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AUTOMATED TEST ENVIRONMENT FOR A 5G RADIO POWER SUPPLY

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ABSTRACT

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This bachelor's thesis was a project made for Nokia Networks. Nokia Networks is a subsidiary of Nokia Corporation which is a global multinational company focusing in telecommunications, information technology and consumer electronics.

The aim was to create an automated test environment for a 5G radio's power supply unit by using another radio unit's power amplifier modules as its adaptive load. This way a power supply designer can create very realistic power ramps to test their new design instead of using inadequate artificial loads. The radio unit acting as a load can be easily configured to use different signals and power levels by using a custom graphical user interface software. The software automates many complicated tasks, such as starting the unit which would otherwise be very time consuming.

A 5G 64T64R massive MIMO radio unit was selected and modified to suit this project's needs. A custom Python software was then created from scratch to communicate with the selected radio unit. Necessary measurements were done to verify the test environment's proper functionality.

Keywords: power amplifier, Python, automatization, mobile networks

ABBREVIATIONS

4G	Fourth generation cellular network
5G	Fifth generation cellular network
BB	Baseband
dB	Decibel
DL	Downlink
DPD	Digital predistortion
DSP	Digital signal processing
DUT	Device under testing
FB	Feedback
FDD	Frequency division duplex
Gbps	Gigabits per second
GUI	Graphical user interface
HW	Hardware
IPR	Intellectual property rights
LTE	Long term evolution
MIMO	Multiple-input multiple-output
NR	New radio
PA	Power amplifier
PSU	Power supply unit
R&D	Research and development
RAM	Random access memory
RF	Radio frequency
RX	Receiver
SISO	Single-input single-output
SMA	Sub Miniature version A
SoC	System on a Chip
SSH	Secure Shell
Tcl	Tool command language
Tkinter	Tk interface
TDD	Time division duplex
Tk	Toolkit
TRX	Transceiver

TX	Transmitter
UE	User equipment
UL	Uplink

TABLE OF CONTENTS

1 INTRODUCTION

This thesis was a project made for Nokia Networks while working full-time in their RF R&D department. Nokia Networks is a subsidiary of Nokia Corporation, which is a global multinational company focusing in telecommunications, information technology and consumer electronics. Nokia was originally founded in Tampere, Finland in 1865 but nowadays its headquarters locates in Espoo, Finland. Nokia's total headcount was around 92,000 in 130 countries with net sales of 21.9 billion euros in 2020 (1). The Oulu site, “Home of Radio”, consists of R&D facilities and a ramp-up factory for new products and prototypes.

The aim of this project was to create an automated test environment for a 5G radio’s power supply unit using an already existing base station radio unit as its adaptive load. This means that a new power supply design can be tested under realistic conditions without the need to use artificial loads. Using artificial loads would lead to inaccurate results because of quick power ramps caused by a constantly switching signal.

The test environment is then used for optimizing the power supply unit’s performance as well as for reliability testing. With this system the testing can be done before implementation in the radio itself. Another key advantage of this system is that the power supply unit can be properly tested without any new software meaning that the implementing process can be started much earlier than before.

The test environment consists of modified hardware and custom software. By using a fully customized Python GUI, the power supply designer can easily configure and boot up the radio with various different parameters while altering the amount of power being drawn from the device under testing. Output power from RF pipes is then converted to heat using terminators instead of using an antenna array as usual.

2 5G NR

The fifth generation cellular network is the successor to its predecessor 4G LTE. With some new technologies 5G is able to achieve wireless networks with speeds never seen before. 5G's most important features are much higher bandwidth, up to a data rate of 10Gbps, sub-millisecond latency, an ability to connect up to 100 times more devices than before and up to 90% better energy efficiency than with 4G (2). With faster downloads and much lower lag 5G will make a significant impact on our daily lives by bringing for instance connected vehicles and traffic systems, e-health systems and mobile cloud gaming (3). Key factors in achieving this kind of connectivity are massive MIMO and beamforming.

The radio unit used in this test environment contains 64 RF chains similar to the one in Figure 1. This means that the radio unit is equipped with baseband (BB) components capable of forming 64 data streams. All of these RF chains have their own dedicated power amplifier modules (PAM) which can be used as load.

