Evolution-Advanced (LTE-A), including picocells, microcells, and macrocells. The smaller LTE-A base stations serving these small cells are interconnected through backhaul links to each other and to the core network.

Most of today's backhaul link infrastructure is provisioned for third generation (3G) speeds (< 100 Mb/s) and simply cannot handle 4G/5G broadband network data rates [1]. For example, LTE-A promises peak uplink and downlink speeds of up to 500 Mb/s and 1 Gb/s, respectively. The backhaul links carry data traffic of one or several LTE-A small cells and require provisioning for multi-gigabit (≥ 1 Gb/s) speeds.

Wired and wireless options are engineering solutions for backhaul links. Copper backhaul links are restricted to low data rates, while fiber has the benefit of almost unlimited capacity for long range, minimal environmental impact, street aesthetics, reliability, and availability at all times. However, installation costs are very high; for example, trenching cost in rural, metropolitan, and urban areas costs about $30/m, $90/m, and $130/m, respectively, and the fiber cost including the fiber, connectors, fusion, and tests is about $7/m.

Wireless backhaul links are more cost effective than wired ones. Table 1 compares microwave and millimeter-wave (mmWave) wireless options for backhaul links. Achieving multi-gigabit data rates at microwave bands requires complex modulation and coding schemes (MCSs) and channel bonding [2], elongating the deployment cycle and adding to the hardware complexity. At the mmWave bands (60 GHz and 70–90 GHz) abundant bandwidth is available, which makes multi-gigabit data rates feasible even with simple modulations, such as binary phase shift keying (BPSK) [2].

The mmWave frequency antennas used for backhaul are highly directional and focus energy in an intended direction. For a fixed antenna aperture the beamwidth is inversely proportional to the operating frequency. Therefore, beamwidth is much narrower at 60 GHz than at microwave frequencies [3]. Moreover, 60 GHz electromagnetic waves decay significantly due to physical barriers such as humans (10–20 dB attenuation), walls, oxygen absorption (15 dB/km at sea level), and water vapor absorption (12 dB/km for 30 mm/h rainfall) [3]. In the case of a 4G/5G small cell layout, a combination of high oxygen absorption and associated reduced range with highly focused antenna(s) and narrow beamwidth become an advantage of 60 GHz over other microwave/mmWave backhaul solutions in that it allows hundreds of links to be installed in a dense area, and very low interference between the PTP links or other 60 GHz devices in proximity.

The proliferation of multi-gigabit WiFi (i.e., IEEE 802.11ad [4] operating at 60 GHz) height-

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ens the availability of a variety of components and subassemblies for 60 GHz devices, thereby improving the affordability of 60 GHz backhaul links. The 60 GHz spectrum (57–64/66 GHz band) is located in the mmWave portion of the electromagnetic spectrum and has 7–9 GHz of license-exempt bandwidth worldwide, while the 70–90 GHz spectrum (71–76, 81–86, and 92–95 GHz) has 13 GHz of licensed bandwidth with site-by-site coordination but without extensive Federal Communications Commission (FCC) action. The August 9, 2013 modifications to the FCC Part 15 rules have motivated the use of 60 GHz spectrum as a relatively low-cost high-capacity short-range backhaul alternative to connect the wireless broadband networks (4G/5G and beyond), which is the focus of this article. The potential for 60 GHz outdoor links is studied through simulations and measurements in [5].

This article presents the following critical points regarding the 60 GHz backhaul link design:
- Two PHY front-end architectures, single-input single-output (SISO) antenna and phased array, for mmWave backhaul links
- A framework that translates the link requirements to important transmitter and receiver system parameters such as antenna count, antenna gain, and input power considering the technology and regulatory limits as well as regional environment influence
- Evaluation of proper channel bandwidth for the 60 GHz backhaul links and calculation of the PHY data rates for the proposed MCSs
- An optimization function to infer the optimum transmitter and receiver system parameters such that the size, cost, and power consumption is minimized for the 60 GHz backhaul links

The rest of the article is organized as follows. The PHY front-end architectures for backhaul links is discussed in the following section. The framework for the backhaul link design and the optimization problem are then elaborated. The article concludes with the final section.

