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Comparative Analysis of Picocell and Femtocell Performance Utilizing Various Propagation Models

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This study provides an in-depth comparison of picocells and femtocells within 4G networks, employing various propagation models. Using both empirical and deterministic methodologies, the investigation thoroughly explores signal propagation, coverage, and capacity aspects of small cell deployments across different environmental conditions. Leveraging insights from multiple propagation models, the research elucidates the effectiveness of picocells and femtocells in urban, suburban, and rural settings. Crucially, these findings, obtained through a user-friendly GUI developed with MATLAB, offer valuable guidance for refining small cell network design and deployment strategies in 4G environments. This contributes significantly to ongoing discussions on optimizing small cell networks, underlining the importance of tailored approaches for efficient deployment and operation across diverse environmental landscapes.

1 Introduction

The utilization of small cell technologies, notably picocells and femtocells, has emerged as a significant strategy for augmenting coverage and capacity within 4G networks. This study conducts a comparative analysis aimed at assessing the performance of picocells and femtocells within such networks, leveraging a variety of propagation models [1]. Recognizing the importance of understanding the operational characteristics of these small cell deployments, this research endeavors to optimize network efficiency and fulfill the escalating demand for high-speed data services. Through the examination of diverse propagation models encompassing empirical and deterministic methodologies, this investigation seeks to offer comprehensive insights into the factors influencing the efficacy of picocells and femtocells across diverse environmental contexts. These insights hold substantial implications for decision-making processes related to the deployment and administration of small cell networks within 4G environments, fostering informed strategies for network enhancement and management.

2 Materials and Methods

i. Throughput performance

This section delves into assessing the capacity of picocells and femtocells, considering parameters like bandwidth, modulation techniques, and MIMO configurations. Bandwidth, a pivotal determinant of capacity throughput, exhibits variability across frequencies and band allocations. For instance, the 800 MHz frequency features three bands, with band 20 widely utilized, offering 30 MHz allocation, while the others provide 15 MHz each. Bandwidth constraints stem from allocations for diverse applications like radio FM/AM, Wi-Fi systems, and military and marine services, with options ranging from 1.4 MHz to 20 MHz [2]. Modulation techniques significantly influence data rates, with higher modulations augmenting rates but also increasing power consumption, particularly notable in uplink scenarios where modulation is typically capped at 64 QAM due to power concerns. Common modulation schemes encompass QPSK, 16 QAM, 64 QAM, and 256 QAM, each presenting distinct bits per symbol and Signal-to-Interference-plus-Noise Ratio (SINR) requirements. Adaptive modulation techniques, a standard practice among mobile carriers, dynamically adjust modulation schemes based on channel conditions to optimize data rates while conserving power and resources [3].

Table 1. Modulation schemes and SINR [3]

Modulation	Bits per symbol	SINR
QPSK	**2**	**6 dB**
16 QAM	**4**	**10 dB**
64 QAM	**6**	**14 dB**
256 QAM	**8**	**22 dB**

Calculating FDD throughput is straightforward. For instance, with a 20 MHz bandwidth (equivalent to 100 resource blocks RB), 12 subcarriers in each RB, 128 QAM modulation (7 bits per symbol), 4×4 MIMO configuration, and 7 symbols of Orthogonal Frequency Division Multiple Access (OFDMA) per 0.5 milliseconds of normal cyclic prefix, resulting in 14 symbols per millisecond, the FDD throughput can be computed using the formula:

$$FDD = RB \times \text{number of subcarriers per RB} \times \text{number of bits} \times \text{OFDMA symbols} \times \text{MIMO}$$

This yields approximately 353 Mb/s for the downlink and approximately 76 Mb/s for the uplink. These calculations consider a 25% overhead margin for factors such as synchronization and other coding details [4].

ii. Propagation loss:

This section is crucial in cellular network design, offering an estimated coverage range for each cell based on factors like power output, signal strength including Signal-to-Interference-plus-Noise Ratio (SINR), and various fading and noise considerations. Unlike traditional methods reliant on distance measurements for path loss calculation, the approach here diverges. Path loss determination involves computing receiver sensitivity, representing the minimum signal power for effective communication, while considering fading and noise levels based on the environment—categorized into outdoor (e.g., urban areas with multiple signal reflections due to tall buildings, wide streets, and heavy traffic) and indoor (e.g., buildings or aircraft). Using path loss values, the propagation model equation is inverted to ascertain the distance each cell can effectively communicate with user equipment. Empirical and deterministic propagation models are employed, with empirical models derived from global urban measurements and deterministic models based on real-world wave propagation [5]. Empirical models are influenced by base station and receiver heights, unlike deterministic models. The discourse begins with Maximum Allowable Path Loss (MAPL) before exploring propagation models.

iii. Maximum Allowable Path Loss (MAPL):

Determining the maximum allowable path loss is crucial for establishing the furthest distance a signal can travel within a cellular network. This assessment considers factors such as Signal-to-Interference and Noise Ratio (SINR), Effective Isotropic Radiated Power (EIRP), environmental fading effects, receiver sensitivity, and noise figure. Higher SINR values generally denote better signal quality, enhancing data rates but potentially increasing power consumption [3]. Reference Signal Received Power (RSRP) determines data rates, aided by Reference Signal Received Quality (RSRQ) for cell handover decisions. EIRP combines total power output and antenna gains, neglecting cable losses due to small cell structures. While small cells may surpass gain values for testing, real-world performance may differ. Notably, Femtocells typically lack gain antennas, unlike conventional Macrocells.

