TASK DESCRIPTION

The establishment of wireless connection for communications among the nodes of an IoT system or sensor network is essential for flexible and maintenance free applications. The reliable operation is a must in many cases to avoid data loss and to maintain a secure communications channel. To assure reliable operation a complex system test has to be performed. The main goal of the Thesis is the implementation of a complex automated test system for a wireless transmitter unit including (i) the communication protocol of the wireless unit, (ii) the automated functional testing of the main blocks of the unit and (iii) the automated test report generation. More specifically, the wireless unit under test is a TRF6900A FSK transceiver produced by TI. During the completion of the task different measurement devices like Signal and Spectrum analyzer, DMM, etc., has to be integrated using a common software platform to perform various automated tests. The measurement of the signals of the wireless unit is performed by a PXI-based professional chassis housing the necessary measurement instruments available at our department. The evaluation of the results has to be performed by the same platform that runs the test and control software to be developed. The results generated during the automated measurements have to be logged in such a way that meets the main requirements of traceability. Tasks to be performed by the student will include:

- Implement the communication protocol to control the TRF6900A IC via parallel port
- Identify the main building blocks of the transmitter unit that are important in terms of functional test
- Elaborate and implement the test procedure for the functional testing of the unit
- Evaluate the test results in an autonomous way
- Implement automated report generation subsystem that provides the main features of traceability

Budapest University of Technology and Economics
Faculty of Electrical Engineering and Informatics
Department of Measurement and Information Systems

Aizhan Beisenbay

AUTOMATED FUNCTIONAL TEST OF WIRELESS EMBEDDED TRANSMITTER

SUPERVISOR
Tamas Krebesz

BUDAPEST, 2019

Table of Content

STUDENT DECLARATION

I, **Aizhan Beisenbay**, the undersigned, hereby declare that the present MSc thesis work has been prepared by myself and without any unauthorized help or assistance. Only the specified sources (references, tools, etc.) were used. All parts taken from other sources word by word, or after rephrasing but with identical meaning, were unambiguously identified with explicit reference to the sources utilized.

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Budapest, 25 May 2019

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Aizhan Beisenbay

Summary

Rise of automated operations and interactions heavily relies on maintenance free application and devices; therefore stable performance is essential for further developments of unsupervised machine to machine interactions. The main goal of the Thesis is the implementation of a complex automated test system for a wireless transmitter unit including (i) the communication protocol of the wireless unit, (ii) the automated functional testing of the main blocks of the unit and (iii) the automated test report generation. First of all, proper communication protocol for controlling the TRF6900A FSK transceiver unit was clarified and implemented. Thus, the transmitter board can be accessed by custom control software in LabVIEW. Next, the PXI unit, which is used for detection and measurement of signals from TRF6900A, is also accessed with National Instrument drivers through LabVIEW. Two main components, the device under test and the measurement unit, are controlled by custom created controls, and these controls are extensively used to implement the whole automated testing system in LabVIEW environment. The system itself is a linear process, where every state corresponds to set up, measurements, or report generation. Measurements assess the main blocks, and the performance of the board components and their influence on generated and transmitted signal is investigated. There are 3 components involved in transmission: direct digital synthesizer (DDS), phase locked loop (PLL) with voltage-controlled oscillator, and power amplifier. Together these components are responsible for the properties of the generated signal and other characteristics of the system like PLL bandwidth and spurious signal level, based on which expectations on the quality of the generated signal can be established. Finally, all of the measurements are presented in predefined Excel report template. The MS office software is accessed by ActiveX extension of LabVIEW. Every cell of an Excel sheet can be accessed and modified to store measured values for assessed characteristics, and this is how report is generated in the automated functional test system. In conclusion, an automated measurement system have been developed, which tests the transmitter characteristics of the TRF6900A board and logs the measurement results in an Excel report. Reporting means that a certain level of traceability is also provided which is crucial in real world automated applications.

Összefoglalás

Az automatizált rendszerek alkalmazásának és az azok közötti együttműködések elterjedése erősen függ a karbantartásmentes megoldások elérhetőségétől. Éppen ezért robosztus és megbízható teljesítőképességre van szükség az ilyen, autonóm eszközök esetén. A Diplomamunka témája a TRF6900A FSK adó-vevő egységhez kapcsolódóan az (i) az adatátviteli protokoll, (ii) az adó oldali funkcionális blokkok automatizált tesztelésének és (iii) az automatizált jegyzőkönyv generálásának implementálása. A TRF6900A vezérlés implemetálásának vizsgálatát és megvalósítását követően a TRF6900A LabVIEW környezetben vezérelhetővé vált. Ezt követően a TRF6900A automatizált teszteléséhez szükséges PXI egység felprogramozása következett amelyel a funkcionális tesztekhez szükséges mérések váltak elvégezhetővé automatizált módon. A két fő komponens, a tesztelt eszköz és a mérőműszer saját fejlesztésű vezérlő szoftver elemek segítségével érhető el és ezek alkalmazásával épül fel a teljes vezérlő és tesztelő rendszer LabVIEW-ban. A rendszer maga egy állapotgép, ahol minden állapothoz egy beállítás, mérés és jegyzőkönyvgenerálás fázis tartozik. A mérések során a TRF6900A funkcionális komponenseinek, és az általuk előállított jelek vizsgálata és kiértékelése történik. Az adásban részt vevő komponensek: direct digital synthesizer (DDS), phase locked loop (PLL) benne a voltage controlled oscillator (VCO). Ezek alkalmazásával történik az adott frekvenciájú jel előállítása. A PLL sávszélesség és a spurious jelek vizsgálata pedig az előállított jel tulajdonságairól adnak információt. A mérési eredmények végül egy előre definiált Excel jegyzőkönyv sablonban kerülnek elmentésre. Az Excel cellái a mért értékekkel elérhetőek és módosíthatóak. Összefoglalva tehát egy olyan teljes automatizált teszrendszer került kidolgozásra és implementálásra, amely a TRF6900A teljes adó oldali automatizált vizsgálatára alkamas és a mérési eredményeket Excel jegyzőkönyvként generálja.

