# 5GAutoConf: A Rapid Data-Driven Autoconfiguration Tool for 5G Base Stations

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***Abstract*—Modeling 5G Radio Access Networks (RANs) at scale requires rapid (re-)configuration of 5G base stations (BSs), e.g., based on open-source software (OSS) stacks, which in general is a challenging task in scenarios with highly dynamic environments and networking demands. Existing solutions are often insufficient to provide an automated configuration functionality based on basic 5G cell parameters. Manual adjustments in such scenarios require specialized knowledge usually not present outside of traditional network providers and established research groups. They are often prone to errors, misconfigurations, and typically do not meet the need for dynamic and timely updates to the networking configuration. In this paper, we present `5GAutoConf`, which, to the best of our knowledge, is the first open source automatic 5G BS configuration tool that uses basic input parameters. `5GAutoConf` implements an automatic data-driven process that rapidly creates configurations for OSS 5G RAN stacks, enabling fast 5G BS adaptation for experimental purposes. Further, `5GAutoConf` integrates both 5G standard-compliant and generated lookup tables (LUTs) for use case-oriented optimization. Since the derivation process of waveform parameters is the most important part of the tool, it is described in detail.**

***Index Terms*—5G NR, RAN, data-driven network optimization, open-source toolkits, automated network configuration, rapid network deployment**

## I. INTRODUCTION

Since the provisioning of a dedicated frequency range in Germany in 2019 for private cellular networks, the popularity of 5G non-public networks (NPNs), or campus networks (CNs), has seen a steady increase in both industrial and academic adaptations. Although, research shifts towards 6G communications, 5G technology remains a foundation on which to build experimental features and integrations. Consequently, the concept of CNs is expected to further drive innovations in 6G-related developments [1].

While industrial users rely on either commercial network provider solutions or custom integrations by specialized contractors, experimental integrations in academia still largely depend on software defined radio (SDR)-based setups using open-source software (OSS) stacks. These stacks serve as a major enabler of academic research in cellular communication. Emergent applications include modeling 5G and 6G Radio Access Networks (RANs) in real-world applications, which require fast adaptability and automated (re-)configuration of base stations (BSs) for experimental purposes.

Widely used OSS 5G RAN and network stacks include `OpenAirInterface5G (OAI5G)`, maintained by the OpenAirInterface Software Alliance (OSA) [2], and `srsRAN`, developed by Software Radio Systems (SRS) [3]. These stacks allow for a detailed fine-tuning of relevant 5G BS parameters. Further, an open, interoperable, and intelligent RAN architecture is enabled through Open Radio Access Network (O-RAN), as defined by the O-RAN Alliance [4].

Implementing 5G BSs tailored to specific operating conditions in academic and industrial research settings as well as production environments requires extensive adjustment of preset configuration parameters—and adapting those settings on regular schedules based on the networking demand. Although the 5G technical specifications (TSs) outline details about the standard, this documentation is not intended to instruct network operators (private, but public as well) on how to build and operate their network infrastructure. The derivation of some 5G cell parameters is inconsistent within the literature and engineering community discussion forums.

Conversely, synthesizing configuration variables from desired 5G cell parameters requires in-depth knowledge of the standards and either manual calculations or a commercial planning software. Neither is sufficient to rapidly (re-)configure a 5G BS based on OSS stacks in academic or industrial settings.

Simultaneously, existing rules and best practices for designing a 5G communication system unfortunately are largely obscured by network providers. As the knowledge is kept within individual organizations, setting up any 5G cell based on OSS stacks requires extensive work to derive parameters from the standard. This holds true especially in the case of newly-formed or reorienting academic work groups, if existing institutional knowledge is insufficient. While some online tutorials address specific OSS 5G RAN stack parameters, they still only cover few adjustable parameters and remain therefore incomplete.

Consequently, rapidly (re-)configuring 5G/6G BSs at scale for RAN modeling applications proves to be a challenging task if anything other than a standard configuration, usually provided by the OSS stack authors, shall be implemented. To speed up the (re-)configuration process and avoid manual editing, an automated software tool is required. Similarly, simultaneously changing multiple interdependent configuration parameters requires extensive calculations beforehand, if only basic 5G cell parameters are given.

