mmWave based vs 2 GHz networks: What is more energy efficient?

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***Abstract*—The demand for increasingly challenging data rates in cellular networks has motivated the pursuit to exploit abundant bandwidth at the millimeter waves (mmWave) spectrum, which offers large bandwidths and near free-space path loss for line of sight links. However, this solution comes at the cost of limited communication range. Thus, mmWave basestations (BS) are expected to be densely deployed to maximize offered service. As the energy consumed in a network is roughly proportional to the number of nodes, how energy efficient a mmWave network will be is a question that remains unanswered so far.**
In this paper, we compare the performance of mmWave cellular networks in terms of energy efficiency (EE) to that of networks operating at 2 GHz. We start from the link budget to determine the average cell radius of two mmWave systems operating at 28 GHz and 60 GHz. Afterwards, intensity of a Poisson Point Process that models mmWave BS locations pertaining to expected operational network parameters is calculated. The probability of coverage offered by investigated systems is evaluated using analytical expressions. Finally, EE is calculated using consumed power model that assumes actual mmWave components. Results suggest that when the deployment environment allows for high signal to interference and noise ratio (SINR) to be achieved at the receiver, mmWave system EE outperforms a 2 GHz system. Conversely, when only low SINR is achievable, 2 GHz system EE is superior to mmW system.

I. Introduction

Pursuing the ambitious data rate targets in future 5G cellular networks has seen advancements on all possible facets of the network. Solutions stretch from new waveforms [1] and Massive-MIMO [2] to embedding network-wide intelligence in the core-network [3]. Exploiting new spectrum, millimeter-waves (mmWave) spectrum in particular, is a strongly advocated approach by research community [4]. Thrust towards mmWave is driven by the abundant available bandwidth that allows for unprecedented high data rates. Implementing mmWave communication for cellular networks offers a fast escape route from the currently congested and cluttered spectrum toward more accommodating spectrum. Path loss for mmWave communication at 28 GHz licensed band is near free-space for line of sight (LOS) links while it is higher for 60 GHz unlicensed band mainly because of oxygen attenuation [5].
The small wavelength of mmWave coupled with advances in antenna array design allow to implement a large number of antennas at both transmitter and receiver resulting in large beamforming gains. Because of its limited feasible communication range, BSs are expected to be densely deployed to provide unobstructed coverage to users. Hence, investigating the capacity benefit of introducing a large number of mmWave nodes to the network relative to the added burden of energy consumption becomes essential. In contrast to focusing on mobile station power consumption, we target the overall network EE in terms of bit-per-joule capacity introduced in [6].
Evaluating energy prospects is of great importance for the network designer and operator for its substantial role in 5G networks. Energy efficiency (EE) has been investigated extensively for legacy cellular systems, e.g., Long Term Evolution (LTE) [7], but not for mmWave. An important question to answer in this context is which of the two, i.e., legacy cellular network and mmWave cellular network, is more energy efficient?. We examine this question for the first time since limited work has been reported in literature investigating EE for mmWave networks. Authors in [8] addressed the EE of mmWave relay operation and concluded that a coverage radius of 150 [m] provides the most efficient service relative to the system parameters. Consumption factor approach was discussed in [9] to assess EE of the combined mmWave communication link. Addressing heterogeneous cellular networks, [10] demonstrated the effectiveness of different macro-cells sleeping strategies while highlighting that EE gain due to small cell deployment tends to saturate as the small cells density increases.

In this paper, we compare EE of a mmWave based cellular network to that of a small cell cellular network operating at 2 GHz, referred to henceforth as RF system. We rely in our investigation on well established analytical expressions available in literature to calculate the probability of coverage which is a substantial factor for determining EE. Moreover, we incorporate power consumption parameters of actual mmWave components either available in the market or proposed in literature. Results indicate that RF and mmWave can complement each other in terms of EE, which supports the control and data plane split architectures being considered for 5G [3]. To the best of our knowledge this is the first work that provides a comparative analysis of EE in RF and mmWave based small cell networks.

The rest of this paper is organized as follows: Section II provides an overview of the investigated systems and elaborates on the considerations of probability of coverage. Section III details the calculation of EE and power consumption model. Results are discussed in Section IV. Finally, Section

978-1-5090-0304-4/16/$31.00 ©2016 IEEE

V concludes the paper.