1 Introduction

Nowadays with more interconnected world than ever, reliable data transmission is crucial for range activities, from instant messaging to space expeditions. In addition, automation is in steady rise replacing monotonic maintenance and test operations on many sites, substituting human labor. Combined these two factors trigger a range of autonomous testing systems, where human input is minimized, and faults are detected early and have fewer consequences.

The MSc Diploma Thesis is inspired by this shift, and the designed automated system can be used on both manufacturing and operational sites for quality and routine checks. First of all, a throughout analysis of TRF6900A transceiver was carried out to identify parts of the device responsible for signal transmission, to investigate the communication protocol between a controller and the board and create a custom control for the test system. Next, suitable test routines have been designed for each of the components ensuring that individual and overall performances are within defined standards. And lastly, all performed tests and their results have been presented in a report providing basic traceability.

LabVIEW software was chosen to be a platform for the automated testing system, which allows customized instrument control and intuitive to understand and use it. Since PXI professional chassis with modular instrumentation and the software come from the same manufacturer, built-in LabVIEW drivers leverage the customization and adjustment of the PXI control for specific needs of transmission that relies on the components of TRF6900A. Other than that, all of controls are designed and implemented specifically for the proposed automated testing system. However, the transceiver has its own control software and reverse engineering of it allows to understand the communication requirements for customize control design. It should be noted that the TRF6900A board supports both transmission and reception of an FSK signal, but since this thesis cover only transmitter components and operation, the board is referenced as a transmitter throughout the thesis. For the measurement report format Excel was chosen due to high popularity and familiarity to the end user, since adequate use of Microsoft Office Suite is implied by default for most of the professional occupations.

Only restriction, other than general requirements of a testing system, is to implement the whole automated system using the basic version of LabVIEW without any external or paid extensions. It allows reducing cost and maintenance expenses of the system.

Structure of this thesis is as follows; literature review and theoretical background of a test and automation are discussed in chapter 2, all the required instruments are introduced in chapter 3, while the automated system is discussed in details in chapter 4. Finally, conclusion completes the main body of the report followed by references and annex with LabVIEW block diagrams of the proposed system.

2 Literature review

Growth and demand for wireless technologies cause increased volume of manufacturing of high frequency, high performance, and miniaturized products. These devices present unique challenges for testing and verification, influencing test complexity, cost efficiency and integration. With increased combination of digital, analog and RF functions in the products traditional testing methods can be inadequate, and test complexity also rises with miniaturization of the devices under test. In addition, high demand fuels manufacturing volumes, which in turn require high throughout and low cost test with non-expensive and portable test equipment [1]. Testing is an important activity for checking correctness of system implementations. It is performed by applying test experiments to the implementation under test, by making observations during the execution of the tests, and by subsequently assigning a verdict about the correct functioning of the implementation [2]. Since testing is required in each level of assembly, integrated strategy impacts cost, time and quality in product realization process. It can reduce test development time and improve time to market, cut product cost by decreasing the capital cost of the test equipment, and improve product quality by enabling innovative approaches [1].

A very common distinction between tests is black box or white box. Black box testing, or functional testing, is focused on inputs and outputs of the system under test, without any of knowledge available by a tester. In white box testing internal structure is known and that knowledge by a tester. Consequently, there is a range of grey box test within these boundaries.

Generating a test scenario to implement and execute is based on the specifications, and any testing is difficult without knowing what to test. The specification is a prescription of what the system should do; the goal of testing is to check, by means of testing, whether the implemented system indeed satisfies this prescription. If testing is considered as an assessment of implementation correctness, what is correct implementation? There are many definitions to explain it [2].

- Input and output assertion: for any input satisfying input assertion there is output satisfying output assertion
- Deterministic specification: for any input with specification defined the implementation provide the same output as specifications
- Coverage and fault models: there are many possible faulty implementations, and how many of them can be detected?

An implementation under test can be accessed depending on correct implementation definitions adopted by a tester. Does the system have the intended functionality, and does it comply with its functional specification (functional tests or conformance tests)? Does the system work as fast as required (performance tests)? How does the system react if its environment shows unexpected or strange behavior (robustness tests)? Can the system cope with heavy loads (stress testing)? How long can we rely on the correct functioning of the system (reliability tests)? What is the availability of the system (availability tests) [2]?

Another aspect of the testing is coverage, a way to ensure that characteristics of the device are analyzed and proper operations ensured. Test case is finite sequence of inputs to be applied to a device under test and results by expected output generated in DUT. There are specifications for the test case output, their constraints and parameters, and they play important role in test case verdict. If observed output satisfies constraints, then the test result is a PASS, if not, it is a FAIL. In addition, INCONCLUSIVE verdict can be observed if test purpose was not covered during the execution of the test. This kind of test is also known as a conforming testing, and its' principle is illustrated in Fig. 2.1 [3].