In this paper, we present `5GAutoConf`, to the best of our knowledge the first open source automatic 5G BS configuration tool utilizing basic input parameters [5]. `5GAutoConf` implements an automated data-driven process that rapidly creates configuration files for OSS 5G RAN stacks, thereby enabling selective implementations of experimental, 6G-oriented feature developments. In its current state, `5GAutoConf` incorporates basic 5G input parameters to generate dynamic configuration files for OSS 5G RAN stacks with the aim to provide bootstrap 5G RAN networks for different scenario configurations and 6G research.

## II. RELATED WORK

In this section, we categorize related work for this paper based on publications in the context of the technical aspects of implementing 5G (and beyond) networks.

A detailed explanation on designing a 5G BS network's Synchronization Signal Block (SSB), Physical Broadcast Channel (PBCH) and Physical Random Access Channel (PRACH) has been presented by Chakrapani [6], which is frequently cited by engineering resources. Still, critical details regarding PRACH cell dimensioning, especially in the context of the number of cyclic shifts $N_{\mathrm{CS}}$, are contradictory to their often cited tabular overview given for the same parameters.

Sesia [7] provides more in-depth computation guidelines for 4G Long-Term Evolution (LTE)-based network design, which partially supports matching aspects of 5G cell design, but is insufficient for parameters introduced with 5G releases. Meanwhile, these parameters are discussed by Cox [8], who also adds some computations. Lin et al. [9] contribute another early tutorial on 5G fundamentals, physical channels and reference signals.

Ahmed et al. [10] demonstrates optimizing coverage and capacity in an `srsRAN`-based testbed for 5G, using power amplifiers and soft configuration-based parameter tuning in O-RAN small cells. Gong et al. [11] described details for achieving Ultra Reliable Low Latency Communications (uRLLC) using `srsRAN` and provide a detailed evaluation of their integration. Erunkulu et al. [12] provides an extensive survey of 5G use cases, their classification, capabilities, and key performance parameters, which can be used for modeling 5G channel characteristics and evaluate experimental integrations.

Commercial operator-grade network management tools offered by large telecomunications equipment vendors include Ericsson's `Network Manager`, Nokia's `NetAct`, and Huawei's `iMaster NCE`, all of which are closed-source software. In addition to `OAI5G` and `srsRAN`, academic tools and testbeds encompass the `MATLAB 5G Toolbox`, the `Vienna 5G System Level Simulator` and `ns-3` with `5G LENA modules`. However, these tools do not provide an automated process for rapid configuration based on few basic input parameters.

In summary, the gap between TS-based standard documentation and OSS-based RAN stack integration becomes clear. While existing literature and software tools may partially provide instructions, they are often insufficient to aid with rapidly (re-)configuring 5G BSs.

## III. TOOL ARCHITECTURE AND DESIGN

This section describes the architecture and system design of `5GAutoConf`. Figure 1 visualizes the packages, overall data flow, and internal dependencies.

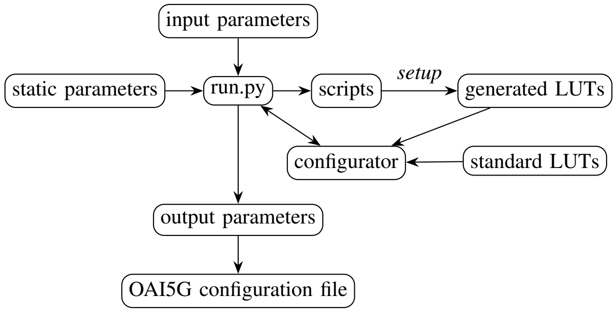

Fig. 1. `5GAutoConf` packages, data flow, and internal dependencies.

The `input parameters` are composed of 5G cell parameters, regulatory parameters and systematic parameters. The 5G cell parameters include the maximum cell radius $r_{\text{cell,max}}$, the maximum user equipment (UE) speed $v_{\max}$, the maximum UE count, the link budget $P_{\text{rx}}$, the channel's multipath propagation characteristics resulting in a maximum delay spread $\tau_{\text{d,max}}$, the minimum channel coherence time $T_{\text{C,min}}$, the beamforming setting, and the maximum permitted PRACH resource overhead. The regulatory parameters consist of the 5G frequency band, which implicitely defines the duplex mode and SSB cases in most cases, and a selection of permitted channel bandwidths. The systematic parameters refer to the SDR used as part of the RAN, as well as the duplex mode if more than one is permitted for the chosen frequency band.

Configuration parameters chosen to remain constant, e.g. for regulatory purposes, can be manually set in a JavaScript Object Notation (JSON) file as `static parameters`.