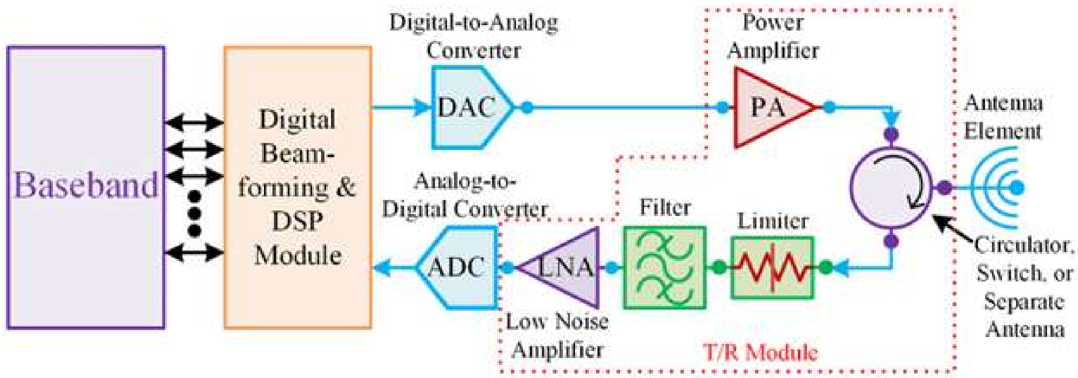

FIGURE 1. Example of a 5G radio's RF chain (4)

2.1 Massive MIMO

Multiple-input multiple-output (MIMO) is a technology that uses two or more transmitting and receiving antennas concurrently to transmit high amounts of data. Every transmitting antenna sends their own data signal via its own radiopath towards the user equipment (UE). The data transmission speed is doubled if the UE receives 2 different bit streams simultaneously instead of just one. Using MIMO instead of conventional single-input single-output (SISO) also increases the connection performance and range by bouncing the signal off objects, such as walls or ceilings (5).

5G Massive MIMO as opposed to regular MIMO has even bigger antenna arrays resulting in better connectivity overall. The total radio throughput is typically increased by anywhere from 500% to 800% under same conditions compared to legacy LTE 2x2 MIMO (6). Currently, the biggest massive MIMO radios available have 64 TRX antennas while even bigger ones are most likely under development. Figure 2 illustrates how a connection between an antenna array and multiple UEs is formed in a massive MIMO environment to create multiple data streams.

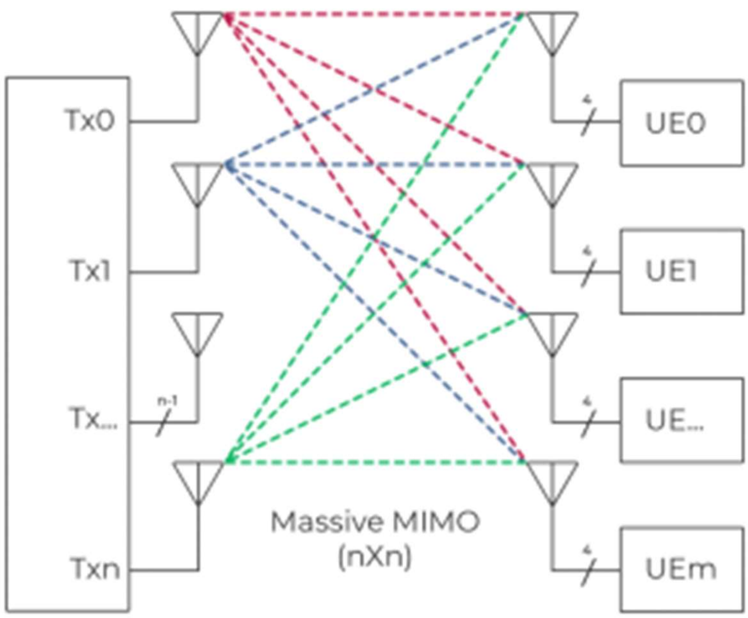

FIGURE 2. Data streams between a massive MIMO antenna array and UEs illustrated (6)

2.2 Beamforming

Beamforming is a technology used to focus narrow data “beams” transmitted by the antenna array in direction of UEs to improve network efficiency and save energy (7). Every UE communicates on the same frequency simultaneously but do not interfere with each other because each one gets their own narrow beam (Figure 3). Normally the radio would emit only one wide data beam and therefore the UEs could not communicate with the radio at the same time. Therefore, using beamforming paired with massive MIMO and high modulation it is possible to achieve a drastically higher throughput than ever before.