II. System Model

We compare a cellular network where coverage is solely provided through mmWave small cells to another system where coverage is based on 2 GHz small cells. Deployment locations of BSs in both cases are modeled with a Poisson Point Process (PPP) of intensity λ and λ_b for the mmWave and the RF systems, respectively. Furthermore, we focus only on outdoor coverage rather than indoor. Mobile stations (MS) of both systems are located at the edge of the coverage range of each BS determined by link budget requirements. Hence, BSs are operating at the maximum possible transmission power in attempt to achieve the required coverage. In consequence, SINR at MS is controlled by the signal shadowing characteristics arising from surrounding buildings geometry. The two networks are comparable since they operate under similar assumptions and the only difference is due to the propagation nature of mmWave and the effect of buildings blockage. While this scenario is hypothetical in the sense that a realistic network will have a indoor/outdoor hybrid mix of legacy and mmWave nodes according to the operators deployment considerations, it still allows to illustrate the system performance trend and how it is affected by deployment environment.

In the mmWave systems, path loss follows the close-in free space reference distance model presented in [5]:

$$PL(d) = PL(d_0) + 10\alpha \log_{10}\left(\frac{d}{d_0}\right) + \chi_\sigma \tag{1}$$

where $PL(d_0)$ is the free space path loss at d_0, i.e., the free space reference distance [m], d is the communication link length [m], α is the path loss exponent and χ_σ is the large-scale shadowing random variable of zero mean and standard deviation σ.
mmWave communication exhibits a near-free space path loss when a LOS exists between MS and BS. The probability that a communication link is LOS is modelled by an exponential probability density function of the form $p(R) = e^{-\beta R}$, where $\frac{1}{\beta}$ is the average LOS range of the network and R is the link distance [11]. The study detailed in [12] suggests approximating $p(R)$ with a step function that is equal to 1 when a BS is inside a ball of radius R_B or a zero otherwise. R_B is called the radius of equivalent LOS ball representing blocking due to buildings and structures surrounding the mmWave network nodes. R_B is determined by path loss model parameters (both LOS and NLOS) and the probability of LOS association for a given scattering elements distribution in an environment. Consequently, the average number of LOS BSs (relative LOS BSs density) is defined as $\rho = \lambda\pi R_B^2$.

In our study, we focus on two distinct frequency bands, 28 GHz and 60 GHz, both considered to belong to mmWave spectrum [5]. The assumption that the same LOS probability holds for multiple mmWave bands is used by authors in [13]. Nevertheless, the authors point out that generalization of this assumption should be exercised with caution. Since mmWave propagation has higher path loss exponent for 60 GHz than that for 28 GHz, we assume that its equivalent LOS ball radius satisfies the following expression:

$$R_B^{60GHz} = \nu R_B^{28GHz} \tag{2}$$

where $\nu \in [0,1]$ is a radius reduction factor introduced to account for signal power losses at higher frequencies due to various phenomena: rain attenuation, oxygen absorption and others. This leads to R_B^{60GHz} having a lower value than R_B^{28GHz} thus affecting the probability of coverage. Furthermore, small scale fading effects are assumed negligible as argued in [12] and [5]. Consequently, in a dense mmWave network the probability of coverage as a function of the SINR threshold γ is approximated as [12]:

$$p_{cm}(\gamma) \approx \rho e^{-\rho} \sum_{\ell=1}^{N} (-1)^{\ell+1} \binom{N}{\ell} \int_0^1 \prod_{k=1}^{4} \exp\Bigg(-\frac{2}{\alpha_L} b_k \rho t \times \left(\ell\eta\gamma\bar{a}_k\right)^{\frac{2}{\alpha_L}} \Gamma\Big(-\frac{2}{\alpha_L}; \ell\eta\gamma\bar{a}_k, \ell\eta\gamma\bar{a}_k t^{\alpha_L/2}\Big)\Bigg) dt \tag{3}$$

where α_L is the LOS path loss exponent, N is the number of approximation terms (assumed to be $N = 5$ hereafter), $\eta = N(N!)^{-\frac{1}{N}}$, $\Gamma(x; a, b) = \int_a^b x^{s-1} e^{-x} dx$, and $\bar{a}_k$ and b_k are antenna geometry parameters, i.e., if M_t, m_t, θ_t and M_r, m_r, θ_r are the main lobe directivity gain, back lobe gain and half-power beamwidth of Tx and Rx antennas respectively, $\bar{a}_k = 1, \frac{m_t}{M_t}, \frac{m_r}{M_r}, \frac{m_r m_t}{M_r M_t}$ and $b_k = \frac{\theta_r\theta_t}{(2\pi)^2}, \frac{\theta_r}{2\pi}\left(1-\frac{\theta_t}{2\pi}\right), \frac{\theta_t}{2\pi}\left(1-\frac{\theta_r}{2\pi}\right), \left(1-\frac{\theta_r}{2\pi}\right)\left(1-\frac{\theta_t}{2\pi}\right)$ for $k = 1, 2, 3, 4$ respectively.