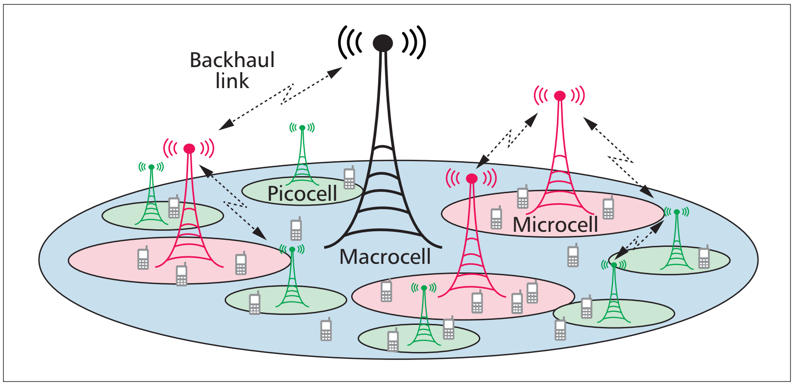

Figure 1. Wireless backhaul links in the LTE-A small-cell cellular network deployment.

Attribute	Microwave link (2.4 GHz)	Millimeter-wave link (60 GHz)
Multi-gigabit capacity complexity	Requires MIMO and channel bonding	MIMO and channel bonding not required
Antenna pattern	Omnidirectional	Directional
Beamwidth	< 120°	< 5°
O_2 attenuation (dB/km)	< 0.02	< 15
Rain attenuation (dB/km at 10 mm/h)	0.5	5
PTP link interference	Significant	Low

Table 1. Comparison of microwave and millimeter-wave wireless option for backhaul links.

PHY Front-End Architecture

Conventional backhaul links use high-gain single-antenna transmitters and receivers to achieve a stable PTP wireless link. Nevertheless, recent advances in silicon technology enable realization of integrated phased array systems at mmWave range to get higher equivalent isotropic radiated power (EIRP) [6]. A phased array system enables PTM links without mechanical rotation of antenna, which has several advantages for small cell backhaul application, such as fast installation, automatic beam alignment, and higher output power. In this section, we discuss the single and phased array antenna front-end architectures for 60 GHz backhaul links.

Single-Antenna PHY Front-End

The SISO PHY front-end architecture is depicted in Fig. 2a, which comprises a single RF chain including one antenna feed. At the transmitter (Tx), the incoming signal is amplified by a power amplifier (PA) and delivered to the antenna for transmission. Likewise, at the receiver (Rx), the received signal is amplified by a low noise amplifier (LNA). Regardless of the antenna type, only one RF path is available in this architecture, which makes it proper for PTP applications.

The advantages of a single antenna structure are simplicity, high efficiency, and possibly lower cost. On the other hand, such architecture offers limited or no beam-steering capability. The antenna gain, which is proportional to the antenna size, is determined by the required link range. In the case of limited output power the antenna size increases to provide the required EIRP. The received power drops sharply if the link is blocked or the antenna is misaligned.

Phased Array Antenna PHY Front-End

A phased array antenna is a multiple-antenna system in which the radiated fields of all elements can be reinforced in a particular direction or suppressed in another direction [6]. Figure 2b illustrates a phased array front-end at both Tx and Rx. Among different phased array architectures, the one shown here, known as an RF-phase shifting array, is considered a low-cost solution [6]. At the Tx side, the incoming modulated data is split between multiple RF paths, phase shifted, amplified, and delivered to each antenna for transmission. Phase shifters are controlled by a beamforming unit, which sets the required phase shifts to steer the array beam toward the desired direction [7].

At the Rx side, the LNA gain must be high enough to reduce the overall noise figure of the array and increase the signal level. The received signals have different phases since the array elements are spatially distributed. Thus, phase shifters are required to make all these received signals coherent at the power combiner.

Link Equation for Phased Arrays: In any wireless link, the transmitter EIRP, defined as the product of the total input power P_t and the total antenna gain G_t, is a key parameter to evaluate the link performance. For a Tx phased array with N_t identical antennas each with P_{t_1} input power and G_{t_1} antenna gain, the total input power is $P_t = N_t \cdot P_{t_1}$, and the maximum Tx antenna gain is $G_t = \eta_t \cdot N_t \cdot G_{t_1}$, where η_t is the Tx array efficiency. It can be shown that the EIRP of a phased array is at most N_t^2 times larger than that of a single antenna transmitter. Likewise, for N_r identical Rx antennas each with G_{r_1} Rx antenna gain, the maximum receive antenna gain is $G_r = \eta_r \cdot N_r \cdot G_{r_1}$, where η_r is the Rx array efficiency. At the receiver, the received signal-to-noise ratio (SNR) determines the quality of the link, particularly