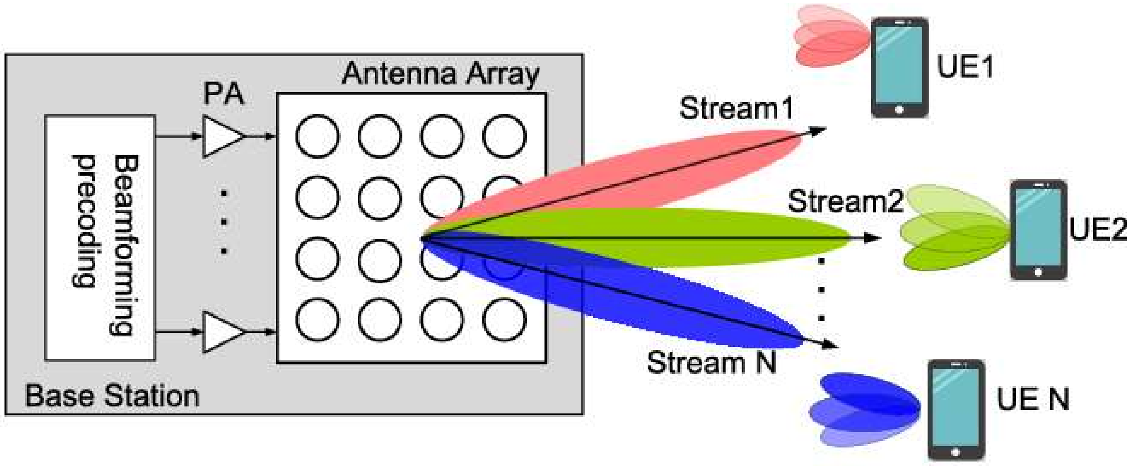

FIGURE 3. Beamforming using multiple antennas and UEs (8)

3 POWER SUPPLIES

Power supply unit is a part of the radio unit that transforms and feeds power to the whole unit. Even though 5G is more energy efficient than any previous generation before, new radios with exponentially increased data traffic require more and more power as technology keeps advancing (Figure 4). More tranceiving antennas correlate to equivalent amount of BB signal processing parts as well as PAMs which all draw more power from the PSU.

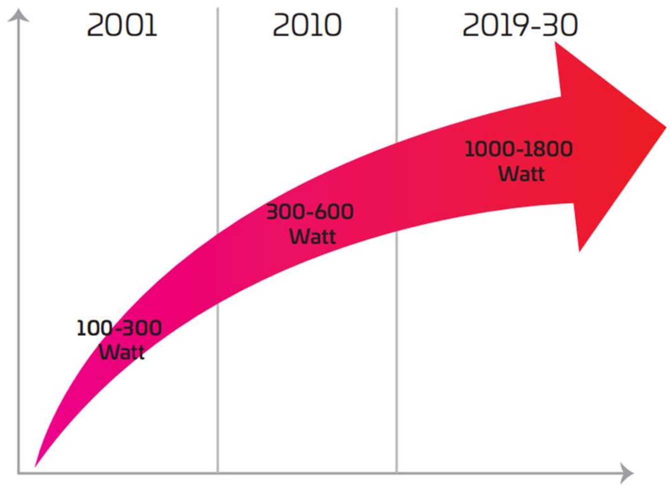

FIGURE 4. Evolution of radio unit power consumption over time (9)

The base station radio unit itself needs different power levels for baseband electronics and RF PAMs. Power amplifiers boost up the RF signal before being redirected to filters and antennas. In a 5G massive MIMO radio every antenna has its own dedicated PAM. PAs are enabled synchronously by using a TX enable signal. This signal enables and disables the signal transmission, so it can be used as an oscilloscope’s trigger input when measuring power ramps.

64 antennas transmitting data simultaneously can take quite a lot of power, which makes designing the PSU a real challenge. The PSU must be able to handle quick power ramps caused by a rapidly switching TDD signal. In TDD mode, UL and DL data are transmitted using same frequencies but at different times. FDD mode on the other hand is constant and uses different frequencies to transmit UL and DL data at the same time (Figure 5). The automated test environment needs to have an option to easily switch between TDD and FDD modes.