The RF system serves as a reference model. Assuming that thermal noise is negligible and interference is characterized by Rayleigh fading, authors in [14] derived a formula for the coverage probability:

$$p_{cb}(\gamma, \alpha) = \frac{1}{1 + g(\gamma, \alpha)} \tag{4}$$

where $g(\gamma, \alpha) = \gamma^{2/\alpha} \int_{\gamma^{-2/\alpha}}^{\infty} \frac{1}{1 + u^{\alpha/2}} du$ and α is the path loss exponent. It has been made clear in [14] that coverage does not depend on λ_b when the system is interference limited, i.e., noise is negligible. Increasing the number of BSs, regardless of cell size, does not affect coverage because the increase in the signal power is counter-balanced by the increase in interference power.

III. Energy Efficiency

Energy efficiency is expressed as the ratio of system throughput to total consumed power in bit per hertz per joules or the area spectral efficiency (ASE) to the per unit area power consumption [10]. ASE is defined as $ASE = \lambda p_c(\gamma) \log_2(1+\gamma)$. Average power consumption $P_{ave} = \lambda P$, where P is the BS power consumption.
Since the coverage is provided by a single type of BS in each of the investigated systems, λ cancels out and EE is then formulated as:

$$EE = \frac{p_c(\gamma)\log_2(1+\gamma)}{P} \tag{5}$$

TABLE I
POWER MODEL PARAMETERS

Parameter	2 GHz	28 GHz	60 GHz
A	2	4	4
P_{PA} [W]	1.1	1.83	3.07
P_{RF} [W]	0.6	3.05	
P_{BB} [W]	2.5	2	
σ_{DC}%	0.09	0.09	0.09
σ_{MS}%	0.11	0.11	0.11

where $p_c(\gamma)$ is the probability of coverage detailed in (3) for mmWave cellular network and (4) for RF cellular network. Power consumption follows the model proposed in [7]:

$$P = A\frac{P_{PA} + P_{RF} + P_{BB}}{(1-\sigma_{DC})(1-\sigma_{MS})} \tag{6}$$

where A is the number of transceiver chains, P_{PA} is the power consumed in the power amplifier to provide a given output power. P_{RF}, P_{BB} refer to the power consumed in RF and baseband (BB) units. σ_{DC}, σ_{MS} are the loss factors due to DC-DC power supply, and mains supply, respectively.

EE of the 2 GHz system is evaluated for a path loss exponent $\alpha = 4$ and power model (6) with parameters of femto cell BS reported in [7] and detailed in Table I. Approximate power consumption values for 60 GHz system are taken from the system detailed in [15]. For the 28 GHz system, we follow the design suggested in [16] and assume HMC6187LP4E power amplifier [17], TI ADC081000 ADC [18], TI DAC5682Z DAC [19]. Xilinx Virtex-6 field programmable gate arrays (FPGAs) are assumed to be used for BB processing [20]. σ_{DC} and σ_{MS} are assumed to remain constant for all systems.

IV. RESULTS

Link budget of mmWave networks is evaluated for the parameters detailed in Table II. Antenna gains are similar to those used in [12] while body loss accounts for fading due to human body movement reported in [21] and [22]. The maximum allowed path loss is found to be $\approx$ 118 dB (as detailed in Table II) which translates using (1) to an average cell radius $r_c^{60GHz} = 153.67$ $[m]$ and $r_c^{28GHz} = 334.98$ $[m]$. Path loss parameters in Table III are the results of measurement campaigns reported in [23] for 60 GHz and [5] for 28 GHz. The cell densities λ calculated through r_c resulting from link budget are then substituted into (3) to determine the ASE for mmWave networks where $r_c = \sqrt{1/\pi\lambda}$. ASE is thus determined and then substituted in (5) to calculate EE using power model in (6).