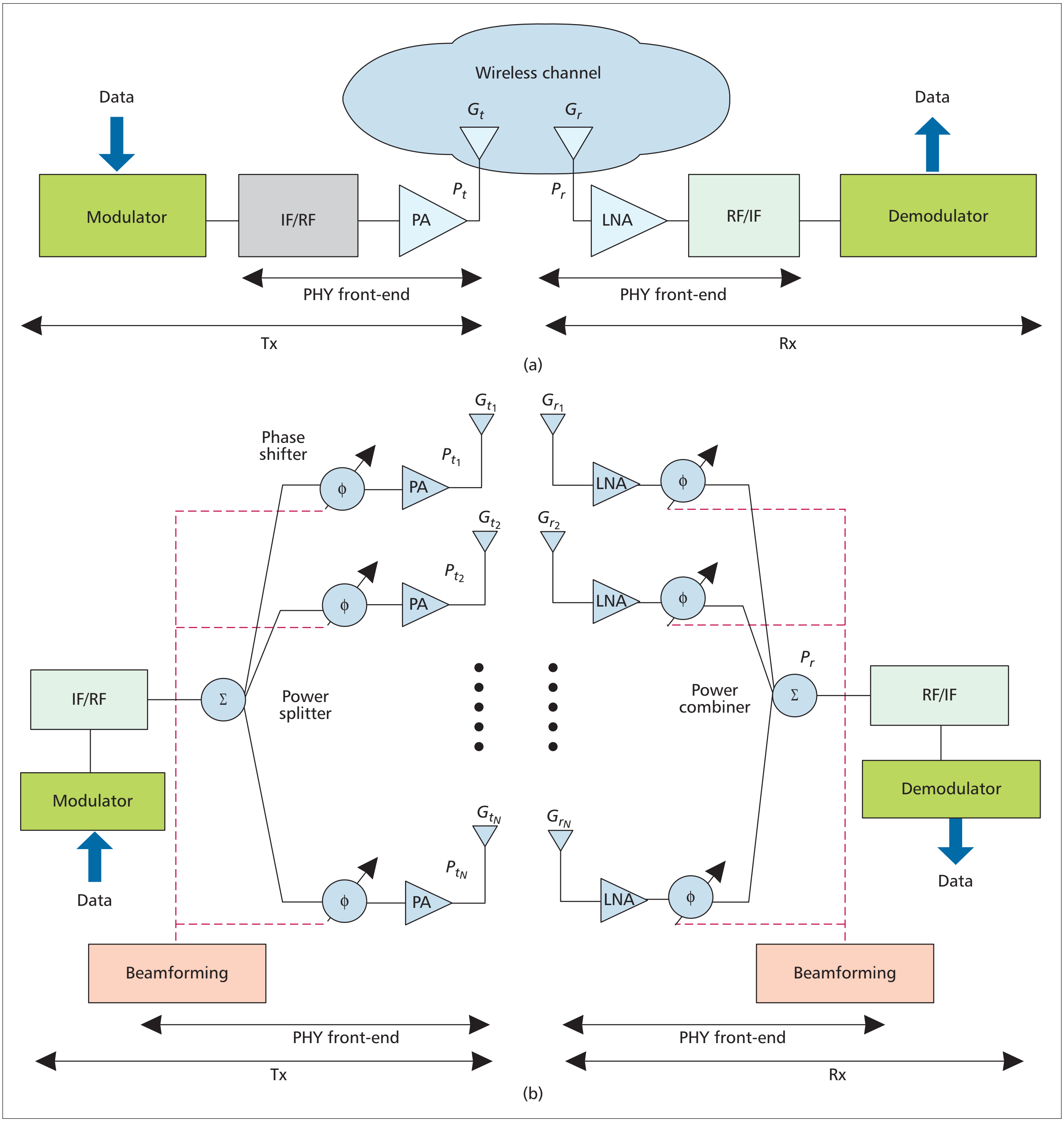

Figure 2. The 60 GHz backhaul link PHY front-end architecture with a) single antenna; b) phased array antenna.

the maximum throughput. The received SNR is given as

$$SNR = P_t \cdot G_t \cdot G_r \cdot \left(\frac{\lambda}{4\pi \cdot \ell}\right)^n \cdot \frac{1}{K_B \cdot T_0 \cdot B_w \cdot N_F \cdot \mathcal{L}}, \quad (1)$$

where λ and ℓ are the carrier wavelength and link range, respectively, and K_B, T_0, B_w, N_F, and $\mathcal{L}$ denote the Boltzmann constant (1.38×10^{-23} J/K), absolute room temperature (290 K), channel bandwidth, receiver noise figure, and losses, respectively. The next section elaborates on different types of losses $\mathcal{L}$. The constant n, called the path loss exponent, is explained below. Depending on the symbol constellation, different values for minimum SNR ($SNR_{\min}$) are required to detect the signal for a desired bit error rate (BER). If $N_t = N_r = 1$, Eq. 1 gives the received SNR of a SISO link.