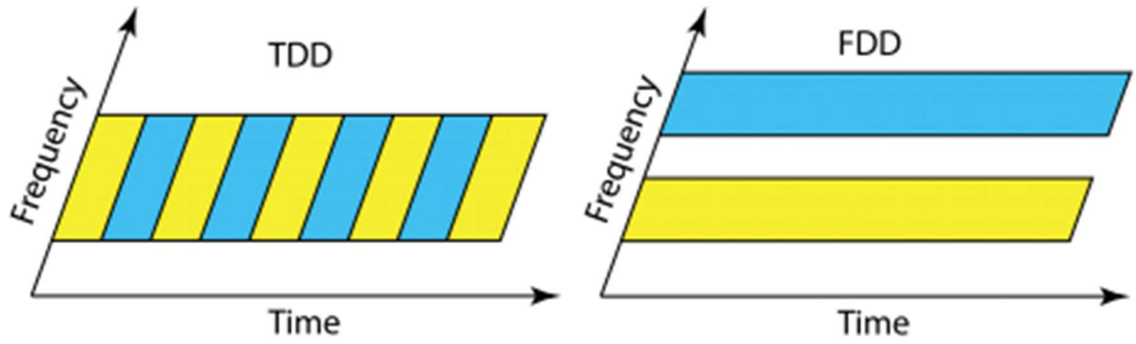

FIGURE 5. Difference between two duplexing modes (10)

4 AUTOMATED TEST ENVIRONMENT

This paragraph explains the purpose of the automated test environment and what kind of hardware and software it consists of. The purpose of the automated test environment is that the end user can use an already existing radio unit as a new PSU's test load. The end user in this case is a PSU designer working on a new product's PSU. This system makes inspecting dynamic performance of the device under testing (DUT) possible before being implemented in the radio which means that testing can be started and possible problems can be found sooner. With this vital information gathered the designer can then modify capacitor configuration as well as feedback compensation.

With the automated test environment, the designer is able to create very realistic power ramps instead of using unreliable artificial loads. Commercial artificial loads cannot provide nearly as quick current rise times as caused by rapidly switching TDD signals.

With a custom Python GUI (Figure 7), the designer can run the radio unit with different RF signals in various configurations while altering the PA output power level. With just a click of a button, the program automates the whole booting process and other functions which would otherwise be very time consuming because every system on chip (SoC) would have to be configured manually by sending a large list of commands over serial connection and SSH. This helps the designer's job tremendously as he does not really have to know anything about the booting process.

4.1 Hardware

The environment utilizes a massive MIMO radio unit with 64 TX and RX antennas. This means that the radio unit has 64 separate PAs that can be used as the DUT's load. The PSU designer can choose to use either half of the PAs for 800W or all of them for a total power consumption of 1600W. Connectors called PA POWER 1 and PA POWER 2 in Figure 6 connect to 32 PAs each. A key requirement for this system was that 32 PAs combined can draw around 700W of power from the DUT. Figure 6 also illustrates how baseband electronics located inside the radio are powered by the radio unit's own integrated PSU while PAs are powered by the DUT. An oscilloscope is used by the designer to monitor the performance of the DUT. A PC is communicating with the radio unit via an external SSH & UART adapter using the GUI.

