Waste Factor: A New Metric for Evaluating Power Efficiency in any Cascade

Mingjun Ying, Dipankar Shakya, Hitesh Poddar, and Theodore S. Rappaport
NYU WIRELESS, Tandon School of Engineering, New York University, Brooklyn, NY, 11201
{yingmingjun, dshakya, hiteshp, tsr}@nyu.edu

Abstract—**In this paper, we expand upon a new metric called the Waste Factor (*W*), a mathematical framework used to evaluate power efficiency in cascaded communication systems, through power wasted in individual components. We show that the derivation of the Waste Factor, a unifying metric for defining wasted power along the signal path of any cascade, is similar to the mathematical approach used by H. Friis in 1944 to develop the Noise Factor, which has since served as a unifying metric for additive noise power in a cascade. Further, we leverage the power usage effectiveness (PUE), which is a widely used energy efficiency metric for data centers, to evaluate *W* for the data center as a whole. The use of *W* allows easy comparison of power efficiency between data centers. Our study further explores how insertion loss of components in a cascaded communication system influences *W* at 28 GHz and 142 GHz along with the data rate performance, evaluated using the consumption efficiency factor (CEF). We observe CEF's marked sensitivity, particularly to phase shifter insertion loss changes. Notably, CEF variations are more prominent in uplink transmissions, whereas downlink transmissions display relative CEF stability. Our exploration also covers the effects of varying User Equipment (UE) and Base Station (BS) numbers on CEF in cellular networks. We underscore the enhanced energy efficiency at 142 GHz, compared to 28 GHz, as UE and BS numbers escalate.**

Index Terms—**Waste Factor, Consumption Efficiency Factor, Energy Efficiency, Power Efficiency, Cascaded System.**

I. Introduction

As the evolution of telecommunications progresses from 5G towards 6G, there is an escalating demand for energy efficiency in both wired and wireless communication systems. Currently, these systems account for approximately 2-3% of the global energy demand, a figure projected to increase beyond 10% by 2030 [1]. This rise is primarily due to the forthcoming 6G networks, which promise ultra-wide bandwidths and increased data rates. These advancements, however, intensify the challenge of managing energy efficiency, especially within the context of resource-limited Internet of Things (IoT) devices [2], [3]. The critical need to reduce energy consumption in wireless networks also stems from the urgency to limit greenhouse gas emissions and mitigate climate change impacts.

In this context, wasted power is becoming a significant enemy of the planet, echoing a parallel from the past. Over 80 years ago, noise was the primary adversary to wireless communication. It was H. Friis who developed the Noise Factor, a unifying metric to deal with additive noise power in a cascade [4]. Today, the Waste Factor (W) emerges as an analogous tool designed to combat wasted power, the current adversary to our environment and energy resources.

The existing advancements in massive MIMO, beamforming, network slicing, renewable energy-powered base stations, and energy harvesting technologies have significantly contributed to reducing energy consumption in 5G networks [5], [6]. Furthermore, artificial intelligence (AI) and machine learning (ML) techniques, including reinforcement learning, are instrumental in maintaining a balance between quality of service (QoS) and energy consumption [7]. Despite these strides, a glaring gap persists in existing research - the lack of a comprehensive theoretical framework to measure and compare power efficiency across diverse wireless system architectures [8].

The W and the Consumption Efficiency Factor (CEF) [9]–[11] aim to fill this gap. By providing a standardized metric for comparing power consumption and energy efficiency across various system designs, they can guide engineers and product designers towards more sustainable and energy-efficient solutions. This approach aligns with the broader objective of achieving sustainability and minimal power consumption in the design of future wireless networks, particularly those operating at sub-THz frequencies [11]. Simulations in [11] also demonstrate that reducing cell size and increasing carrier frequency and channel bandwidth lead to lower energy expenditure per bit, confirming the relevance and utility of W in achieving energy-efficient design. In the current study, we further extend and apply these theoretical constructs, making the following contributions:

- While the concept and perceived usage of Waste Factor was first introduced in [11], we provide here for the first time a detailed mathematical derivation of W as well as intuitive analogies to Noise Factor based on H. Friis original mathematical derivations in [4].
- We extend the concept of Waste Factor to generalized communication systems, using the case of energy consumption in data centers as a primary example. Additionally, we illustrate the effectiveness of W through an example comparing the power waste of two data centers.
- We explore the impact of varying component efficiency for a transmitter (TX) and receiver (RX) cascade, particularly the phase shifter's insertion loss on CEF at 28 GHz and 142 GHz.
- We analyze the influence of varying user equipment (UE) and base station (BS) numbers on CEF of the network.