The `standard lookup tables (LUTs)` are based on 5G TSs and ensure conformity with the 5G standard for computing parameters. During setup, the `scripts` package creates the following `generated LUTs` using the specified modules:

- `build_long_guard_time_prach_pusch_combination_tables`: combinations of PRACH and Physical Uplink Shared Channel (PUSCH) configuration parameters that result in longer guard times (GTs),
- `build_prach_ssb_collision_free_tables`: collision-free combinations of PRACH and SSB,
- `build_tau_d_max_rtd_max_table`: $\tau_{\text{d,max}}$ and $t_{\text{RT,max}}$ for all valid combinations of PRACH and PUSCH configuration parameters.

The `configurator` package offers three modules: `generator` for creating and formatting the configurations files to match `OAI5G`'s format; `tables` to interface the `standard LUTs`; and `tools` which offers computational functions.

The computational process is initiated by executing `run.py` with command-line arguments containing the `input parameters`. `run.py` then invokes the `standard LUTs` and `generated LUTs`, performs rapid calculations using the `configurator` package, and finally generates the `output parameters` in a configuration file for `OAI5G` and a more general JSON file for the subsequent use with alternative software stacks for 5G BSs.

At the time of publication, `5GAutoConf` is still work-in-progress and limited to analyzing chosen configuration variables. Synthesizing these variables from 5G cell parameters as described below needs to include integrating optimization rules, in case variables produce a range of permitted values to satisfy the 5G cell parameter requirements.

## IV. CELL CONFIGURATION PARAMETER COMPUTATION

This section describes how `5GAutoConf` utilizes basic `input parameters` to compute some exemplary 5G BS cell configuration parameters, namely the waveform parameters for PRACH, data and control channels. These waveform parameters are constraint by the following cell parameters: the cell's maximum round-trip delay $t_{\text{RT,max}}$, which is caused by the physical cell radius $r_{\text{cell,max}}$; the maximum delay spread $\tau_{\text{d,max}}$, which is caused by multipath propagation within the radio channel; and the minimum channel coherence time $T_{\text{C,min}}$, which is caused by either UE motion with maximum speed $v_{\text{max}}$ relative to the BS antenna (resulting in a maximum Doppler shift $\frac{1}{D_{\text{s,max}}}$) in combination with multipath propagation or reflective structures moving with $v_{\text{max}}$ in the radio channel, as described in Equation (1). To shorten the formulae presented in this section, we imply that any subcarrier spacing (SCS) $\Delta f$ is derived from the respective numerology $\mu$: $\Delta f = 2^{\mu} \cdot 15\,\text{kHz}$ [13]. The computation flow for these cell parameters visualized in Figure 2.

$$T_{\text{C,min}} = \frac{1}{D_{\text{s,max}}} = \frac{c_n}{2 \cdot v_{\text{max}} \cdot f_{\text{c}}} = \frac{c_0}{n \cdot 2 \cdot v_{\text{max}} \cdot f_{\text{c}}} \qquad (1)$$

$f_{\text{c}}$ is the center frequency of the transmitter and $c_n$ is the speed of light in a medium with refractive index $n$.

### A. PRACH Guard Times

For all PRACH formats except `A1-A3`, a GT $T_{\text{GT}}$ occurs after the rearmost Zadoff-Chu (ZC) sequence due to additional time resources within the assigned Random Access Channel occasion (RO) duration. Here, the PRACH cyclic prefix (CP) mainly constraints $\tau_{\text{d,max}}$ as well as other minor timing uncertainties.

$$t_{\text{RT,max}} \leq T_{\text{GT,min}} = \left(N_{\text{dur}}^{\text{RA}} - (N_{\text{CP}}^{\text{RA}} + N_{\text{u}})\right) \cdot \kappa \cdot T_{\text{c}} \qquad (2)$$

$N_{\text{dur}}^{\text{RA}}$, $N_{\text{CP}}^{\text{RA}}$, $N_{\text{u}}$, $\kappa$, and $T_{\text{c}}$ are defined by the 5G TS in [13]. For PRACH formats `0-3` $N_{\text{dur}}^{\text{RA}} = 0$ applies, so the specific PRACH resources to be reserved are not aligned to the overall time resource grid and thus not fully defined. Here, an implicit GT duration can not be clearly assumed from the standard. This creates a discrepancy between the standard, existing integrations, and scientific publications, some of which have published values without disclosing the basis for their calculations. Accordingly, we replace $N_{\text{dur}}^{\text{RA}}$ in Equation (2) by the smallest number of subframes in the PRACH reference grid to exceed $N_{\text{CP}}^{\text{RA}} + N_{\text{u}}$, in agreement with Cox [8]. The resulting implicit GTs are thus roughly similar to values previously published by Chakrapani [6]. When expanding `5GAutoConf` to serve multiple 5G/6G BS stack solutions, this calculation can be adapted to the corresponding integrations.