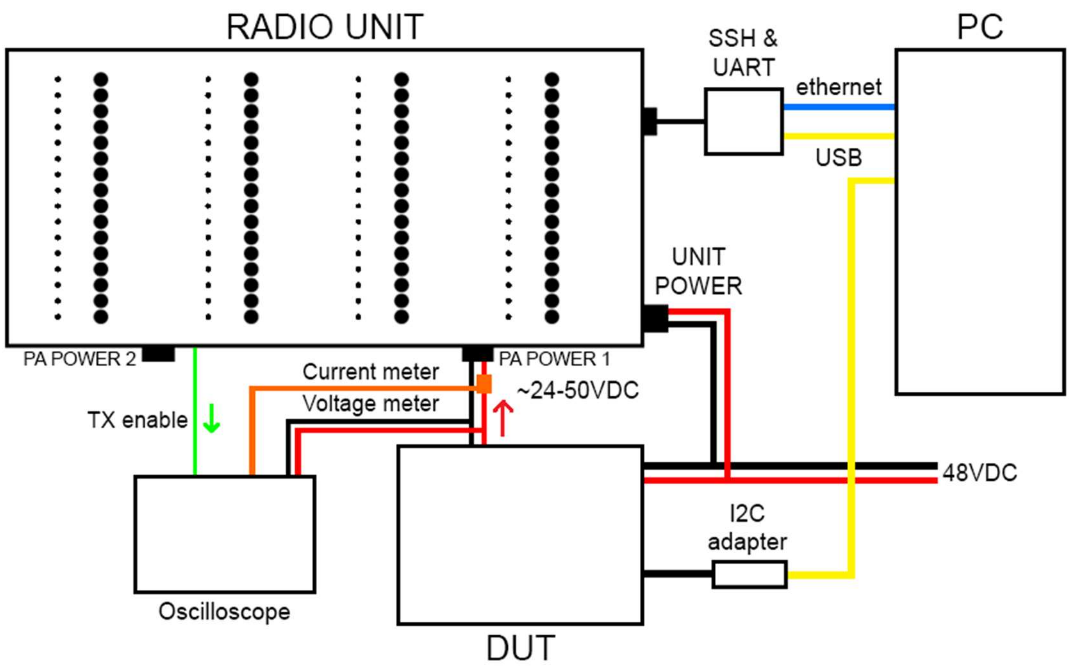

FIGURE 6. The test environment with a laboratory PC, DUT and measuring equipment connected.

The radio unit's structure had to be modified a bit in order to directly feed voltage to its PAs. This was done by taking the whole unit apart and machining cutouts in the mechanic for power cables. Original PA power input lines were then truncated and fed directly with short 6mm^2 cables. All RF pipes are terminated with 50Ω termination resistors instead of radiating the signal with antennas.

Another necessary modification was to extract a TX enable signal that is used as a trigger input when measuring signal timing. This was done by soldering an SMA male cable to a capacitor's pad and ground next to one PA. The cable was then routed outside the radio unit through a machined hole in the mechanic.

4.2 Graphical user interface

The GUI is what ties everything together in this test environment. It automates the radio's complicated startup process with user parameters which would otherwise be done manually and take a very long time. It was made using Tkinter, which is the standard Python interface to the Tcl/Tk GUI toolkit (11). The finished code version 1.0 has 651 rows or 25 549 characters of code but it cannot be shared to public due to Nokia's IPR policies.

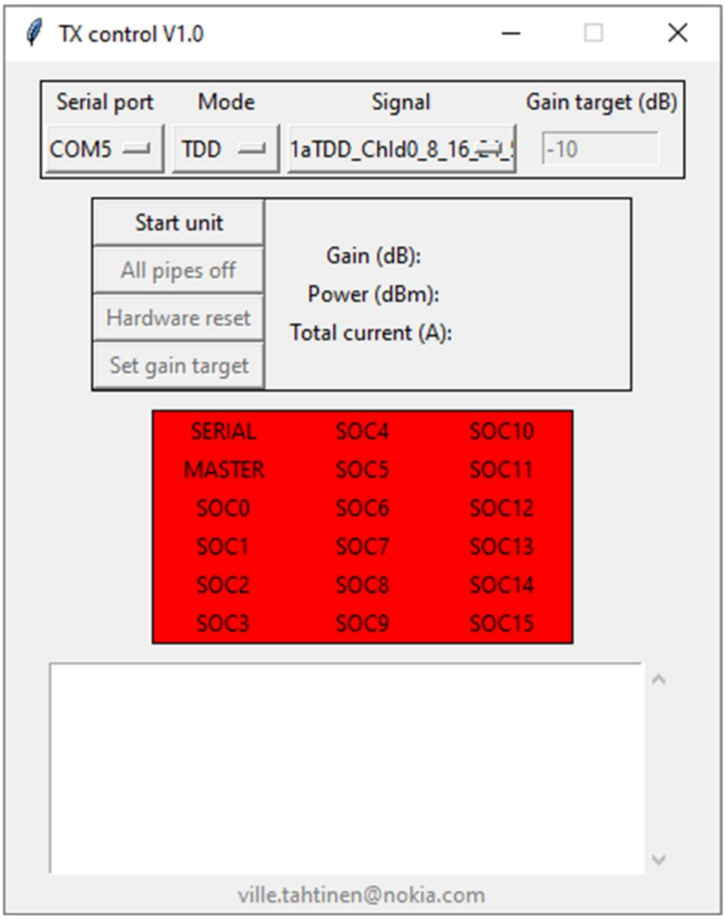

FIGURE 7. The graphical user interface's default view.

With many different features built-in the software, the PSU designer is able to quickly change between signals and configurations. The GUI has been split into 5 different sections.

The first section is for configurations that include a serial port selection, duplexing mode, a signal file selection and a gain target. The program automatically saves and loads previous user configurations from a file called config.cfg. A correct serial port is the one with SSH and UART adapter connected, a CP210x USB to UART driver must be installed for it to be recognized correctly. Duplexing mode determines if the signal will run in TDD or FDD configuration. Selecting either mode will use a list of equivalent configuration commands when starting the unit. Signal files (.ccf or .txt) have to be placed in the same directory as the program in order to be recognized. Signal files contain pre-coded signal waveforms that can be used to load PAs. They must be inserted into a SoC's internal or external RAM to run. The gain target can be used to control RF output power which affects the total current draw. The gain target must be used with caution because the PAs will likely burn if they are too overpowered.