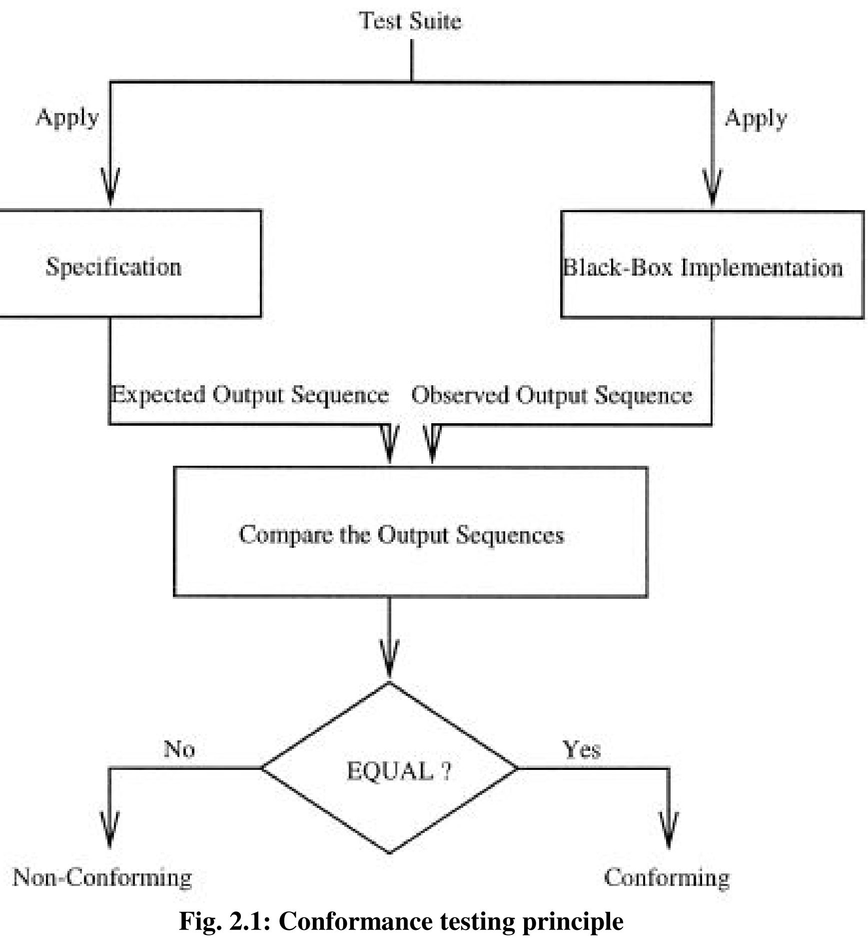

Fig. 2.1: Conformance testing principle

When a test with precise specifications can require too much time and effort, automation seems to be logical solution. Automation may help in making the testing process faster, in making it less susceptible to human error by automating routine or error-prone tasks, and in making it more reproducible by making it less dependent on human interpretation. Another advantage of automation is achieved when test has to be executed several times, which is case in device manufacturing.

According to [2] adaptation of a test automation should proceed in 4 steps:

1. Defined test strategy should take into account quality objectives and specific characteristics of a test object
2. Test automation goals should be clear. It could be a shorter market reach time, cost effectiveness, better quality of a product, or any combinations of these or other goals
3. Strategies merging diverse test automation approaches are more effective than ones with a single approach
4. Frequent evaluation of automation approach allows constant improvement and goals adjustment

Based on the research and observational data collected, an automated functional testing system for the TRF6900A transmitter was proposed. It accesses correct implementation based on input and output assertion, and analyses compliance of the device to its functional specifications. For the automation purposes, a black box type of the testing is used. The main objective of the test is quality of the signal generated by the embedded wireless transmitter, whose main components involved in generation are assessed. It is proposed to use the automated functional test for manufacturing and remote site maintenance.

3 Equipment

In terms of the equipment required the proposed test system consists of a TRF6900A transmitter, a PXI Chassis, a control computer with running LabVIEW program, and a 8.5V power supply for the transmitter. For a test system focused on performance evaluation of the embedded transmitter setup of the equipment used for the test is important (Fig. 3.1). Communication between the device under test and control PC requires parallel port (also known as printer port) connection. In addition, attenuators on transmitter output and PXI Chassis input should be matched for accurate measurement and optimal performance of the test. There are no specific requirements to control PC as long as it supports LabVIEW software, Excel application and allows access to the parallel port.