The structure of this paper is as follows. Section II derives the Waste Factor, elucidating the merits of W and drawing an analogy between its mathematical form and that of the Noise Factor. Section III uses a generalized W for data centers. In Section IV, we apply W to analyze future communication systems' energy efficiency. Section V discusses potential future research directions about Waste Factor. Finally, Section

VI concludes the paper.

II. Introduction to F and W

In this section we will focus on two parameters, F and W, that can be used to evaluate noise and power waste of communication systems, respectively.

A. Noise Factor

Noise factor (F) refers to the degradation of signal-to-noise ratio (SNR) in a cascade. Specifically, the noise factor F is defined as the ratio of the input SNR to output SNR, which is expressed as $F = SNR_i/SNR_o$. F expressed in dB is the noise figure (NF) and a value of 0 dB indicates no noise and degradation in SNR. Friis's formula is a mathematical equation widely used to calculate the overall F of cascaded devices, where each device has its own individual F and power gain, G. Once the total F is calculated, it can be used to determine the overall NF of the entire cascade. Based on [4], F for the cascaded system is

$$F = F_1 + \frac{(F_2-1)}{G_1} + \frac{(F_3-1)}{G_1G_2} + \ldots + \frac{(F_N-1)}{\prod_{i=1}^{N-1} G_i}, \quad (1)$$

where F_i represents the noise factor of the i-th device, and G_i represents its power gain (linear, not in dB).

B. Waste Factor

The Waste Factor characterizes power efficiency of a cascaded system by looking at the power wasted by components of the cascade. Akin to F, the power wasted by a device/cascade can also be examined by observing the progressive power waste, based on the output power at each stage, as the signal propagates down the cascade. Such formulation provides an intuitive way to understand power waste at each stage of the cascade and serves as a metric to directly compare the power efficiency of two devices/systems through wasted power.

For analysis, the power consumed ($P_{consumed}$) is split into three principal components:

- Signal power (P_{signal}): Power delivered to the device/cascade output (e.g., power amplifier output to matched load).
- Non-signal power ($P_{non-signal}$): Power consumed by devices to facilitate signal transfer in the cascade (e.g., standby power drawn by an amplifier).
- Non-path power ($P_{non-path}$): Power consumption of components that do not contribute to the signal and are not along the cascade (e.g., oscillators, displays, etc.).

Thus, $P_{consumed} = P_{signal} + P_{non-signal} + P_{non-path}$.

Fundamentally, W is defined as the ratio of power consumed by the signal path components to the useful signal power delivered along the cascaded communication system ($W = P_{consumed}/P_{signal,out}$) [11]. As W is based on the useful signal power output, it is referred to the output.

The formulation of W for a cascaded system is illustrated through a simple cascade of two devices in Fig. 1, neglecting $P_{non-path}$ from auxiliary components. Here, we define

$$P_{consumed} = W \times P_{signal,out}. \quad (2)$$

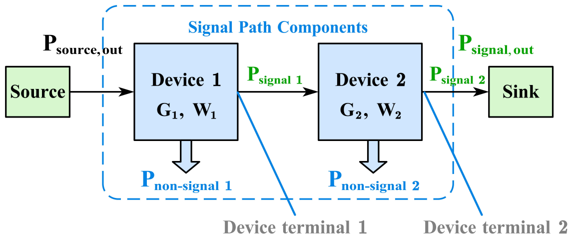


Fig. 1. A general cascade communication system composed of two devices.