It's important to mention that the anticipated power output of the cells is displayed in Table 2.:

Table 2: Picocell and Femtocell EIRP

Cell type	Transmitted power (dBm)	Gain (dB)	EIRP (dBm)
Picocell	25	6	31
Femtocell	20	0	20

Fading phenomena are influenced by environmental variables, particularly in urban areas where dense surroundings and towering structures contribute to heightened fading, accentuated by the elevated rooftops relative to small cell base stations. Similar considerations extend to suburban and rural environments, with suburban areas potentially featuring structures surpassing base station heights, impacting fading assumptions to a lesser extent compared to urban settings. Conversely, rural locales are expected to exhibit minimal fading estimates.

Receiver sensitivity represents the minimum signal strength required for receivers, including user equipment, to accurately receive and interpret signals sans errors [6]. This sensitivity calculation incorporates multiple factors, such as SINR and thermal noise, expressed as:

$$\text{Receiver sensitivity} = 10 \times \log (K \times T \times B) + 30 \text{ dB}$$

Here, K denotes Boltzmann's constant, T signifies temperature in Kelvin, and B represents bandwidth in Hertz. The addition of 30 dB compensates for the "KTB" calculation to ensure values are expressed in dBW. Receiver sensitivity integrates thermal noise, SNR, and bandwidth, with the latter specified in MHz to align with 4G LTE's high capacity achievable by small cells. Notably, the bandwidth considered represents 90% of the total bandwidth, with the remaining 10% allocated for guard band purposes. The noise figure, maintaining a consistent value of 6 dB, reflects the receiver's noise impact on incoming signals.

Consequently, the equation for maximum allowable path loss (MAPL) is established as:

MAPL = EIRP – Receiver sensitivity – fading - noise figure.

Following MAPL computation, it is compared with the path loss derived from various propagation models to delineate a given cell's range, a methodology commonly employed in radio link budget creation [6].

iv. Okumora-Hata Model

Often known as the Hata model, this version is an advanced form of Okumura's graphical path loss model. Highly regarded in mobile communication, it's a preferred choice for assessing propagation loss in diverse settings, including urban, suburban, and rural areas, specifically tailored for outdoor environments. Originating from Tokyo, Japan, its application in selected scenarios will demonstrate its effectiveness and disparities. Notably, this model solely addresses outdoor settings and overlooks indoor losses. Covering a frequency range of 150 MHz to 2000 MHz, it was also employed for the 2300 MHz frequency for comparison. It's vital to recognize that being an empirical model, it generates theoretical results that may not perfectly reflect real-world conditions [5].

The general formula for this model is:

$$PL = 69.55 + 26.16 \times \log(f) - 13.82 \log(H_B) - a(H_M) + (44.9 - 6.55 \times \log(H_B)) \times \log(D) + C_M$$

Table 3: Okumura-Hata Model parameters [5]

Geolocation	Parameters	
	$a(H_M)$	C_M
urban	$3.2 \times (\log(11.75 \times H_M))^2 - 4.97$	0
suburban	$(1.1\times\log(f) - 0.7) \times H_M - 1.56 \times \log(f) + 0.8$	$-2 \times (\log(f/28))^2 - 5.4$
Rural	$(1.1\times\log(f) - 0.7) \times H_M - 1.56 \times \log(f) + 0.8$	$-4.78\times(\log(f))^2 + 18.33\times\log(f) - 40.94$

v. Multi Wall Multi Floor Model (MWMF)

This specific propagation model is specialized for indoor settings, notable for its intricate consideration of indoor elements like walls, floors, clutter, and furniture, although the version utilized here focuses solely on walls and floors. This simplification was prompted by time constraints, as full implementation would require additional time and effort, along with clear objectives regarding measured parameters, considering unique propagation losses in each environment. The MWMF model, developed through ray tracing modeling, delineates diminishing loss parameters with increasing propagation obstacles. Notably, losses considered were based on the 5 GHz unlicensed spectrum, despite testing with the 2.6 GHz spectrum, yielding noteworthy results. This adaptation was due to insufficient 2.6 GHz data, necessitating assumptions for comparative analysis [7]. The employed formula is expressed as follows:

$$PL = 20 \times \log(4\pi/\lambda) + 20.2 + 6.3$$

Here, 20.2 dB denotes one floor loss, while 6.3 dB represents one wall loss, and the initial segment of the equation accounts for free space loss [7].

vi. ITU-R P.1238-9 model:

This relatively recent model, developed by the International Telecommunication Union Radiocommunication sector's study groups, is designed for frequencies between 300 MHz and 100 GHz, primarily for indoor use. It provides detailed insights into various indoor losses encountered in most scenarios. Tailored to specific situations, the model was crafted using authentic measurement equipment, capturing parameters outlined in ITU-R reference material. In this study, it was exclusively applied to femtocell indoor deployment. The formula employed, known as a general site formula, integrates predetermined measurements from the ITU-R reference [8].

$$PL = 20 \times \log(f) - 28 + A$$

In urban areas, characterized by apartments, A signifies a 13 dB indoor loss, while in suburban and rural areas dominated by houses, A denotes a 7 dB indoor loss, reflecting typical structural compositions [8].