The next section has 4 buttons for different built-in functions. One for starting the unit, one for switching off all RF pipes, which disables the load, one for a hardware reset and one for setting a new gain target. Every button launches a new thread in the software to execute different functions in parallel to each other. Every function does their own task by performing different SSH command sequences.

Right next to buttons there is a section for showing different reading values from the radio unit. These readings are gain, RF power and total current draw. Gain and RF power are read from a SoC over the SSH connection. RF power readings consist of transmission (TX) and feedback (FB) power measured in decibels. TX power is RF power coming out from a PA. FB power is TX power after it has been fed back to a digital predistortion (DPD) unit through a feedback loop. Total current is a calculated sum of every used PA's estimated current based on TX power. It is calculated using the following formula:

$$\frac{RF\ output\ power * amount\ of\ PAs}{Operating\ voltage} * \frac{1}{PA\ efficiency}$$

The RF output power is TX power reading converted to watts. The amount of PAs is determined by how many of them are being powered by the DUT. The operating voltage is the voltage fed to PAs and it can be anywhere from 24 to 50 volts. The PA efficiency can vary by components used but the software uses an assumption of 40%. The equation must be multiplied with the inverse number of assumed PA efficiency because TX power is only as small as PA efficiency times PA input power.

In the middle there is a simple grid that displays the serial connection state and the SSH connection state for every SoC. Each cell of the grid changes color from red to green when the connection is established successfully.

Below, there is a status log that receives updates from different parts of the program. The log is very useful as the user can see up to date information about different processes while they are running. It is very easy to check what went wrong in case of an error. It is also possible to enable a debugging mode that updates the log more frequently.

4.2.1 Startup process

A startup process (Figure 8) begins when the Start unit button is clicked. The first thing it does is checking if the radio unit has already been started. If it has been already started once, a booting process can be skipped and new parameters can be configured to all SoCs.

The next phase is initiating a serial connection to a serial port chosen by the user. If a connection is created successfully, the program will read every line of the radio unit's serial output until it requests user authentication. A username and a password are sent over serial port and after a successful login the Ethernet will be enabled.

After enabling the Ethernet, the program will wait for all SoCs to boot up and respond. After everything is booted up and a 30 second delay has passed, it is time to start a new thread for every SoC. Every SoC will be configured parallel over SSH connections with their own threads to save time. A selected signal file is uploaded to every SoC's flash memory. Next up is signal insertion which loads and runs the selected signal file from flash memory to RAM. Signal insertion is successful if RF power becomes enabled and no error messages appear in the status log.