Equivalent LOS ball radius R_B is determined by analyzing actual buildings distribution. E.g., authors in [12] analyzed a snapshot obtained from Google maps of a university campus to find R_B that describes the blocking environment. In the following, we fix R_B^{28GHz} and evaluate reduction parameter ν in (2) at values $\{0.5, 0.75, 0.9\}$ to provide insight about a range of probable propagation scenarios and their effect on ASE. Given the system parameters listed in Tables I, II, and III, we report the following observations. Considering an environment with $R_B^{28GHz} = 200$ $[m]$, Fig. 1 illustrates EE

TABLE II
MMWAVE SYSTEM LINK BUDGET

Parameter	Value
Tx Power [W]	2
BS Antenna gain [dB]	10
BS Cable Loss + Connectors [dB]	4
Effective Tx Power [dBm]	39
Body Loss [dBi]	35
MS Rx sensitivity [dBm]	-104
MS Antenna gain [dB]	10
Maximum Allowed Path Loss [dB]	118

TABLE III
SYSTEM PARAMETERS

Parameter	Value
BS Antenna front lobe gain [dB]	10
BS Antenna back lobe gain [dB]	-10
BS Antenna half-power beamwidth	30°
MS Antenna front lobe gain [dB]	10
MS Antenna back lobe gain [dB]	-10
MS Antenna half-power beamwidth	90°
LOS path loss exponent α_L (28/60 GHz)	2.25/2.1
LOS path loss standard deviation σ_L [dB] (28/60 GHz)	2/3.6

of the RF system, a 28 GHz mmWave system and multiple 60 GHz mmWave systems. In this case, $R_B^{28GHz} < r_c^{28GHz}$. Therefore, a 28 GHz cell suffers from building blockage within its coverage range resulting in lower EE compared to 60 GHz and RF. When the value of ν yields $R_B^{60GHz} < r_c^{60GHz}$, we observe a similar effect of efficiency degradation at 60 GHz.

We notice that a 60 GHz system is more energy efficient than a 28 GHz for all examined values of ν because of the higher probability of coverage at 60 GHz with a cell radius $r_c^{60GHz} < r_c^{28GHz}$. Relaxing the constraint imposed by R_B^{60GHz} - by assuming a larger ν - allows for a higher EE of the 60 GHz system.

EE of mmWave systems degrades when operating in a an environment with closely located buildings. This is captured in Fig. 2. We observe that the intersection point between RF curve and those of mmWave is shifted to the right indicating that RF system offers lower energy cost for a wider range of

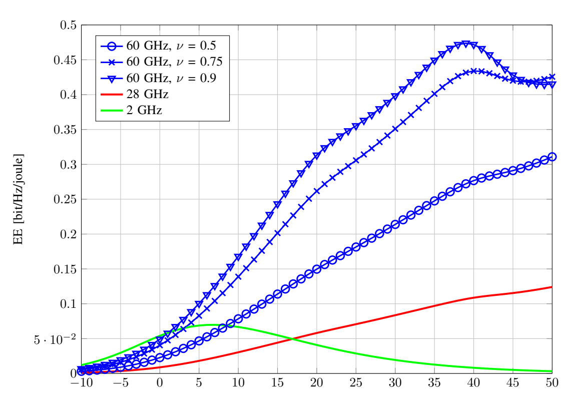

Fig. 1. $R_B^{28GHz} = 200[m]$

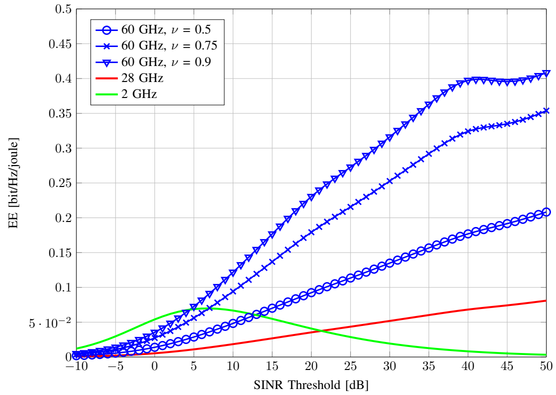

Fig. 2. $R_B^{28GHz} = 150[m]$

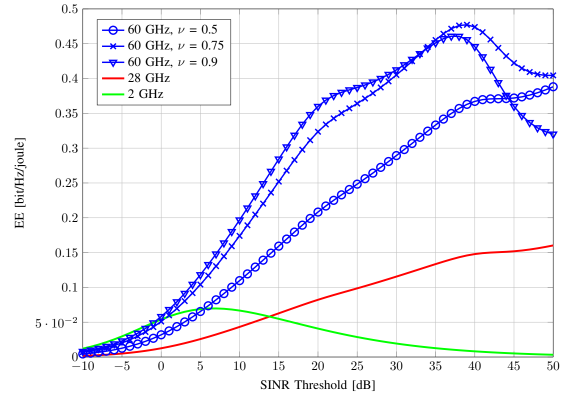

Fig. 3. $R_B^{28GHz} = 250[m]$

SINR in this type of environment.