Path Loss Exponent for Outdoor Channel: Table 11 in [3] summarizes six indoor and outdoor path loss measurement campaigns at 60 GHz. For an outdoor channel, the path loss exponent is between 1.33–2.5, while [8] suggests using $n = 2.2$ for outdoor channels. The problem is that most of these measurements are performed with low altitude antennas (i.e., the antenna height is close to the objects on the ground), whereas for backhaul applications antennas are mounted on posts/towers, which are at least 3 m above ground, which makes the channel close to line of sight (LOS). In addition, these measurements are performed with antenna gain less than 24 dBi, while, as we show, a higher antenna gain is required for a 60 GHz backhaul link, with a consequently narrower beamwidth. These requirements also make the channel closer to LOS. In this work we use $n = 2$ for illustration purpose only, but for a conservative design $n = 2.2$ is recommended.

Array Efficiency: This is an important parameter of a phased array system often neglected in link design equations. It represents the portion of the total input power that is radiated into the space [9]. Usually, array efficiency drops as the array size or antenna gain enlarges due to the increase in the antenna feeding network loss. To model the array efficiency, we use an exponential dependency on the square root of the total antenna gain as

$$\eta_t = e^{-\alpha\sqrt{N_t \cdot G_{t1}}},$$

where α is a constant dependent on the array fabrication technology. The array antenna designer can determine the proper value for α from simulation or measurement. This relation gives a high efficiency for small arrays with small array count (or number of antennas) or low element gain, while it drops gradually as the array enlarges.

Self-Organizing Backhaul Network: Phased array systems are the ultimate solution for a self-organized backhaul network because of the electronic beam-steering capability. This eases network planning and link installation, making one-man one-ladder deployment feasible. On the other hand, this capability alleviates the issue of link outage due to blockage or antenna misalignment.

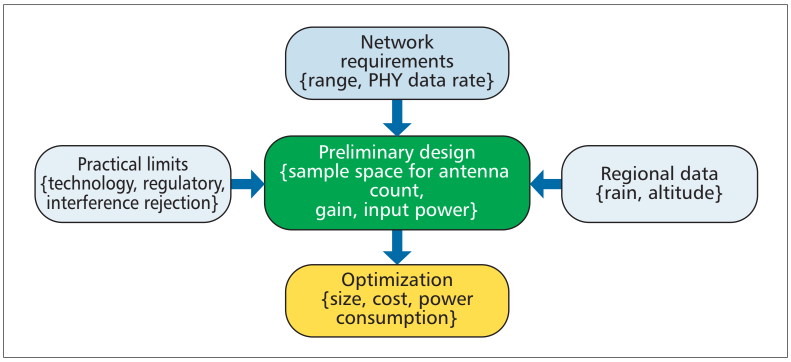

Figure 3. Framework for the 60 GHz backhaul link design.

Spatial Power Combination: Low-cost silicon technologies, such as complementary metal oxide semiconductor (CMOS), impose a hard limit on the maximum output power of a single RF path $P_{t_1} < 10$ dBm. The use of phased array increases the total transmitted power by coherent combination of individual transmitted signals in a desired direction ($P_t = N_t \cdot P_{t_1}$).

Backhaul Link Design

In this section, we present a framework shown in Fig. 3 for the backhaul link design. The goal is to determine the critical Tx and Rx system parameters such as the number of antennas, individual antenna gain, and individual input power, to achieve a predetermined PHY data rate at a given range in certain atmospheric conditions using Eq. 1. The link designer must have a realistic understanding of the network requirements, 60 GHz technology, and regional environment before embarking on the link design. For phased array implementation, where the designer may come up with multiple solutions, the antenna count can be determined by cost optimization. Each design process is explained below.

Network Requirements

A network operator determines the basic link requirements such as coverage range and PHY data rate considering the deployment scenario. These are the inputs of the link design problem. For example, achieving a minimum of 1 Gb/s PHY data rate at 500 m range could be a reasonable goal for a typical small cell backhaul link.

Practical Limits

The selection of Tx and Rx system parameters is restricted by practical limits originating from technology and regulatory limits as explained in the following.

FCC Power Limit: In the recent (August 2013) FCC ruling [10], the average EIRP limit for 60 GHz devices with antennas located outdoors increased from 40 dBm to 82 dBm minus 2 dB for every dB that the antenna gain is below 51 dBi. Similarly, the peak EIRP limit was increased from 43 dBm to 85 dBm minus 2 dB for every dB that the antenna gain is below 51 dBi.