3 Results and Discussion

The provided data represents a subset of results obtained from the implemented tool, focusing on 800 MHz and 1800 MHz FDD frequencies with a 20 MHz bandwidth and 16 QAM modulation. Notably, 128 and 256 QAM modulations, prevalent in South Korea and Thailand, are primarily used with bandwidths exceeding 30 MHz due to their higher power consumption and increased bits transmission, potentially incurring additional costs. While some outcomes, particularly those from empirical models, may not directly mirror real-world scenarios, they are included to illustrate the impact of higher modulation schemes on range estimation. The Estimated Maximum Allowable Path Loss (MAPL) serves as a benchmark, compared to actual field experiment measurements, with variations in estimated range contingent on the propagation model used. Model loss indicates the MAPL achieved during field experimentation using the same propagation model, albeit with potentially different parameters. The comparison excludes range measurements in meters during the field experiment.

i. Picocell simulated results:

The Picocell exhibits significantly reduced range, particularly in urban areas, with distances of 81 and 48 meters for 800 MHz and 1800 MHz frequencies respectively due to a base station height of 5 meters. Despite variations, Picocells generally offer ranges from 40 to 400 meters. In rural environments, the model aligns closely with real-world measurements, demonstrating acceptable accuracy within a 10% error margin. However, the Hata model's compatibility varies across environments, performing best in urban and rural settings but experiencing greater losses in suburban areas due to limited data. Notably, the Picocell's results are skewed by the low base station height, particularly in urban, suburban and rural regions [9].

Table 4: MATLAB simulated results for Picocells using Hata Model

Area	Frequency	Estimated Range (m)	Estimated MAPL (dBm)	Model Loss (dBm)	Measured Loss (dBm)
Urban	800	81	91.9	114	125
	1800	48			
Suburban	800	187	96.9	108	130
	1800	126			
Rural	800	599	98.9	110	106
	1800	443			

ii. Femtocell simulated results:

The outcomes discussed are derived from non-line-of-sight measurements [42], chosen for their ability to reflect realistic ranges for small cells. While the simulated ranges align reasonably with real-life Femtocell limitations, they are theoretical and subject to some degree of accuracy.

The multiple wall multiple floor (MWMF) model produced ranges of 13 and 6 meters respectively for the stated frequencies, with an 88 dBm loss, exhibiting an 8% deviation from both real and field test measurements. Despite variations in parameters and environmental conditions, this discrepancy remains acceptable due to the deterministic nature of the model.

Subsequent testing with the modified ITU-R 1238-9 model, now accommodating additional frequencies, yielded ranges of 17 and 10 meters respectively, maintaining an 88 dBm loss. Comparing these findings to actual measurements revealed a 12% margin of error, positioning the ITU model between the MWMF and previous models in terms of accuracy.

Key conclusions:

- The MWMF model displays superior accuracy, likely attributable to its precise loss parameters.
- The ITU model closely approximates the MWMF model's accuracy, with a 12% margin of deviation from actual measurements.
- These variances stem from differences in equations, parameter derivation methods, and underlying principles, impacting resultant ranges despite identical loss values.

Table 5: MATLAB simulated results for femtocells using indoor models

Area	Frequency (MHz)	Estimated Range (m)	Estimated MAPL (dBm)	Model loss (dBm)	Measured loss (dBm)
MWMF	2600	13	88	95	95
	5200	6			
ITU-R P.1238-9	2600	17		82	98
	5200	10			

4 Conclusions

In conclusion, our investigation thoroughly explores the effectiveness of picocells and femtocells within the realm of 4G networks, employing a range of propagation models to scrutinize their performance. Our findings accentuate the pivotal importance of precise propagation modeling in the strategic deployment of small cells. Particularly, the reliability of the MWMF and ITU models in evaluating coverage and signal dispersion offers significant insights into the intricate dynamics within indoor environments. Through a comprehensive approach encompassing empirical testing and simulations, we provide valuable insights into the extent and effectiveness of signal transmission across diverse scenarios.

This study significantly enriches the ongoing discourse surrounding the optimization of small cell networks, emphasizing the indispensable need for tailored propagation models to craft efficient deployment strategies. Looking ahead, these findings possess the potential to serve as a guiding beacon for network engineers and policymakers alike, empowering them to enhance the performance of 4G networks and prepare diligently for the forthcoming transition to 5G technology. By heeding the insights gleaned from our research, stakeholders can proactively address the evolving demands of telecommunications infrastructure, ensuring robust and seamless connectivity for future generations.

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