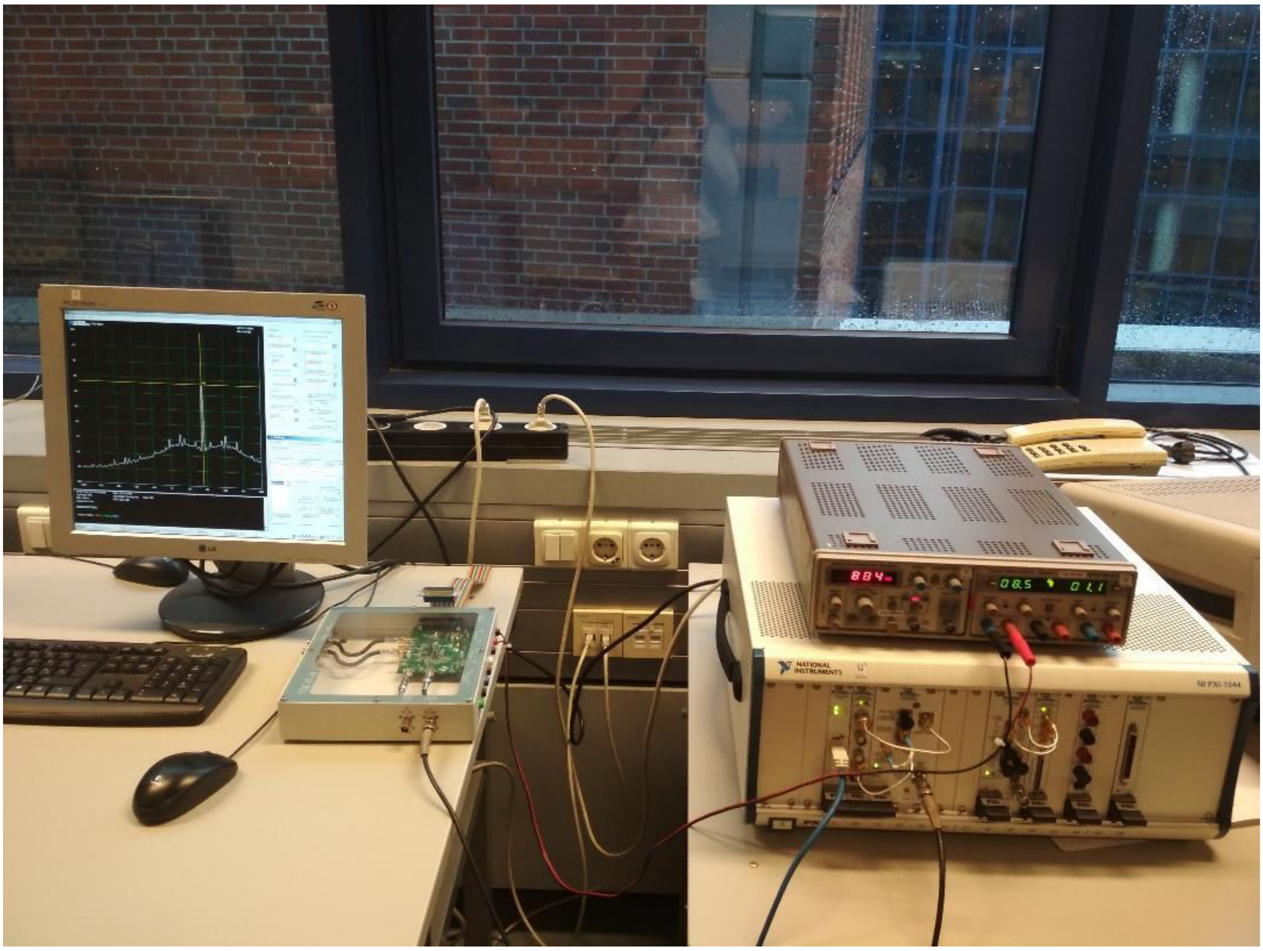

Fig. 3.1: Equipment setup for the testing system from left to right: control computer, TRF6900A transmitter, power supply and PXI Chassis

3.1 LabVIEW

The name LabVIEW is a shortened form of its description: Laboratory Virtual Instrument Engineering Workbench [4]. It was developed by National Instruments as a workbench for controlling test instrumentation. However, its applications have spread well beyond just test instrumentation to the whole field of system design and operation. The main principle of LabVIEW is a graphical structured dataflow language, which enables different elements to be joined together to provide the required flow. The software acts as a portal for a variety of facilities, bring them together under a single element that is easy to manage. This property makes LabVIEW very attractive for equipment and manufacturing test development, since it is intuitively understandable and contains an ever-expanding library of supported hardware drivers. Not only can it be used for equipment control (including the control of the large Hadron Collider at CERN) but also a variety of data acquisition applications (including car development simulation where Big Data monitoring is undertaken) to the system design arena where it has been used for development of projects from RF circuitry to biomedical equipment, green technology and much more. LabVIEW runs on Windows, OS X (Apple) and Linux platforms, making it suitable for most computing systems. The working environment of the LabVIEW consists of coding (block diagram) and user interface (front panel) windows. On the front panel only controls and indicators (input and outputs) are available for a user to manipulate.

For the proposed automated testing system LabVIEW is extensively used for instrument control (both TRF6900A transmitter and PXI Chassis) and as a test environment.

3.2 PXI Chassis

PXI Chassis, or PCI eXtensions for Instrumentation (PXI), is a modular electronic instrumentation platform providing means to build electronic test equipment, automation systems and laboratory instrument. It has a shared timing and synchronization for all modules populating it, and there is only size restriction on the possible modules allowing high degree of customization. In addition, the control of the modules can be build-in to the chassis or external. The chassis are usually used in high-performance measurements and test applications. For the test system implementation PXI-1044 is used (Fig. 3.2), with high output power supply, high level of maintainability, advanced timing and synchronization. The key features of the PXI-1044 include the following [5]:

- 3U-sized, 14-slot chassis
- Universal AC input: automatic voltage and frequency ranging
- Temperature-sensing module that can adjust fan speed based on air-intake temperature to minimize audible noise
- Front-panel LED that can indicate power supply failure
- 10 MHz REF IN and OUT BNC connectors for synchronizing multiple chassis using PXI_CLK10

Fig. 3.2: PXI-1044 chassis

Although the chassis is the most visible part of a PXI system, modular instruments in the slot of the chassis are functional units used for a test. There is a wide range of modules for a variety of measurements (voltage, current, frequency as well as signal and waveform generators), as well as for other functions including boundary scan testing, digital or analogue input and output, image acquisition, power supplies, switching and much more.

For the automated test system discussed in this report PXI vector signal analyzer instrument, PXI-5660, is used to acquire and measure output signal of the transmitter under test (Fig. 3.3). As its name suggests the module performs vector signal analysis and spectrum analysis to deliver extremely high-throughput and high-performance RF measurements [6]. PXI Vector Signal Analyzers are ideal for microwave test, wireless test, RADAR test, spectral monitoring, software-defined radio (SDR), radio monitoring, interference detection, and signal intelligence.

Fig. 3.3: PXI-5660 module

3.3 TRF6900A transmitter

As the device under test in the proposed automation system, TRF6900A has a more detailed description. The TRF6900A is a single chip transceiver with operation range between 850MHz to 950MHz, which includes two ISM (industrial, scientific, medical) frequencies 868MHz and 915 MHz. As the name suggests the system on chip supports Frequency Modulation and Frequency Shift Keying operations in transmit and receive modes. The Fig. 3.4 below is functional block diagram of the TRF6900A chip. There are three main components involved in generation and transmission of a signal: power amplifier, direct digital synthesizer (DDS) and phase locked loop (PLL) with voltage-controlled oscillator. DDS generates a signal with reference frequency (3.57 MHz) for the PLL which multiplies it in frequency into the RF region while the power amplifier adjusts the required power level.