Transmit Power Limit: The transmitted power of an RF integrated circuit (RFIC) at mmWave is limited by the semiconductor processing technology.

Modulation	Code rate	Information bits/symbol	Channel bandwidth (MHz)					
			100	400	800	1200	1600	2000
			PHY data rate (Mb/s)*					
BPSK	1/2	1/2	47	188	375	563	750	938
BPSK	3/4	3/4	70	281	563	844	1125	1407
QPSK	1/2	1	94	375	750	1125	1500	1875
QPSK	3/4	3/2	141	563	1125	1688	2250	2813
16-QAM	1/2	2	188	750	1500	2250	3000	3750
16-QAM	3/4	3	281	1125	2250	3375	4500	5625
64-QAM	3/4	9/2	422	1688	3375	5063	6750	8438
256-QAM	3/4	6	563	2250	4500	6750	9000	11250
256-QAM	5/6	20/3	623	2490	4980	7470	9960	12450

*Low-density parity check (LDPC) block size and LDPC guard interval size are 512 (same as in 802.11ad) symbols and 32 (64 in 802.11ad) symbols, respectively.

Table 2. PHY data rate for various combinations of modulation scheme, code rate, and channel bandwidth.

For example, the 1 dB compression point (P_{1dB}) for a PA designed in a low-cost silicon-based technology such as 65 nm CMOS at 60 GHz is below 10 dBm. The Tx PA must operate below the 1 dB compression point to be in the linear region ($P_t < P_{1dB}$). This is crucial for amplitude modulation schemes such as rectangular 16-quadrature amplitude modulation (QAM), but less important for phase modulation techniques such as binary phase shift keying (BPSK). One way to obtain high transmitted power with low-cost technology is to use array architecture at Tx [11].

Parameter	Value	Description
B_w	400 MHz	Channel bandwidth
$EIRP_{max}$	82 dBm	FCC average EIRP limit
N_F	10 dB[1]	Rx noise figure
$\mathcal{L}_m$	5 dB[2]	Miscellaneous loss
$\mathcal{N}$	$1 \leq \mathcal{N} \leq 64$	Antenna count
$\mathcal{G}$	$1 \leq \mathcal{G} \leq 36$ dBi	Individual antenna gain
η	$0.7 \leq \eta \leq 1$	Array efficiency
ℓ	$50 \leq \ell \leq 1000$ m	Link range
$\mathcal{R}$	$0 < \mathcal{R} < 2500$ Mb/s	PHY data rate

[1] Noise figure in 802.11ad is 10 dB.
[2] Implementation loss in 802.11ad is 5 dB.

Table 3. Parameter configuration for link design framework.

Interference Rejection: Interference rejection is a top priority in the 4G/5G cellular networks as the 57–66 GHz unlicensed band deployments become prevalent. Dynamic frequency selection (DFS) is a mechanism by which radios continuously scan the available channels for clear spectrum and assign it for usage. The number of available channels for operation are increased by customizing the channel bandwidth B_w. This brings an interesting question about the proper channel bandwidth required to deploy a backhaul link.

Table 2 shows the PHY data rates for various combinations of channel bandwidth, modulation scheme, and code rate, varying from simple BPSK to complex modulations such as 256-QAM. The PHY data rates are calculated according to 802.11ad [4] single-carrier (SC) PHY. It is seen that multi-gigabit PHY data rates are never achieved for narrow channel bandwidths (100 MHz). Wider channel bandwidths (≥ 1600 MHz) with a simple modulation (BPSK) ensure multi-gigabit PHY data rates. Such transceivers have a simple structure with relaxed phase noise and noise figure requirements. Thus, a moderate value for channel bandwidth ($400 \leq B_w \leq 800$ MHz) balances the hardware complexity and interference resistance. The 802.11ad offers 4 channels, each 2.16 GHz wide (centered at 58.32, 60.48, 62.64, and 64.8 GHz), for WiFi applications, but this channel bandwidth is too large to mitigate the overall interference between links in a backhaul network. Conversely, 400 MHz bandwidth results in more than 20 channels in the unlicensed 60 GHz band, which improve the DFS performance significantly.

Loss Budget Calculation: The atmospheric loss is summation of oxygen absorption loss $\mathcal{L}_{o_2}$ and the precipitation loss $\mathcal{L}_{rain}$. The oxygen absorption loss can be as high as 15 dB/km at sea level at 60 GHz, while the precipitation loss is 5 dB/km and 12 dB/km for rain intensity of 10 mm/h and 30 mm/h, respectively, according to International Telecommunications Union — Radiocommunication (ITU-R) P676-6. The other sources of losses $\mathcal{L}_m$ are antenna misalignment loss, receiver implementation loss, transmitting losses, processing losses, shadowing and fading loss, and beam-shaping losses for phased arrays. Underestimating the total loss will limit the link range and performance in critical weather conditions.