Now, we can define the power consumed at device 1's terminal as:

$$P_{consumed,D1} = W_1 P_{signal\,1}, \quad (3)$$

and removing the input power to the device ($P_{source,out}$) the power consumption of device 1 alone is

$$P_{consumed\,1} = W_1 P_{signal\,1} - P_{source,out}, \quad (4)$$

similar to that, the power consumption of device 2 alone is

$$P_{consumed\,2} = W_2 P_{signal\,2} - P_{signal\,1}. \quad (5)$$

Intuitively, the total power consumed can be expressed as in Equation (6). This total power consumption is the sum of the power consumption of each individual device and the power input to the system.

$$P_{consumed} = P_{consumed\,1} + P_{consumed\,2} + P_{source,out}. \quad (6)$$

Also, we know that the output of the system is

$$P_{signal,out} = P_{signal\,2} = G_2 P_{signal\,1}, \quad (7)$$

based on the above equation(3)-(7), we can have

$$\begin{aligned} P_{consumed} &= W_2 P_{signal\,2} + (W_1 - 1) P_{signal\,1} \\ &= (W_2 + \frac{(W_1-1)}{G_2}) P_{signal,out}. \end{aligned} \quad (8)$$

Since (8) is equal to (2), then we have the power waste factor for the cascaded system

$$W = (W_2 + \frac{(W_1-1)}{G_2}). \quad (9)$$

Based on (9), W for a cascaded system with N devices can be generalized to (10).

$$W = \{W_N + \frac{(W_{N-1}-1)}{G_N} + \frac{(W_{N-2}-1)}{G_N G_{N-1}} + \ldots + \frac{(W_1-1)}{\prod_{i=2}^{N} G_i}\}. \quad (10)$$

C. Analogies between F and W

The analogous mathematical formulation of F and W is immediately visible from (1) and (10). There are, however, important characteristics of each metric to keep in mind when using them.

As the noise figure is a measure of the degradation of the SNR caused by the components in a cascaded system, it quantifies the amount of noise added to the signal at the input of the cascade. Therefore, F is referred to the cascade input and (1) progresses from device 1 to N. On the other hand, the W is a measure of the power efficiency of a cascaded system. It quantifies the amount of power consumed by the cascade to transmit or receive a bit of information. Since it is a measure of the power consumed by the cascade, it is referred to the cascade output and (10) progresses from device N to 1.

A higher W intuitively signifies more power wasted. The value of W is always equal to or greater than 1, with $W = 1$ signifying that all power supplied to a cascaded component or network is fully utilized in the signal output (optimal, no power wasted). Conversely, $W \to \infty$ indicates that no power is contributed to the signal output, and all power is squandered (e.g., a perfect dummy load or an entirely lossy channel). The merits of F and W has been summarized in Table I.

In conclusion, both the F and W are indispensable in the analysis of communication systems. The F is a well-established metric that provides a measure of the degradation of the signal-to-noise ratio, and W is a newer metric that provides a measure of the power efficiency of the system. Both metrics are important for wireless communication systems. With the increasing importance of energy efficiency in the industry, the W can become a vital metric for enabling green communications.

III. Implementations of Waste Factor

In the realm of communication systems, effective implementation of W is crucial in order to foster more energy-efficient solutions. In particular, the concerns that W may not be applicable to all types of communication systems and may not capture all aspects of energy consumption warrant further exploration. In this paper, we expand the existing theoretical framework to encompass all data communication systems, including data centers, by considering superposition of power as a means of dissecting energy consumption. The analysis resembles the consumption factor analysis in [10]. This approach allows us to distinguish between the power required for conveying information and that consumed by other ancillary processes.

By employing W, we aim to quantify the power wasted by all devices on a signal path in a cascade, which in turn enables engineers to pinpoint areas where power is being squandered and implement measures to curtail power waste. Furthermore, we will explore the applicability of similar waste factor concepts to govern the "other ancillary things" in data centers and other power consumers, such as cooling systems, lighting, and other non-essential components.