Results for an environment with sparsely distributed scatterers are depicted in Fig. 3. In addition to previously stated observations and by comparing with results presented in Fig. 2, we notice that 60 GHz system reaches the maximum achievable EE faster (i.e., for lower SINR) when R_B^{60GHz} is large. It is noticeable that the 60 GHz system with $\left(\nu = 0.9, R_B^{60GHz} = 225\ [m]\right)$ becomes less energy efficient than the system with $\left(\nu = 0.75, R_B^{60GHz} = 187.5\ [m]\right)$ after a given SINR threshold. This can be explained by observing the probability of coverage illustrated in Fig. 4 as follows: a system with $R_B^{60GHz} > r_c^{60GHz}$ will allow for more BSs to lie within the same equivalent LOS ball (in our case, $r_c^{60GHz} \approx 153\ [m]$). Therefore, it allows for interference limitation to be introduced, lowering the probability of coverage after a given SINR threshold and thus bounding the achievable ASE for a certain power consumption. On the other hand, a lower R_B^{60GHz} that is still larger than r_c^{60GHz} allows for fewer BSs in the same equivalent LOS ball which delays the interference limitation effect to a higher SINR threshold. Suffering from increased interference after reaching the maximum, EE starts to decline.

An RF system delivers better EE than both studied mmWave systems when the geometric distribution of surrounding buildings (represented by R_B) greatly obstructs mmWave signals allowing for comparably low SINR at the MS. This is because of the higher probability of coverage associated with RF propagation in such cases.

When the environment allows for a higher SINR at the MS, it is evident that mmWave system is superior to RF in terms of spectral efficiency and EE. mmWave potential to deliver very high SINR will permit to exploit higher order modulation schemes. E.g., authors in [24] identify the minimum required carrier to noise ratio values for quasi-error-free reception by a coded 3/4 OFDM system with 1/4 guard interval in Rayleigh channels as 10.7 dB for QPSK, 16.7 dB for 16-QAM, and 21.7 dB for 64-QAM, respectively. This is clearly achievable with higher EE by mmWave.

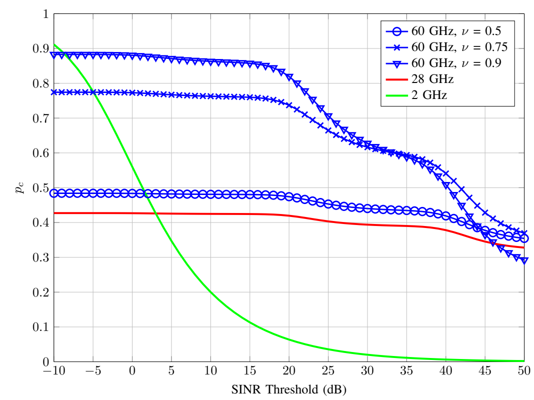

Fig. 4. Probability of coverage, $R_B^{28GHz} = 250[m]$

V. Conclusion

We analyze and compare the EE of mmWave systems at 28 GHz and 60 GHz to that of a cellular network operating at 2 GHz. The deployment environment has been shown to be a limiting factor of the achievable EE. In environments with high buildings blockage, RF system provides superior EE because of the favorable propagation characteristics of 2 GHz signals. When the blockage restrictions are lifted, further facilitating LOS links, mmWave systems offer significant improvement in EE.

These findings reveal that RF and mmWave can effectively complement each other in terms of EE in the control and data plane split architectures being considered for 5G. In such architectures, achievable SINR can be estimated and regularly updated by a polling procedure initiated by the BS. Afterwards, small cell BS can be operated at mmWave on high SINR when achievable, whereas control macro BS can be operated on RF bank in low SINR. The outcome is a more energy efficient network, compared to that where dense RF small cells have to be operated at high SINR resulting in low energy efficiency.

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