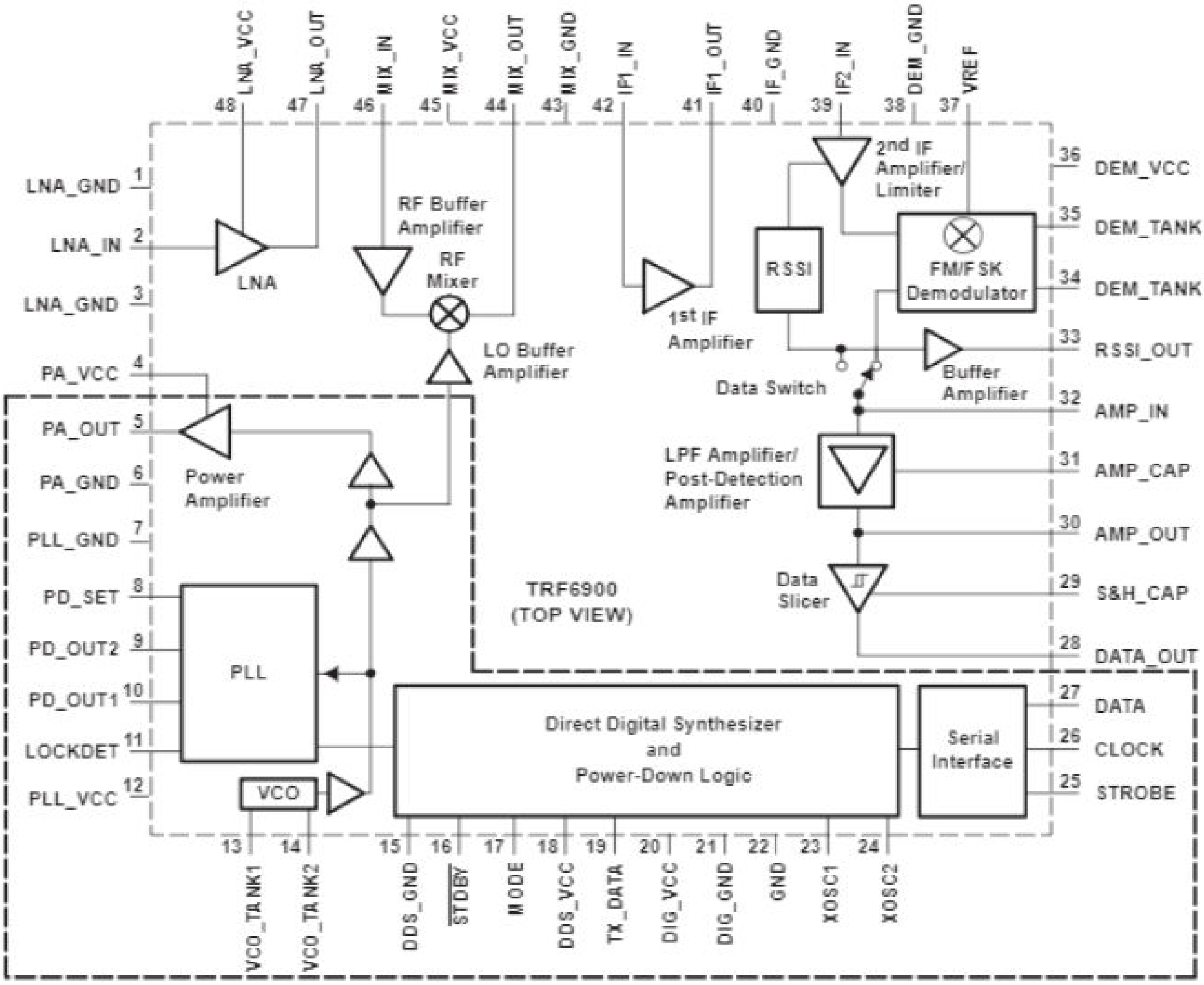

Fig. 3.4: Chip layout of TRF6900A transceiver [7] with dashed area representing transmitter

Base principle of DDS is generating sine wave signal in digital domain, and its benefits include high precision, wide frequency range, high degree of software programmability and fast lock times [8]. All of them contribute to robustness and reliability of the transmitter in addition to adjustability to different tasks confronting a wireless device.

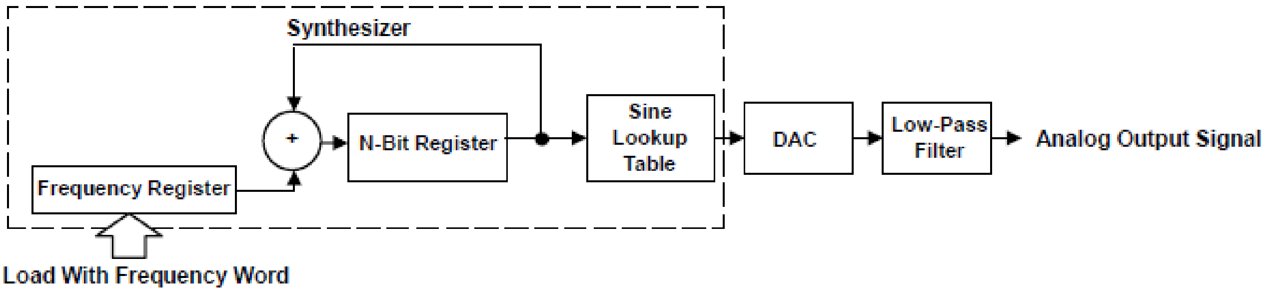

Fig. 3.5: Typical DDS Block Diagram

A block diagram above (Fig. 3.5) shows a typical structure of DDS, consisting of an accumulator, sine lookup table, a digital to analog converter and a low pass filer. All of digital blocks are clocked by a reference oscillator, whose frequency is DDS sample frequency and it determines maximum output frequency of the synthesizer too.

Wireless transmission requires modulated signal waves to be sent over long distances, and range of the transmission depends on a power magnitude of the signal. That characteristic of the transmitter under test is defined by power amplifier, which when enabled changes the magnitude with 0dB, 10dB, or 20dB attenuation.

Last, but not least component in the dashed is serial interface with three inputs, data, clock and strobe. The inputs are essential control signals sand should be generated by the control interface of the TRF6900A, which is discussed next.

3.3.1 Control of TRF6900A

As it was mentioned the transmitter has serial interface which receives three control inputs and setup the components responsible for signal generation.