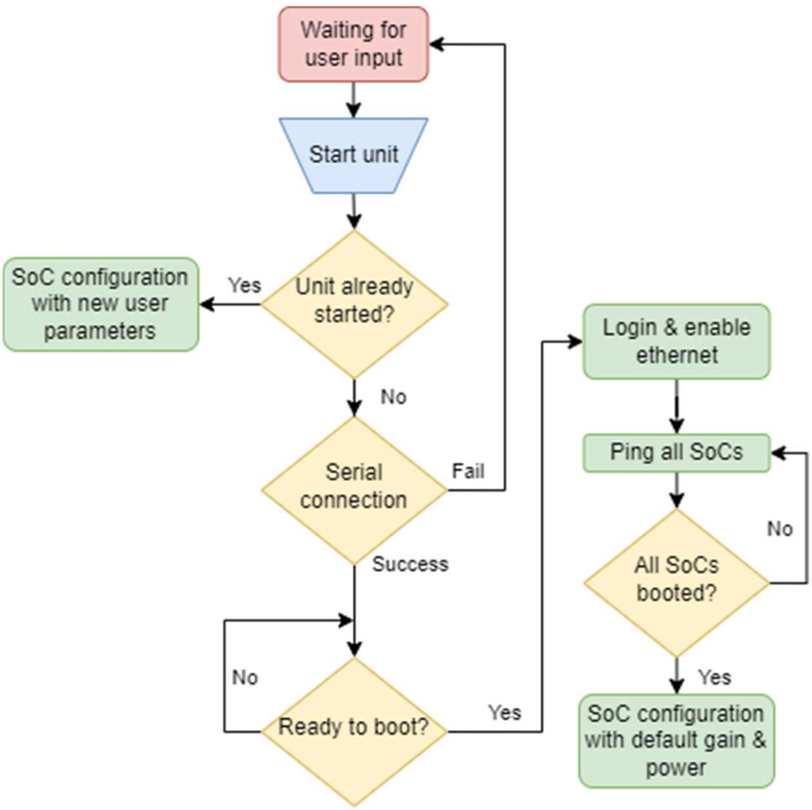

FIGURE 8. The flowchart of Start unit function

The whole startup process takes about an hour if everything is done manually. By automating and optimizing every step, it only takes mere 6 minutes. This means that the software achieves a total reduction of 90% in startup time alone.

After a successful signal insertion, the user will be free to change the parameters (Figure 9). The first startup will always use low preset gain of -10dB to ensure a safe boot and avoid a possible damage. A hardware reset button is gray and cannot be used unless all RF pipes have been turned off first.

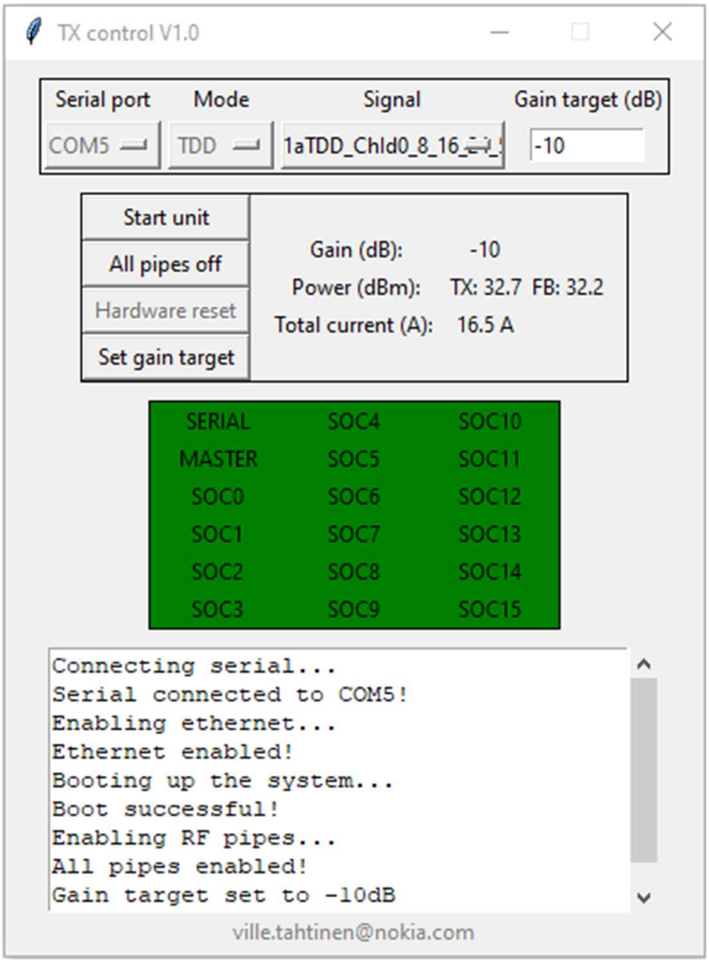

FIGURE 9. Graphical user interface after a successful startup.

4.2.1 Measurements

Some measurements were performed in order to verify that the test environment works as it should. These measurements use a 50µs long TDD signal with a 79% duty cycle. A signal is down for 10.7 µs and up for 39.3 µs as shown in Figure 10. This measurement has been taken from the end of an active RF pipe.

FIGURE 10. 50 µs long TDD signal in a signal analyzer

TX mode is enabled for 74% and RX mode for 26% of the time. Figure 11 shows an oscilloscope view of the TX enable signal where transmission is enabled for 3.7 ms and disabled for 1.3 ms.

FIGURE 11. TX enable signal measured with an oscilloscope

It is possible to run the PAs overpowered using the GUI's built-in gain control. It was necessary to perform some testing on how far the PAs can be pushed power wise before they suffer any damage.

