Chapter 2: State of the Art

2.1 The Imperative of Smart City IoT

The concept of the "Smart City" has evolved from a purely technological vision to a holistic urban strategy aimed at enhancing quality of life through digital optimization. A Smart City can be defined not merely by the presence of ICT infrastructure, but by the intelligent integration of human, collective, and artificial intelligence to serve urban needs. This integration relies fundamentally on the Internet of Things (IoT)—a pervasive network of sensors and actuators that requires a connectivity layer distinct from traditional human-centric mobile broadband (Alahi et al., 2023).

The connectivity requirements for Public IoT networks in urban scenarios differ significantly from consumer cellular networks. While human users prioritize high downlink throughput and low latency for video or gaming, smart city applications—ranging from smart metering (Utilities) to waste management (Construction/Services)—often prioritize coverage ubiquity, device density, and energy efficiency over peak data rates (Zaman et al., 2024).

The current landscape of wireless technologies for these scenarios is bifurcated between Low-Power Wide-Area Networks (LPWAN) and cellular-based IoT (NB-IoT, LTE-M, and 5G NR). LPWAN technologies, such as LoRaWAN and Sigfox, utilize unlicensed spectrum to offer deep indoor coverage and multi-year battery life, making them ideal for massive machine-type communications (mMTC). Conversely, cellular technologies leverage existing licensed spectrum and infrastructure to provide higher reliability, lower latency, and guaranteed Quality of Service (QoS), essential for mission-critical verticals like public safety or autonomous transport (Marini et al., 2022) (Ikpehai et al., 2018) (Kanellopoulos et al., 2023).

A critical challenge in planning these networks is the "densification" imperative. As noted in the Cisco Annual Internet Report (2020), the number of devices per capita is growing exponentially, creating a contention problem that traditional cell planning—optimized for fewer, high-bandwidth users—struggles to address efficiently. Consequently, a sizing model for modern smart cities must be technology-agnostic, capable of simulating both the massive connection density of LPWAN and the throughput requirements of 5G, depending on the specific urban vertical being dimensioned.

2.2 Smart City Service Taxonomies & Traffic Theory

Standard bodies such as the ITU-T and NIST have proposed various taxonomies to categorize smart city services. The "Municipal IoT Blueprint" (Barkis et al., 2019) and the Global City Teams Challenge (SuperClusters, n.d.) advocate for a vertical-based segmentation—grouping use cases into categories such as Energy, Transportation, Public Safety, and City Services. This taxonomy aligns with the "Verticals" approach adopted in the proposed artifact (e.g., Agriculture, Utilities, Construction), verifying that a service-centric input structure is industry-standard practice. Translating these verticals into network load requires robust Traffic Engineering.

In classical telecommunications, dimensioning relies on Erlang theory, which assumes Poisson arrival processes for voice calls. However, IoT traffic is often packet-switched and bursty, rendering simple Erlang-B calculations insufficient without modification (S. Sharma & Bhatt, 2024) (Hussein & Ibnkahla, 2023). Modern dimensioning employs "Traffic Profiling," which segments devices based on their throughput buckets (e.g., <0.5 Mbps vs. >10 Mbps) and duty cycles (Shannon, 1948).

A pivotal concept in this dimensioning is the "Busy Hour"—the continuous 60-minute period during which the maximum total traffic load occurs. While originated for telephony, the Busy Hour remains the standard dimensioning criterion for packet networks to ensure the infrastructure can handle peak contention without packet loss (Ozovehe et al., 2018) (García-Dorado et al., 2011).

Furthermore, the concept of "Headroom" is critical in public infrastructure planning. Unlike commercial networks that may tolerate some congestion, public utility and safety networks require a guaranteed capacity buffer to handle emergency spikes or future growth. Integrating a configurable Headroom parameter (often 20-30%) into the dimensioning logic allows planners to move from "best-effort" sizing to "resilient" infrastructure planning, ensuring that the theoretical capacity calculated today remains viable for the operational reality of tomorrow. (Artime et al., 2024) (Carnell et al., 1999) (Nweke et al., 2022) (Zhang et al., 2021).

2.3 Fundamentals of Network Dimensioning

Network dimensioning is fundamentally a bi-dimensional problem involving both capacity and coverage (Ghazzai et al., 2015) (Laiho et al., 2005). While coverage ensures a signal exists, capacity ensures the network can sustain the aggregate service demand. In modern IoT scenarios, where device density often outpaces spatial constraints, Capacity Planning becomes the primary dimensioning driver.

Capacity models determine the maximum throughput or number of simultaneous active sessions a single base station can support without degrading Quality of Service (QoS). As highlighted by Khatiwoda et al. (2024), 5G and IoT networks are frequently "capacity-limited" rather than "coverage-limited." This necessitates a calculation logic that compares the Peak Concurrent Devices Traffic (Demand) against the Maximum Throughput for Downlink per Site (Supply) (Taufique et al., 2017). This aligns with industry practices where the total available network throughput is divided among active users to determine saturation levels (CellTeks, 2025). If the demand density exceeds the site capacity, the network requires cell splitting or additional carrier frequencies, regardless of the physical reach of the signal.