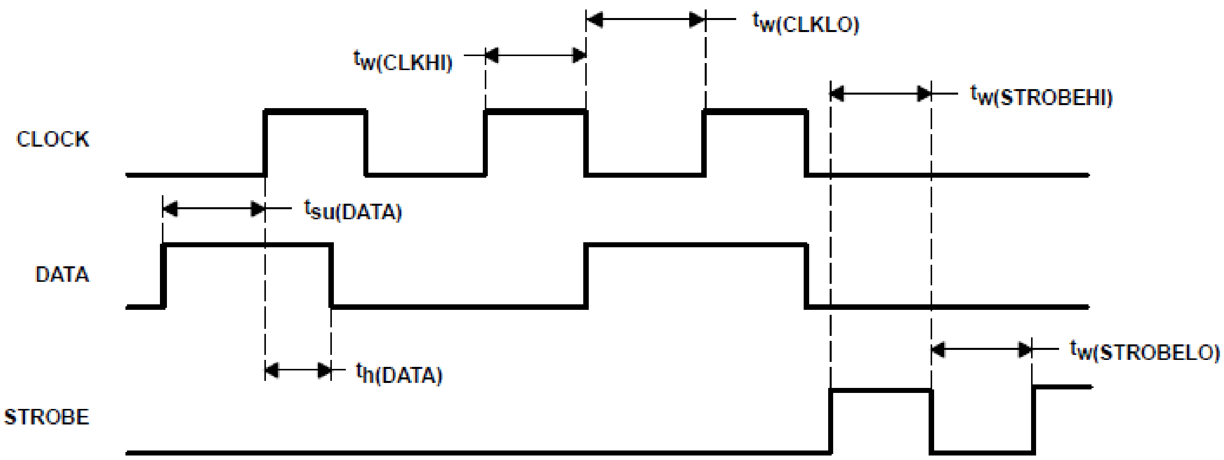

Fig. 3.6: TRF6900A serial interface timing diagram

The Fig. 3.6 shows the timing diagram of the input signals. The data input is loaded to the chip register only when the clock's high level is stable. In addition, with high level on the strobe signal all other inputs should be low. Obviously, only data signal carries the actual setup information for the transmitter chip (as it can be seen in Fig. 3.7). In the documentation of TRF6900A [8] there are 4 pieces of 24-bit long sequences (Fig. 3.8) used to code setting commands to the chip and all of them are transmitted by data input of the serial interface. There is an extra E-register (Fig. 3.7) for redundancy and additional reliability.

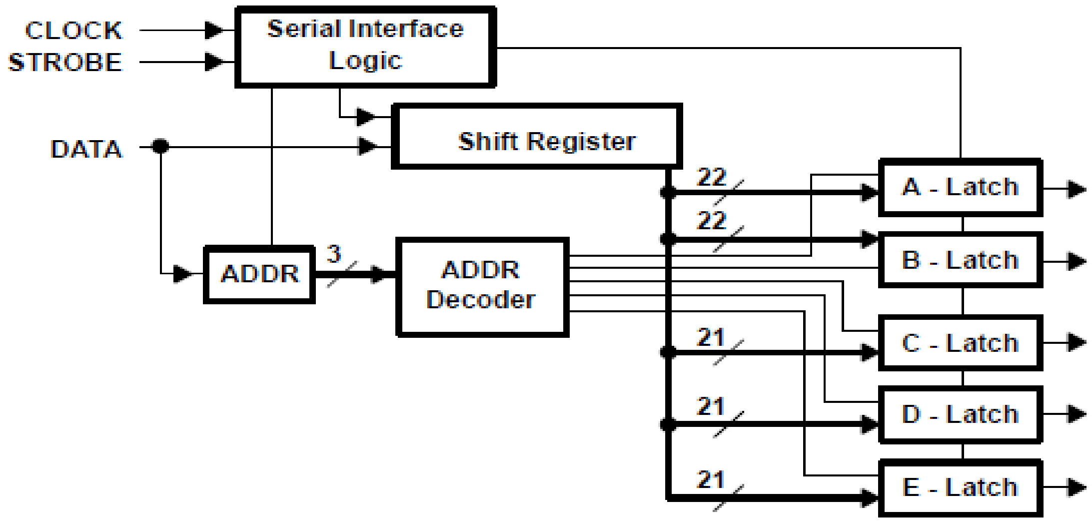

Fig. 3.7: Decoding input signals of TRF6900A

Fig. 3.8 is a detailed view of the codewords used for the chip control. The most significant bits of each codeword correspond to an address the certain code-word should be stored to. As it can be seen first two codewords A and B contain settings for DDS frequency register. The two code-words can be different since the chip supports rapid switch between 2 modes. The 24-bit accumulator of DDS (frequency register on Fig. 3.5) can be programmed by registers corresponding to the codewords A and B with two MSB set to 00 and 01 accordingly. The VCO output frequency depends of DDS frequency settings and calculated according to formula below:

$$f_{out} = (N) * \frac{f_{ref} * DDS}{2^{24}} \qquad rearranging \qquad DDS = \frac{\frac{f_{out}}{N} * 2^{24}}{f_{ref}} \qquad 3.1$$