Preliminary Design

The purpose of preliminary design is to derive a sample solution for the Tx and Rx system parameters using Eq. 1 considering the system requirements and practical limits elaborated above. Table 3 shows the input and output parameters of the preliminary design as well as some practical ranges or values that do not affect the generality of the approach.

Figure 4 shows the results of the preliminary link design in terms of the maximum achievable $\mathcal{R}$ under clear sky conditions ($\mathcal{L}_{rain}$ = 0 dB) for various combinations of $\mathcal{N}$ and $\mathcal{G}$ for ℓ = 100, 500, and 1000 m. For each combination of these parameters, SNR is calculated as defined in Eq. 1, and the maximum achievable $\mathcal{R}$ with 400 MHz channel bandwidth is deduced using Table 2. If the EIRP is higher than the FCC average EIRP limit, the total input power P_t is reduced to meet the limit, and the new PHY data rate is calculated. The light colored strip (yellow) distinguishes the low $\mathcal{R}$ (< 1 Gb/s) subspace (blue) from high $\mathcal{R}$ (≥ 1 Gb/s) subspace (red). As the link range increases, this border shifts toward the right because of the decrease in the SNR, which is compensated by either increasing the antenna count, the individual antenna gain, or both to maintain a predefined $\mathcal{R}$.

Regional Data

The link designer must take into account the precipitation history of the region. Figure 5 illustrates the impact of rainfall on the maximum achievable $\mathcal{R}$ for ℓ = 500 m, $\mathcal{G}$ = 24 dBi, and $\mathcal{N}$ = 6, 12, and 16, respectively. Putting rainfall intensity into perspective, San Diego, California, London, United Kingdom, and Bangkok, Thailand experience on average up to 10, 15, and 30 mm/h of rainfall. Higher precipitation intensity increases the signal loss and reduces the SNR at the receiver. Depending on the choice of $\mathcal{N}$ and $\mathcal{G}$, a backhaul link designer configures the link margin, which is $SNR - SNR_{min}^{R=1\text{Gb/s}}$, where $SNR_{min}^{R=1\text{Gb/s}}$ is the minimum SNR required to detect signals at $\mathcal{R}$ = 1 Gb/s and a given BER. A large positive link margin ensures $\mathcal{R}$ ≥ 1 Gb/s for higher rainfall values, but has implications on the cost.

Design Summary

A small cell backhaul link range of 1000 m is considered an extreme case, while a 400–600 m range is more common since a typical 4G/5G small cell radius is 10–200 m. As seen in Fig. 4, achieving PHY data rate of 1125 Mb/s in 400 MHz channel bandwidth using a single antenna ($\mathcal{N}$ = 1) for short-, medium-, and long-range backhaul links (ℓ = 100, 500, and 1000 m) requires 24 dBi, 31 dBi, and 36 dBi antenna gain, respectively. For a small array size ($\mathcal{N}$ ≤ 12), 1125 Mb/s in 400 MHz channel bandwidth is achieved for short-, medium-, and long-range backhaul links with a minimum of 14 dBi, 21 dBi, and 26 dBi individual antenna gain, respectively. Similarly, for large size arrays ($\mathcal{N}$ = 64), 1125 Mb/s in 400 MHz channel bandwidth is achieved for short-, medium-, and long-range backhaul links with a minimum of 7 dBi, 13 dBi, and 18 dBi individual antenna gain, respectively.

The FCC regulations and technology limitations restrict the increase of input power (P_{t_1}). A link designer may compensate the impact of rain and other sources of losses by appropriately provisioning the backhaul link margin. For example, to add around 10 dB link margin, a designer may