Once the capacity baseline is established, the physical validity of the network is confirmed through Coverage Planning and the "Link Budget." This is to account for all gains and losses from the transmitter to the receiver to ensure the signal-to-noise ratio (SNR) exceeds the receiver sensitivity (P. K. Sharma et al., 2016).

$$P_{RX} = P_{TX} + G_{TX} + G_{RX} - L_{path} - L_{misc}$$

Where L_{path} (Path Loss) is the most variable and critical component. For initial high-level dimensioning, the industry relies on empirical channel models rather than computationally expensive ray-tracing simulations.

Historically, models like Hata or Okumura were sufficient for macro-cellular planning in sub-2GHz bands. However, the advent of 5G and IoT deployments in higher frequency bands (mmWave) necessitated new standards. The 3rd Generation Partnership Project (3GPP) released Technical Reports TR 38.900 (ETSI & 3GPP, 2017) and TR 38.901 (ETSI & 3GPP, 2022) to standardize channel models for frequencies from 0.5 to 100 GHz. These reports provide the industry-standard formulas for calculating path loss in Non-Line-of-Sight (NLOS) urban canyons—a typical environment for smart city sensors (e.g., smart meters in basements or streetlights) (Jiang et al., 2021) (Mondal et al., 2015).

While high-fidelity tools utilize 3D ray-tracing to map every building reflection, such precision requires strictly defined geographical data often unavailable in the early strategic planning phase. A formula-based approach, utilizing the 3GPP/ETSI generic models, offers a necessary trade-off: it sacrifices site-specific precision for the agility to estimate coverage radii and site counts across vast urban regions rapidly (Azevedo & Mendonça, 2024). This validation of formula-based path loss is crucial for justifying a spreadsheet-based sizing tool, which cannot natively perform complex geospatial ray-tracing.

2.4 The "Research and Tooling Gap" in Network Planning

A review of the current state of the art reveals a distinct polarization in network planning tools, creating a "tooling gap" for public authorities and strategic planners.

On one end of the spectrum lie Professional Engineering Tools (e.g., Atoll, Planet, NS-3). These platforms are highly sophisticated, offering granular simulation of interference, ray-tracing, and protocol-level latency. However, they are "black-box" systems—expensive, requiring specialized training, and demanding detailed inputs (precise antenna coordinates, 3D building maps) that are rarely available during the initial feasibility or budgeting phases (Khatiwoda et al., 2024).

On the other end are Ad-hoc Spreadsheets. These are often created by individual engineers for specific tasks. While flexible, they typically lack a standardized structure, making them fragile, difficult to audit, and hard to scale across different verticals or technologies (Power Streamline, 2024).

Recent comprehensive reviews characterize the current body of smart city research as "fragmented" and "technology-driven" rather than holistic (Bibri & Krogstie, 2017) (Özkaynak et al., 2024). The literature indicates that academic effort is predominantly funneled into isolated silos. For example, extensive frameworks exist for **assessing security and privacy risks** (Cui et al., 2018) (Colic et al., 2020), while other distinct bodies of work focus heavily on **optimizing energy-efficient routing protocols** (O'Dwyer et al., 2019). Similarly, research into the **data processing and middleware layers** often treats the underlying connectivity infrastructure as a static assumption rather than a dynamic variable (floLive, 2022). There is a notable lack of "Middle-Tier" frameworks that bridge these silos, integrating the specific constraints of energy, security, and traffic into a unified, technology-agnostic dimensioning model accessible to strategic planners.

This gap is particularly acute for Smart City planners who need to answer "What if?" questions rapidly (e.g., "What is the cost difference between 4G and 5G for this district?"). The rigid nature of simulators and the chaotic nature of ad-hoc sheets fail to provide the *transparent, assumption-driven* environment necessary for this level of strategic decision-making.

2.5 Spreadsheet Modeling & Automation (VBA) in Engineering

Despite the rise of Python and web-based tools, Microsoft Excel remains the dominant "End-User Computing" (EUC) platform in engineering. Its ubiquity ensures that tools built within it are immediately accessible to a broad range of stakeholders without requiring software installation or specialized IT approval.

However, standard "static" spreadsheets (hard-coded cell references) suffer from scalability issues. To address this, advanced engineering models employ a "Declarative" architecture using Visual Basic for Applications (VBA). The artifact VBA code decouples the *definition* of the model (inputs, headers, structure) from its *execution*. The user defines parameters abstractly (e.g., in a "Configurator" sheet), and the VBA engine dynamically constructs the model.

Power Streamline (2024) notes that while VBA has limitations regarding execution speed and version control compared to modern languages, it remains unrivaled for rapid prototyping in corporate environments where "Low-Code/No-Code" flexibility is required. In the context of this thesis, VBA transforms Excel from a simple calculator into an **Application-Specific Tool**. It automates the repetitive generation of scenarios (e.g., CreateTablesFromInput), drastically reducing the manual error rate associated with traditional spreadsheets while attempting to maintain the transparency of cell-based formulas for the final calculations.

2.6 Conclusion

The review of the state of the art identifies a potential utility for the tool developed in this thesis. The complexity of Smart City verticals (Albino et al., 2015) and the specificities of IoT traffic (Zaman et al., 2024) suggest that relying solely on simple throughput calculations may not capture the full range of planning requirements. While 3GPP standards (ETSI, 2017/2022) provide the physics for dimensioning, there is an opportunity to bridge the gap between these complex engineering formulas and the strategic need for agile estimation. By leveraging the ubiquity of Excel and the automation power of VBA, the proposed artifact aims to provide a transparent and accessible option for early-stage public IoT network sizing.