Based on (10), we extend W to a generalized communication system with an information source, sink, and a channel for communicating information between the source and sink. Then we have:

$$\begin{aligned} W = W_{sink} &+ \frac{1}{G_{RX}}\left(\frac{1}{G_{channel}} - 1\right) \\ &+ \frac{1}{G_{RX}G_{channel}}\left(W_{source} - 1\right). \end{aligned} \tag{11}$$

A. Generalized Waste Factor for data center

The generalized formulation can be implemented taking data center as an example. The power usage effectiveness (PUE) is introduced as a measure of energy efficiency in data centers, which is the ratio between the amount of energy consumed by computing equipment for data operations to the total overhead energy used for supporting equipment, including cooling [13].

$$PUE = \frac{\text{Computing equipment energy}}{\text{Auxiliary equipment energy}}. \tag{12}$$

With the help of (11) we will elucidate our approach to extend the existing mathematical framework to all energy-consuming systems within the communication process, ultimately establishing a generalized waste factor that serves as a metric for system energy efficiency. By doing so, we strive to enhance the applicability of W to a wide range of power consumers, including data centers and other complex systems, in order to bolster energy efficiency and diminish overall power consumption. Here we adopt a data center to explain how W can be applied to a generalized system.

In the process of data transmission within a data center, the major power consumption is typically attributed to servers, storage devices, and network equipment, while the minor power consumption is associated with cooling systems, power distribution units (PDUs), and other auxiliary equipment. According to Barroso and Hölzle's findings [12], server and networking equipment account for about 60-70% of the overall power consumption in a data center. Cooling systems contribute to around 30-40% of the total power consumption, while the remainder is consumed by PDUs and other auxiliary equipment.

Total data center power consumption can be modeled as:

$$P_{consumed} = P_{info} + P_{non-info} + P_{aux}, \tag{13}$$

where P_{info} is the sum of all powers of each component (e.g. routers, switches, and other network equipments) that has been used for carrying information (bit stream) in the system, $P_{non-info}$ is the power used by the other components but not directly involved in data transmission (e.g. servers, storage devices, firewalls), and P_{aux} is the power used by the cooling systems, PDUs, and other auxiliary equipment apart from the data transmission. And based on [13], the PUE is a common measure of energy efficiency in data centers. PUE assesses the ratio between the amount of energy consumed by computing equipments and the total overhead energy used for supporting equipments, including cooling. Here, we can have

$$PUE = \frac{P_{info} + P_{non-info}}{P_{aux}}. \tag{14}$$

Also, by introducing the power efficiency for overall data transactions in the data center

$$\eta = \frac{P_{info}}{P_{info} + P_{non-info}}. \tag{15}$$

The power consumption can be derived considering the data center as a single component

$$P_{consumed} = P_{info}\overline{W} + P_{aux}, \tag{16}$$

where $\overline{W}$ represents the Waste Factor for the data center, and based on (14), (15), and (16)

$$\overline{W} = \eta^{-1} = \frac{P_{aux}PUE}{P_{info}}. \tag{17}$$

Based on (9), we extend W to a generalized cascaded communication network with power consumption including one data centers as the source and the other as sink, we have:

$$\begin{aligned} W = \overline{W}_{sink} &+ \frac{1}{G_{RX}}\left(\frac{1}{G_{channel}} - 1\right) \\ &+ \frac{1}{G_{RX}G_{channel}}\left(\overline{W}_{source} - 1\right). \end{aligned} \tag{18}$$

TABLE I
MERITS OF NOISE FACTOR AND WASTE FACTOR

	Merits
Noise Factor	• Measures degradation of signal-to-noise ratio by components in cascade. • Widely used in industry, leading to widespread understanding and ease of application.
Waste Factor	• Quantifies the power waste of a cascaded system for designing energy-efficient networks. • Accounts for power consumption at each device in the cascade, offering a holistic view of power efficiency. • Helps engineers design energy-efficient networks by identifying areas where power waste can be minimized.

Here the $W_{channel}$ for the communication channel is obtained by treating it as a passive attenuator with gain, $G_{channel}$ [11].

B. Comparison of data centers using W

Let's consider two data centers, Data Center A and B, each with distinct initial power settings. Despite its wide adoption, the PUE metric cannot serve as a universal yardstick for energy efficiency comparison, especially when the PUEs of the two data centers are identical. Therefore, we ensure that both data centers have the same PUE for this comparison. For Data Center A, the power allocation is as follows: $P_{infoA} = 140$ kWh for information transmission, $P_{non-infoA} = 40$ kWh for non-data transmission components, and $P_{auxA} = 150$ kWh for auxiliary equipment. In comparison, Data Center B allocates $P_{infoB} = 60$ kWh of power for information transmission, $P_{non-infoB} = 30$ kWh for non-data transmission components, and $P_{auxB} = 75$ kWh for auxiliary equipment.