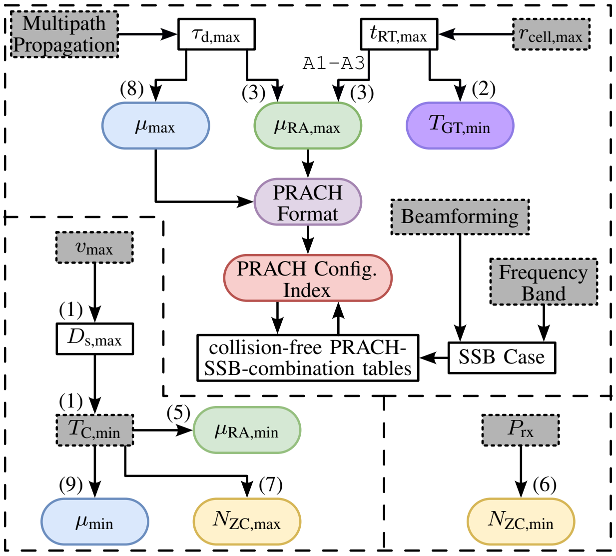

Fig. 2. `5GAutoConf`'s cell-parameter-based computation flow. Dotted boxes: `input parameters`; rounded boxes: `output parameters`; regular boxes: intermediate parameters; (x): equations described in Section IV.

### B. PRACH Subcarrier Spacing

For PRACH formats `A1-A3` no GT is implied in the specification and the PRACH preamble fully utilizes its slot duration. Thus, the PRACH preamble's CP constraints both $t_{\text{RT,max}}$ and $\tau_{\text{d,max}}$, as well as other minor timing uncertainties.

The formats `A1-A3` are designed for very small $r_{\text{cell,max}}$, since any $t_{\text{RT,max}}$ longer than a few samples causes the PRACH sequence to leak into the subsequently scheduled data and control channels. This is exacerbated if $\tau_{\text{d,max}}$ is at least as long as the CP of these subsequent channels, requiring CP adjustment.

As specified in Equation (3), the upper bound of PRACH SCS $\Delta f_{\text{RA,max}}$, and therefore $\mu_{\text{RA,max}}$, depends on both $t_{\text{RT,max}}$ and $\tau_{\text{d,max}}$.

$$\mu_{\text{RA,max}} = \left\lfloor -\log_2 \left( \frac{\tau_{\text{d,max}} + t_{\text{RT,max}}}{N_{\text{CP,pre}}^{\text{RA}} \cdot \kappa \cdot T_{\text{c}}} \right) \right\rfloor \qquad (3)$$

$$N_{\text{CP}}^{\text{RA}} = N_{\text{CP,pre}}^{\text{RA}} \cdot \kappa \cdot 2^{-\mu_{\text{RA}}} \qquad (4)$$

Since a GT occurs for all PRACH formats other than `A1-A3`, Equation (3) is changed accordingly by omitting $t_{\text{RT,max}}$. The number of PRACH CP symbols $N_{\text{CP}}^{\text{RA}}$ in Equation (4) is provided by the 5G TS in [13]. The prefix of the $N_{\text{CP}}^{\text{RA}}$ equations from [13] is represented by $N_{\text{CP,pre}}^{\text{RA}}$ in Equation (3).