f_{out}: $VCO\ output\ frequency$

N: $divide\ by\ ratio\ of\ the\ prescaler$

f_{ref}: f_{clock} $system\ clock\ frequency$

DDS: $DDS\ word\ value\ in\ decimal\ format$

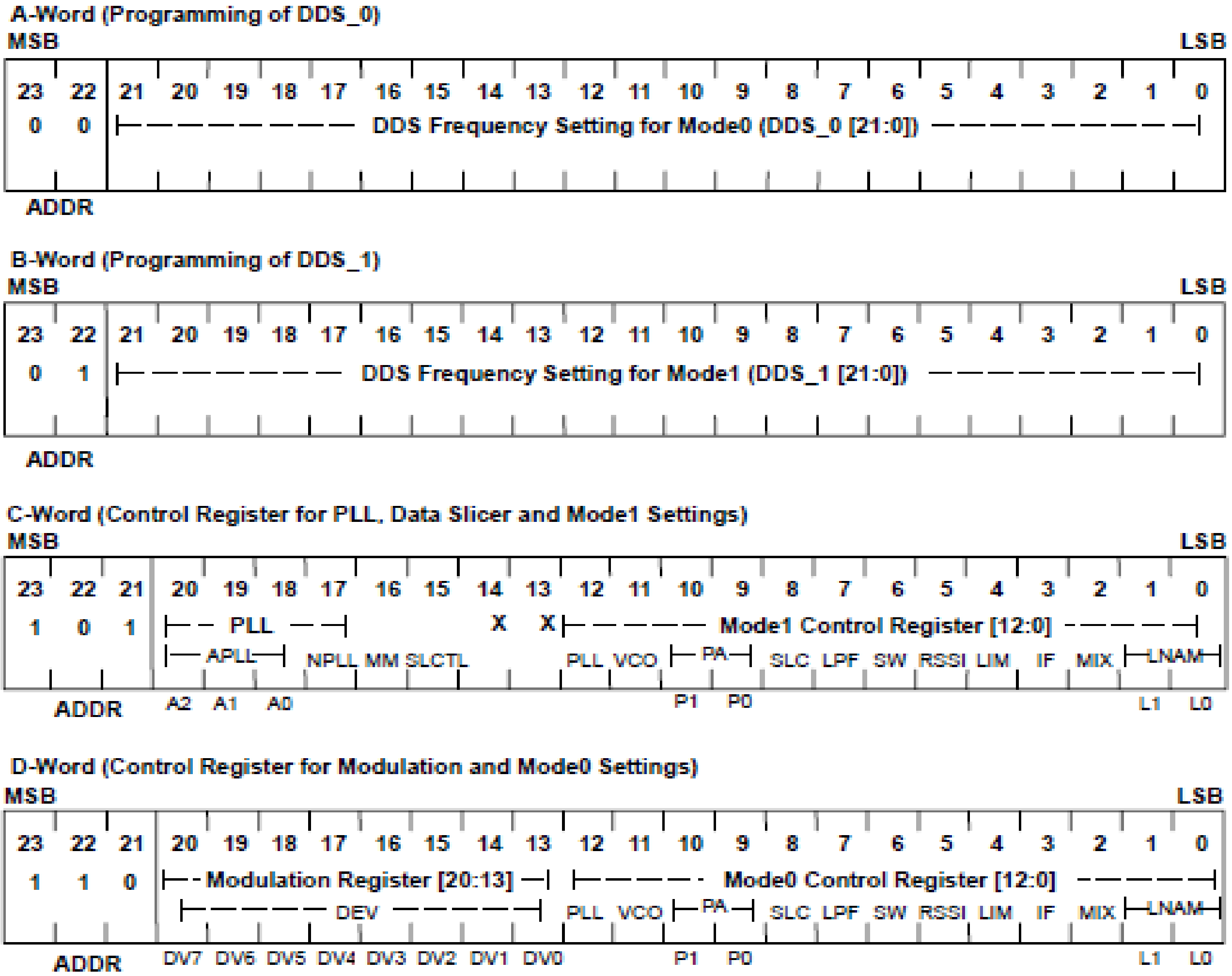

Fig. 3.8: Codeword for TRF6900A control

Table 3.1 Miscellaneous control register description [8]

SYMBOL	WORD	BIT LOCATION	NUMBER OF BITS	DESCRIPTION	INITIAL SETTINGS AFTER POWER-UP	
					DEFAULT STATE	DEFAULT VALUE
DDS_0	A-word	[21:0]	22	DDS frequency setting in Mode0	Zero	All zeroes
DDS_1	B-word	[21:0]	22	DDS frequency setting in Mode1	Zero	All zeroes
DEV	D-word	[20:13]	8	FSK frequency deviation register	Zero	All zeroes
SLCTL	C-word	[15]	1	Slicer mode select bit 0 : hold mode 1 : learning mode	Hold mode	0b
APLL	C-word	[20:18]	3	Acceleration factor for the frequency acquisition aid charge pump A2 A1 A0 0 0 0 : 1 0 0 1 : 20 0 1 0 : 40 0 1 1 : 60 : 1 1 1 : 140	Zero	000b
NPLL	C-word	[17]	1	PLL divider ratio 0 : 256 1 : 512	256	0b
MM	C-word	[16]	1	Modulation mode select. Sets the behavior of pin TX_DATA to FSK data input. 0 : FSK/FM 1 : Do not use	FSK mode	0b

Other important registers of the transmitter are presented in Table 3.1 and they can be found in different codewords. For example, main frequency settings are programmed into codewords A and B, but FSK frequency deviation value is found in codeword D. Characteristics of DDS block, such as PLL divider ratio or slicer mode corresponds to bits 17 and 15 in C codeword.

It is worth to take a look at the last codeword; since it requires inputs for frequency and settings, the D codeword is a perfect example of how control data is generated in the custom controller of the TRF6900A transmitter. Three MSB bits of the codeword are reserved for its' address, leaving only 21 bit to be programmed (Fig. 3.8). Next 8 bits are FSK frequency deviation bits, generated by formula on page 18, but only LSB bits of that calculation are used in codeword D (see page 35). The remaining bits are used to enable different components of the chip, select operation mode of amplifiers and switch between receiver and transmitter sections of the TRF6900A chip.