Here, we assume that Data Center A is a larger facility with more equipment, hence a higher total energy consumption. Conversely, Data Center B is smaller and uses less total energy. If we were to simply compare their total energy use, it might seem that Data Center B is more efficient. But using the Waste Factor might paint a different picture. First, we calculate the power efficiency for data transactions in computing equipment (η) for both data centers using equation (15):

$$\eta_A = \frac{P_{infoA}}{P_{infoA} + P_{non-infoA}} = \frac{140}{140+40} \approx 0.778,$$

$$\eta_B = \frac{P_{infoB}}{P_{infoB} + P_{non-infoB}} = \frac{60}{60+30} \approx 0.667,$$

where η_A and η_B denote the power efficiency of overall data transactions in Data Center A and Data Center B, respectively.

Next, we calculate the PUE for both data centers using equation (14):

$$PUE_A = \frac{P_{infoA} + P_{non-infoA}}{P_{auxA}} = \frac{140+40}{150} = 1.2,$$

$$PUE_B = \frac{P_{infoB} + P_{non-infoB}}{P_{auxB}} = \frac{60+30}{75} = 1.2,$$

where PUE_A and PUE_B denote the PUE of Data Center A and Data Center B, respectively.

Finally, we calculate the Waste Factor ($\overline{W}$) for both data centers using equation (17):

$$\overline{W}_A = \frac{P_{auxA} PUE_A}{P_{infoA}} = \frac{150 \times 1.2}{140} \approx 1.286,$$

$$\overline{W}_B = \frac{P_{auxB} PUE_B}{P_{infoB}} = \frac{75 \times 1.2}{60} = 1.5,$$

The Waste Factors of both data centers ($\overline{W}_A$ and $\overline{W}_B$) allow us to identify the more energy-efficient one. Our calculations indicate that Data Center A is more energy efficient due to its lower Waste Factor ($\overline{W}_A < \overline{W}_B$). The PUE metric, despite being a common measure, only accounts for the energy consumed by computing and supporting equipment, neglecting variations in operational conditions, equipment type, and workload characteristics. This necessitates more comprehensive metrics, such as the Waste Factor.

By introducing the generalized W as an energy efficiency metric, we can calculate the W for complex systems like data centers using the proposed formula (18). This approach extends the applicability of the Waste Factor to a variety of power consumers, including data centers and other systems with significant energy consumption.

IV. EVALUATING PERFORMANCE WITH THE CONSUMPTION EFFICIENCY FACTOR

The Consumption Efficiency Factor is defined as the maximum data rate delivered by the communication system to the total power consumed. With the help of W , the CEF can be derived as [10]:

$$\text{CEF} = \frac{R_{max}}{W \times P_{signal,out}}, \tag{19}$$

where R is the data rate in bps, and R_{max} is the maximum data rate supported by the communication system.