To preserve the autocorrelation properties of a singular ZC sequence of length $N_{\text{ZC}}$, the lower bound for the PRACH SCS $\Delta f_{\text{RA,min}}$, via $\mu_{\text{RA,min}}$, depends on $T_{\text{C,min}}$ (see Equation (5)).

$$\mu_{\text{RA,min}} = \left\lceil -\log_2\left(\frac{T_{\text{C,min}}}{N_{\text{ZC}}\cdot\kappa\cdot T_{\text{c}}}\right)\right\rceil \tag{5}$$

### C. PRACH Sequence Length

A longer $N_{\text{ZC}}$ produces a higher correlation peak, which increases the required minimum detection threshold. Then, the lower bound for the minimum ZC sequence length $N_{\text{ZC,min}}$ issued for PRACH is defined by the overall link budget $P_{\text{rx}}$ in dB, as shown in Equation (6).

$$N_{\text{ZC,min}} = \min\left\{N \in \{139, 571, 839, 1151\} \mid N \geq 10^{\frac{P_{\text{rx}}}{20\,\text{dB}}}\right\} \tag{6}$$

$T_{\text{C,min}}$ defines the upper bound for the maximum ZC sequence length $N_{\text{ZC,max}}$, including $N_{\text{CP}}^{\text{RA}}$ to preserve its correlation properties, as described in Equation (7).

$$N_{\text{ZC,max}} + N_{\text{CP}}^{\text{RA}} \leq T_{\text{C,min}} \tag{7}$$

### D. Overall Subcarrier Spacing

The choice of the SCS varies between PRACH and subsequent data and control channels, the latter of which are subjected to the timing advance (TA) command [14].

Hence, the upper limit for a channel's SCS $\Delta f_{\text{max}}$ is defined by the CP duration $N_{\text{CP},l}^{\mu}$ being the upper bound for $\tau_{d,\text{max}}$. This is analogous to $\Delta f_{\text{RA,max}}$ for all PRACH formats other than `A1-A3`. Equation (8) describes the computation for the respective $\mu_{\text{max}}$. Since $\Delta f_{\text{max}}$ is limited by shorter symbol durations, the relevant $N_{\text{CP},l}^{\mu}$ is computed for orthogonal frequency-division multiplexing (OFDM) symbols $l \neq 0$ und $l \neq 7 \cdot 2^{\mu}$. Following [13], the factor $144$ is replaced with $512$ for the extended CP option.

$$\mu_{\text{max}} = \left\lfloor -\log_2\left(\frac{\tau_{\text{d,max}}}{144\cdot\kappa\cdot T_{\text{c}}}\right)\right\rfloor \tag{8}$$

Similarly to $\Delta f_{\text{RA,min}}$, the lower limit for a channel's SCS $\Delta f_{\text{min}}$ is defined by $T_{\text{C,min}}$ given in Equation (1). To preserve the circular convolution properties and thus the orthogonality, $T_{\text{C,min}} \geq N_{\text{CP},l}^{\mu} + N_{\text{u}}^{\mu}$ needs to apply. Equation (9) computes the respective $\mu_{\text{min}}$.

$$\mu_{\text{min}} = \left\lceil -\log_2\left(\frac{T_{\text{C,min}} - 16\cdot\kappa\cdot T_{\text{c}}}{2192\cdot\kappa\cdot T_{\text{c}}}\right)\right\rceil \tag{9}$$

The equations for $N_{\text{CP},l}^{\mu}$ and the OFDM symbol duration $N_{\text{u}}^{\mu}$ for all signals except PRACH and Remote Interference Management Reference Signal (RIM-RS) are given by the 5G TS in [13]. Computing separate SCSs for all channels subsequent to PRACH offers an optimization opportunity for the 5G BS's configuration by freeing up resources otherwise used to mitigate $t_{\text{RT,max}}$ in PRACH.

## V. Conclusion and Future Work

In this paper, we presented `5GAutoConf` as the first open source automatic 5G BS configuration tool that uses basic input parameters [5]. `5GAutoConf` implements an automatic data-driven process that rapidly creates configurations for OSS 5G RAN stacks, enabling fast adaptation of 5G and later 6G BSs. `5GAutoConf` integrates both 5G standard-compliant and generated LUTs for use case-oriented optimization. We also described the derivation process for waveform parameters of PRACH as well as data and control channels.

For preliminary evaluation, we manually computed cell configuration parameters as described in Section IV and verified the results of `5GAutoConf`'s analysis.

Future work includes finalizing the automated configuration parameter generation. The next step is the integration into a testbed to enable automatic rapid generation of scenarios incorporating 5G BSs for various use cases. Additionally, we aim to conduct a larger-scale evaluation of `5GAutoConf`'s performance and edge-case handling to aid improvement and optimization. Furthermore, the JSON-based secondary output shall be expanded to serve further OSS 5G stack software, such as the `srsRAN` Project. Finally, the ongoing development of `5GAutoConf` should be aligned with the continuing 6G-related research and incorporate its findings.

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