Figures 12 and 13 show current and voltage behaviour of 9 PAs at 50V operating voltage with different gain targets. Channel 1 (yellow) is connected to a current meter between the DUT and PAs while channel 2 (green) is for measuring the PA operating voltage level. Current is about 3.97A with the -1.5 dB gain target in Figure 12, while in Figure 13 current is 4.50A with the -0.5 dB gain target. This confirms that changing the gain control from the GUI actually affects power consumption. -0.5 dB was the absolute maximum before damaging anything. With these values in mind, 32 PAs would draw around 706W at the -1.5 dB gain target or a maximum of 800W at the -0.5 dB gain target. This leaves a safety margin of 1 dB between the required 700W and absolute maximum power. There are some noticeable power spikes and voltage fluctuations visible due to an inadequate laboratory power supply and too long cables used for these measurements. This was not ideal but sufficient enough to verify the functionality of gain target control and that different signals behave as they should.

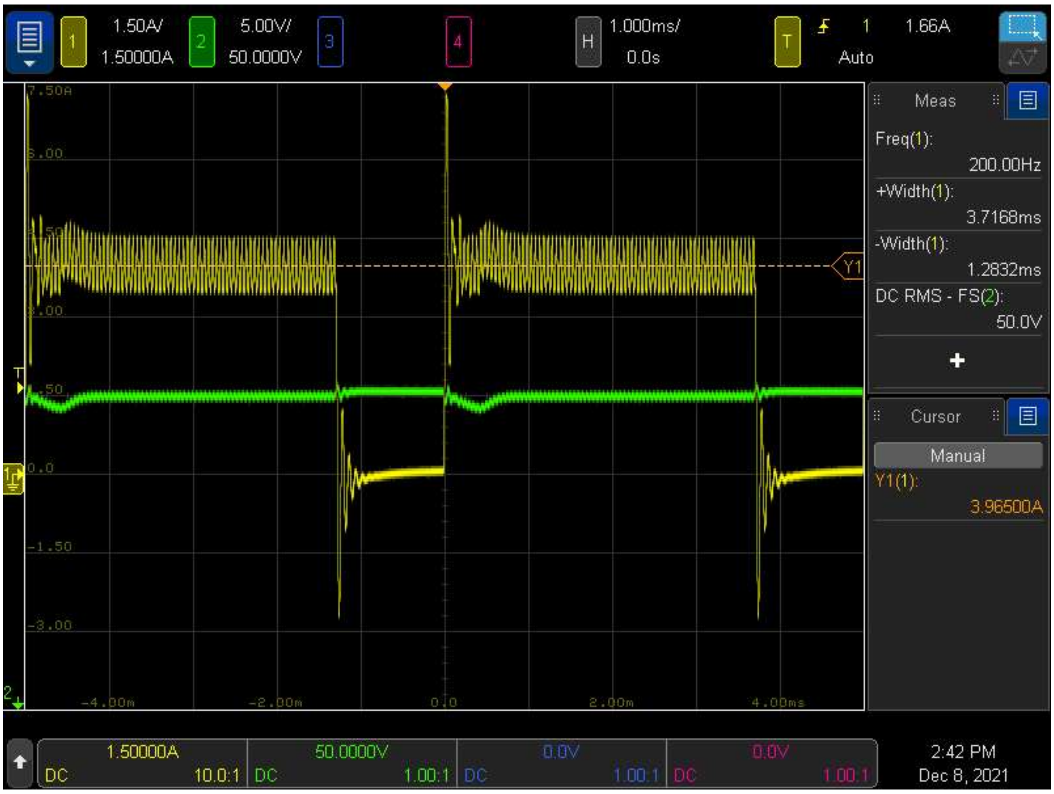

FIGURE 12. Current and voltage waveforms of 9 PAs with -1.5 dB gain target

FIGURE 13. Current and voltage waveforms of 9 PAs with -0.5 dB gain target

5 CONCLUSION

The aim of this project was to create an automated test environment for a 5G radio's power supply unit by using a base station radio unit as its adaptive load. A suitable 5G massive MIMO base station radio unit was chosen and modified according to Figure 6. A Python GUI, which can be used to start and configure the base station unit automatically was created. Functionality of the test environment was verified with necessary measurements. The end user is able to test and monitor the performance of their new PSU design under realistic loads.

Overall, everything went as planned and the project was successful in every way imaginable. The schedule that was planned prior to the project held quite accurately as there were no major setbacks. Requirements set by the end user were all fulfilled, and his work has been greatly facilitated. The software was created specifically for one radio model running a certain firmware version but it is easy to update in the future if necessary.

This project taught me personally a lot about the internals of a modern radio unit and GUI programming with Python. Especially, the functionality and purpose of different RF components is something that was not clear to me before. It was also a good introduction to what kinds of projects I will be working on in the future as an HW test automatization engineer.

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