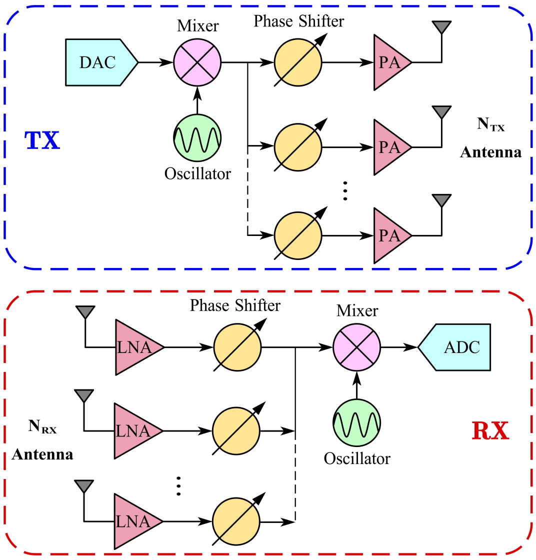
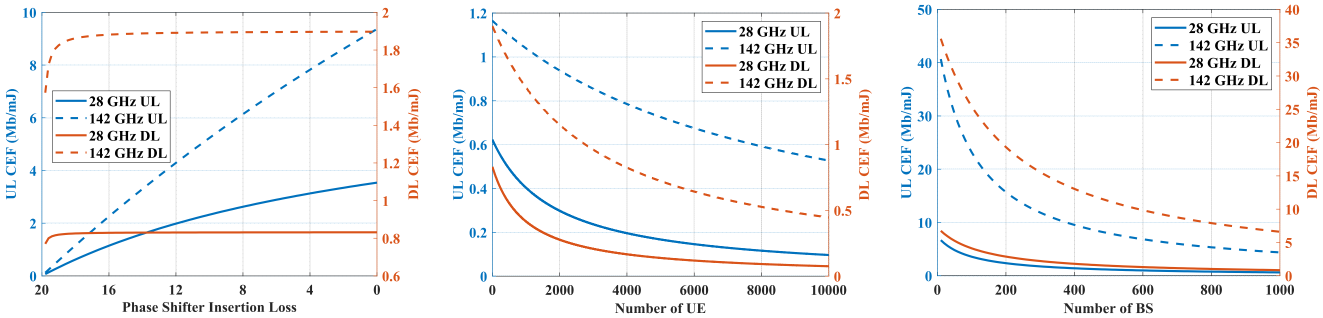


Fig. 2. Architecture of the TX and RX considered for power analysis.

To analyze the impact of component efficiecy on W, and ultimately CEF, here we assume a transceiver and receiver

TABLE II
SIMULATION PARAMETERS COMPARISON OF MMWAVE AND SUB-THZ SYSTEMS

Parameter	**mmWave (28 GHz)**	**Sub-THz (142 GHz)**	**Units**
Bandwidth	400	4000	MHz
Antenna aperture area - BS	0.5	0.5	m^2
Antenna aperture area - UE	0.0005	0.0005	m^2
Antenna gain - BS	45.2	59.1	dBi
Antenna gain - UE	15.2	29.1	dBi
Path loss exponent - LOS	2.0	2.0	-
Path loss exponent - NLOS	3.2	3.2	-
Number of BS antenna elements	1024	4096	-
Number of UE antenna elements	8	64	-
Low-noise amplifiers (LNA) figure of merit	24.83	8.33	mW^{-1}
LNA gain	20	20	dB
Mixer insertion loss	6	6	dB
Phase shifter insertion loss	10	10	dB
Local oscillator power	10	19.9	dBm
TX power amplifier (PA) efficiency	28	20.8	%
Antenna efficiency	0.6	0.6	-
Cooling overhead at the BS	20	20	%
UE screen power consumption	500	500	mW



(a) The effect of PS insertion loss (dB) on CEF.
(b) The effect of the UE number on the CEF.
(c) The effect of the BS number on the CEF.

Fig. 3. The impact of different component efficiency and different number of UE and BS on CEF

structure illustrated by Fig. 2 with analog beamforming at both TX and RX. The simulation is conducted under mmWave (28 GHz) and sub-THz (142 GHz) communication systems, and the detailed simulation parameters for the comparison of two communication systems are summarized in Table II, and the selection of parameters from the table as simulation parameters is mainly based on [11]. In the following simulations, we employ the CEF owing to its comprehensive encapsulation of system performance, encompassing aspects of both power consumption and data rate. This metric not only assists in the optimization of system efficiency, but also affords a convenient benchmark for comparison across disparate systems or configurations.

We would like to specifically emphasize here, that the low-noise amplifier (LNA) is not considered as an on-path component for power consumption analysis. The reason being that the DC power consumed by the LNA is independent of the input signal power. In other words, the gain and efficiency of the LNA remain relatively constant within its linear operating range, and do not vary significantly with input power. Since the input power to the LNA is typically weak, coming from the RX antenna, the LNA's gain of over 30 dB amplifies the signal to a level that can be processed by the subsequent circuitry. Therefore, in the power consumption analysis, the power drawn by the LNA is added as non-path power to the overall power consumed by the system, while the power efficiency is taken into account using the Figure of Merit (FoM) of the LNA. By considering the LNA in this way, the overall power consumption of the system can be accurately estimated, while maintaining a reasonable level of modeling complexity.