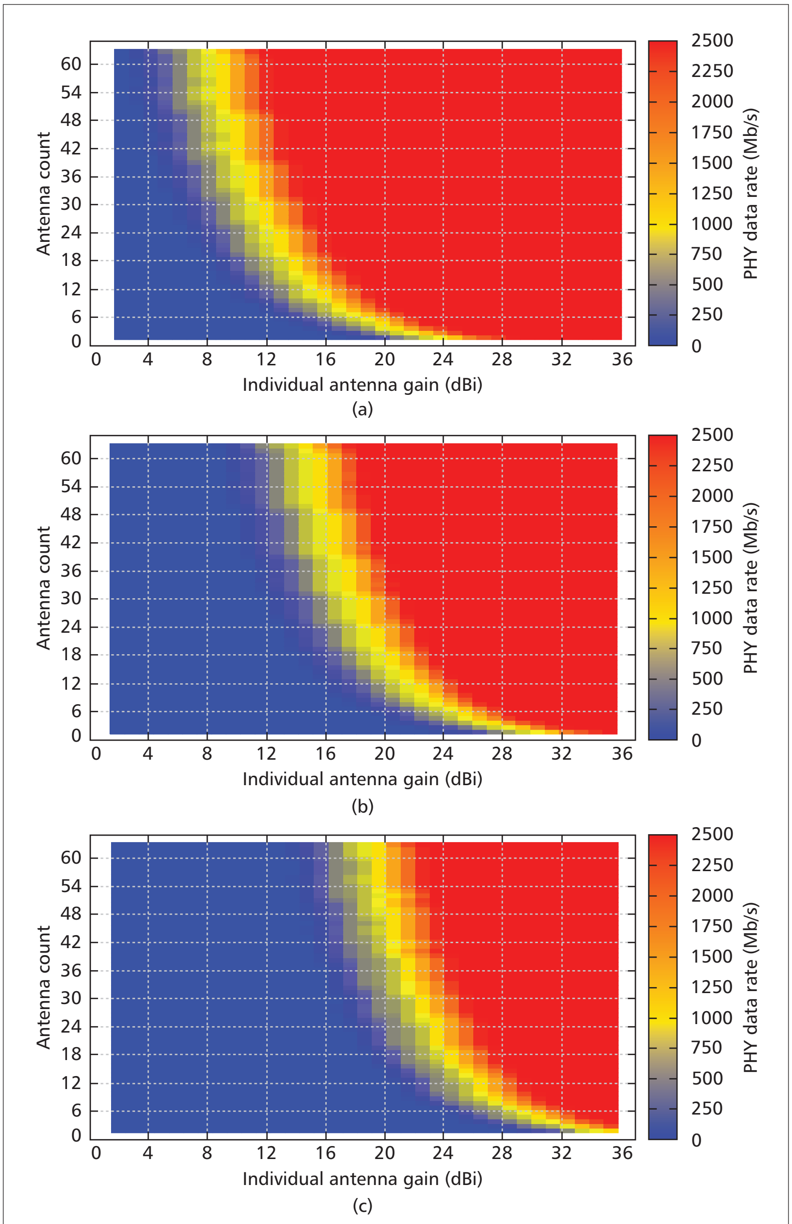

Figure 4. Maximum achievable PHY data rate under clear sky conditions for various combinations of individual antenna gain and antenna count for link range of: a) 100 m; b) 500 m; c) 1000 m.

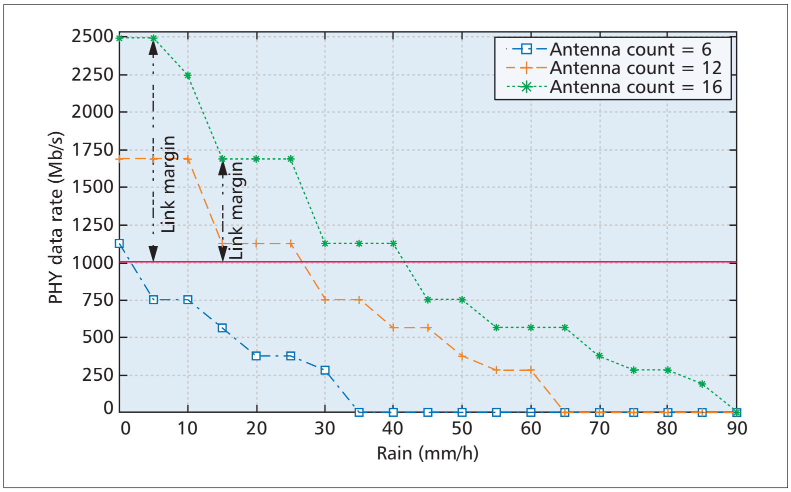

Figure 5. Impact of rainfall on the maximum achievable PHY data rate for individual antenna gain of 24 dBi and antenna count of 6, 12, and 16 for link range of 500 m.