A. The Impact of Different Component Efficiency on CEF

Fig. 3(a), takes the variation in the PS insertion loss as an example and the results indicate sensitivity of CEF to the PS performance. Moreover, we observed that the changes in CEF with varying PS insertion loss were more pronounced in the 28 GHz and 142 GHz uplink transmissions, while the changes in the downlink transmissions were relatively stable in subsequent regions. Furthermore, we found that the CEF for both uplink and downlink transmissions at 142 GHz was higher than that at 28 GHz, implying that sub-THz systems require less RF power to achieve the same SNR as mmWave systems due to the high CEF it shows.

B. The Impact of Different Number of UE and BS on CEF

Expanding on the work in [11], we explore the impact of varying user equipment (UE) and base station (BS) numbers on CEF through simulation. It can be clearly observed from Fig. 3(b) that the 142 GHz scenario yields significantly larger uplink CEF, as compared to other scenarios, under varying UE numbers. Furthermore, with the increase in UE numbers, the rate of reduction in uplink CEF for 142 GHz is evidently lower than other scenarios, which indicates that sub THz communication exhibits good energy efficiency.

Regarding the 28 GHz frequency band, it has been observed in Fig. 3(c) that there is a strong similarity in the CEF trend between the uplink and downlink transmission links. Moreover, these trends are significantly higher compared to transmissions under a 142 GHz environment. Additionally, an increase in base station quantity may aid and improve performance for CEF during downlink transmissions at 142 GHz frequencies. These findings have important implications for wireless communication as they suggest potential strategies for optimizing transmission capacity within different frequency bands by adjusting parameters such as base station density to improve signal reliability while minimizing interference from neighboring cells. Furthermore, these insights could help inform regulatory policies aimed at allocating specific portions of spectrum more effectively so that optimal bandwidth utilization can be achieved across different parts of the RF spectrum without significant interference or degradation of overall system performance or integrity through poor-quality link reception along remote corridors.

V. Future Research Directions

IoT devices will be critical in future wireless systems, necessitating energy-efficient solutions due to their limited battery capacities [14]. RF energy harvesting techniques could provide a portion of required energy at mmWave and sub-THz frequencies [15]. A deeper exploration is needed to see if a mathematical framework can be used to analyze the caching, algorithmic design, and energy consumption of non-path devices.

With the rise of small cells, the energy needs of the network will surge [16], highlighting the need for energy-efficient network design to ensure sustainable 6G communication. Narrower beamwidths at sub-THz frequencies, however, increase the search space and power consumption [17], [18], requiring new beam management techniques. The Waste Factor W might be a useful analytical tool in this context.

In 6G, Reconfigurable Intelligent Surface (RIS) has gained significant attention due to its potential to revolutionize wireless communications [19]. The use of W for analysis can help identify optimal RIS placements for maximal energy efficiency, providing a useful tool for design and optimization efforts.

VI. Conclusion

In this work, we have comprehensively elaborated the Waste Factor, presenting an enhanced framework for evaluating power efficiency across diverse wireless system architectures. The derivation of W, referred to the output of a cascaded system, reveals strong analogies to H. Friis' F, which is referred to the input. The power usage effectiveness for a data center was used to obtain W for the data center as a whole and compare different data centers. We investigated the impact of system parameters on W and ultimately the data rate performance through CEF at 28 GHz and 142 GHz. We focused on the phase shifter's insertion loss and revealed CEF's sensitivity to phase shifter insertion loss variations. Notably, CEF fluctuations were more pronounced in uplink transmissions. Our study also probed the influence of varying UE and BS numbers on CEF, highlighting improved energy efficiency at 142 GHz with increased UE and BS. These findings hold potential to guide regulatory policies for efficient spectrum allocation and bandwidth optimization, enhancing signal reliability and reducing interference. In conclusion, our work has advanced the W into a versatile framework for evaluating energy efficiency in any cascaded communication systems. We've offered invaluable metrics to optimize next-generation communications, spanning various network components such as data centers and transceivers. By laying a foundational framework for analyzing waste power, this research paves the way for energy-efficient algorithm design and strategy formulation in future green communications, thereby contributing to the overarching discourse on energy efficiency.

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