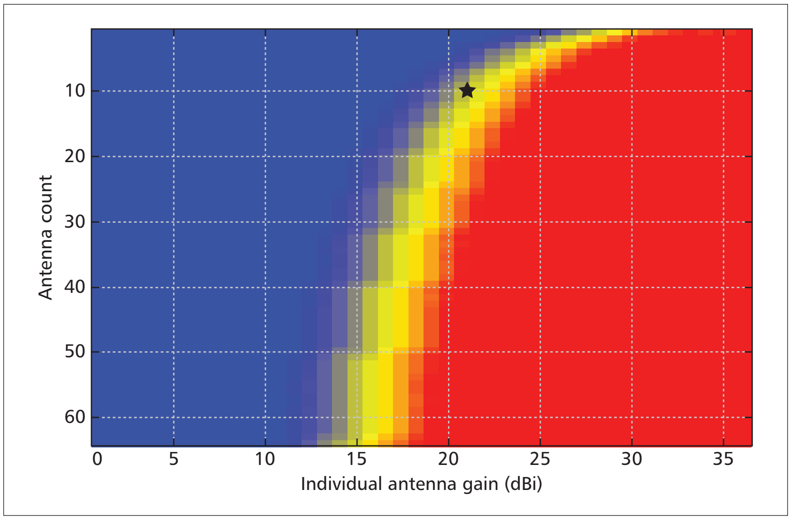

Figure 6. The cost optimization results for selecting the optimal antenna count and individual antenna gain to achieve PHY data rate of 1125 Mb/s at link range of 500 m. The black star shows the optimum point.

increase the Tx and Rx antenna gain (P_t, G_t) by 5 dBi each, double the number of Tx and Rx array antennas (N_t, N_r) (9 dB link margin), or increase the channel bandwidth (B_w).

Cost Optimization

Figure 4 illustrates that several combinations of individual antenna gain and antenna count can provide the required PHY data rate (e.g., $\mathcal{R} \geq 1$ Gb/s). To find optimum values for $\mathcal{N}$ and $\mathcal{G}$, we can define a proper cost function for a phased array link, and choose the corresponding values of $\mathcal{N}$ and $\mathcal{G}$ that minimize it. The link cost function consists of at least three parts:

- The antenna array cost $f_A(\mathcal{N}, \mathcal{G})$, which depends on the antenna count and individual antenna gain
- Radio hardware cost $f_R(\mathcal{N})$, which depends on the number of RF paths and silicon technology
- Power consumption cost $f_P(\mathcal{N})$, which depends on the number of RF paths and the power per path [12]

Thus, a generalized phased array cost function is defined as

$$c(\mathcal{N}, \mathcal{G}) = a_1 \cdot f_A(\mathcal{N}, \mathcal{G}) + a_2 \cdot f_R(\mathcal{N}) + a_3 \cdot f_P(\mathcal{N}), \quad (2)$$

where a_1, a_2, and a_3 are constants with the sum equal to one and determine the contribution of each part. Usually, the array cost scales linearly with the antenna count, that is, $f_A(\mathcal{N}, \mathcal{G}) = \mathcal{N} \cdot f_G(\mathcal{G})$, where $f_G(\mathcal{G})$ is the cost of one antenna. As a case study, we calculate a simplified cost function for $a_1 = 1$, and $a_2 = a_3 = 0$, defined as

$$c = \frac{\mathcal{G} \cdot \mathcal{N}}{\max(\mathcal{G} \cdot \mathcal{N})}, \quad (3)$$

for the data set shown in Fig. 4b. Equation 3 represents a case where antenna array cost has the major contribution in the link cost ($a_1 \gg a_2, a_3$). This is the case for mmWave backhaul applications, where high gain antennas with relatively large size are required. Figure 6 shows the calculated cost function to achieve $\mathcal{R} = 1125$ Mb/s at $\ell = 500$ m under clear sky conditions. It is seen that the optimal point, marked by a black star, occurs when $\mathcal{G} = 21$ dBi and $\mathcal{N} = 10$. The red region shows the possible options that give $\mathcal{R} > 1125$ Mb/s, while the blue region corresponds to $\mathcal{R} < 1125$ Mb/s. For the points on the border between the blue and red regions, the cost function varies from a minimum of 0.63 (optimal point) to a maximum of 1.

Conclusion

The recent modifications to Part 15 of the FCC regulations foster the development of a very high-speed longer-range 60 GHz backhaul alternative to connect wireless broadband networks. 60 GHz is an ideal solution for 4G/5G small cell backhaul links since it promises to be cost effective and further benefits from proliferation of 802.11ad, which reduces the cost of 60 GHz technology. We present a 60 GHz backhaul link design framework that translates the link requirements to important transmitter and receiver system parameters. The approach includes a preliminary design that generates the input data set for an optimization problem. The SISO and phased array PHY front-end architectures are discussed. We evaluate the proper channel bandwidth for the backhaul links and calculate the PHY data rates for the proposed MCSs. For the backhaul links designed with phased array antenna, an optimization problem is defined to find the optimum transmitter and receiver system parameters such that the size, cost, and power consumption are minimized.

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Biographies

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