Table 3.2 Control registers description for codeword D

SYMBOL	BIT LOCATION	NUMBER OF BITS	DESCRIPTION	INITIAL SETTINGS AFTER POWER-UP	
				DEFAULT STATE	DEFAULT VALUE
0_LNAM	[1:0]	2	Low-noise amplifier operation mode L1 L0 0 0 : LNA disabled 0 1 : LNA enable – low-gain mode 1 0 : LNA disabled 1 1 : LNA enable – normal operation mode	Disabled	00b
0_MIX	[2]	1	Enable mixer 1: enabled 0: disabled	Disabled	0b
0_IF	[3]	1	Enable 1st IF amplifier 1: enabled 0: disabled	Disabled	0b
0_LIM	[4]	1	Enable limiter 1: enabled 0: disabled	Disabled	0b
0_RSSI	[5]	1	Enable RSSI 1: enabled 0: disabled	Disabled	0b
0_SW	[6]	1	Data switch 0 : LPF amplifier input routed to demodulator (FSK/FM) 1 : LPF amplifier input routed to RSSI (OOK/ASK)	Routed to Demodulator	0b
0_LPF	[7]	1	Enable LPF amplifier 1: enabled 0: disabled	Disabled	0b
0_SLC	[8]	1	Enable data slicer 1: enabled 0: disabled	Disabled	0b
0_PA	[10:9]	2	Power amplifier mode P1 P0 0 0 : disabled 0 1 : 10-dB attenuation, enable modulation via TX_DATA 1 0 : 20-dB attenuation, enable modulation via TX_DATA 1 1 : 0-dB attenuation, enable modulation via TX_DATA	Disabled	00b
0_VCO	[11]	1	During operation, this bit should always be enabled (1: enabled), unless an external VCO is used.	Disabled	0b
0_PLL	[12]	1	Enable PLL (DDS system, RF, VCO, divider, phase comparator and charge pump) 1: enabled 0: disabled	Disabled	0b

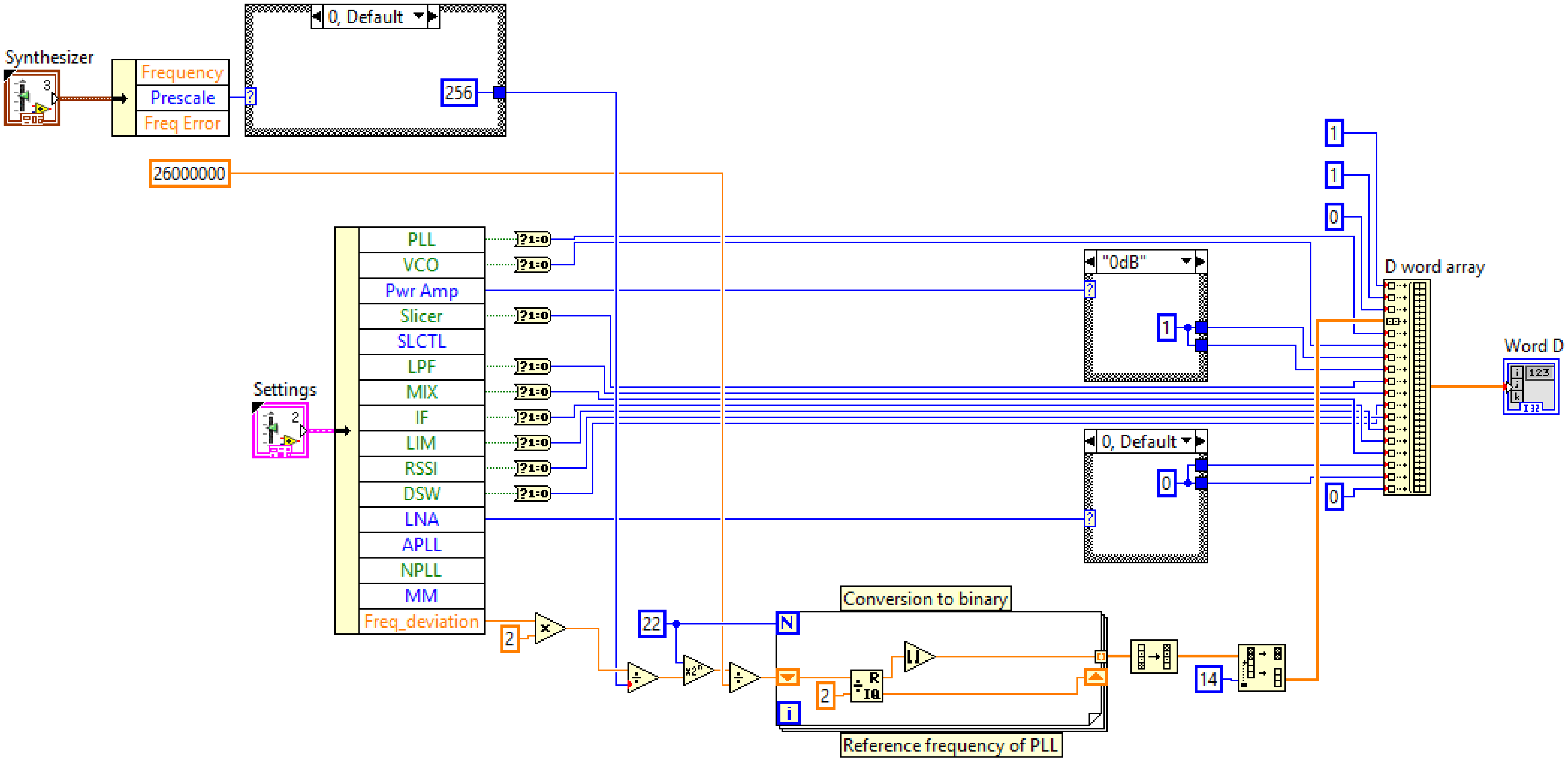

Fig. 3.9: Codeword D implementation in LabVIEW

On the Fig. 3.9 LabVIEW block diagram shows how codeword D is constructed. As it can be seen the settings input has all parameters listed in Table 3.2 for D word. Among them is power amplifier, which is responsible for output signal power level and should be tested by the automated system. Another input parameter for the codeword construction is synthesizer with prescale parameter needed for the frequency value conversion from decimal to binary format accepted by the TRF6900A chip. The process is on the bottom of the Fig. 3.9, and is exactly the same as used for A and B codeword generation with only exception being 22-bit long sequence instead of only 8 in this case.

Codewords imply calculation of frequency value or arrangement of ON/OFF bits, and then they are combined together because the chip has a serial interface. However, ABCD sequence of codewords contains only programming information of the chip. So, if we take a look on parallel port used for TRF6900A transmitter communication, there are additional signals for clock, strobe, TXData, Enable, and Mode (Fig. 3.10). Most of them are straight forward, where strobe signal differentiates between codewords from one another in the series of DataIn.

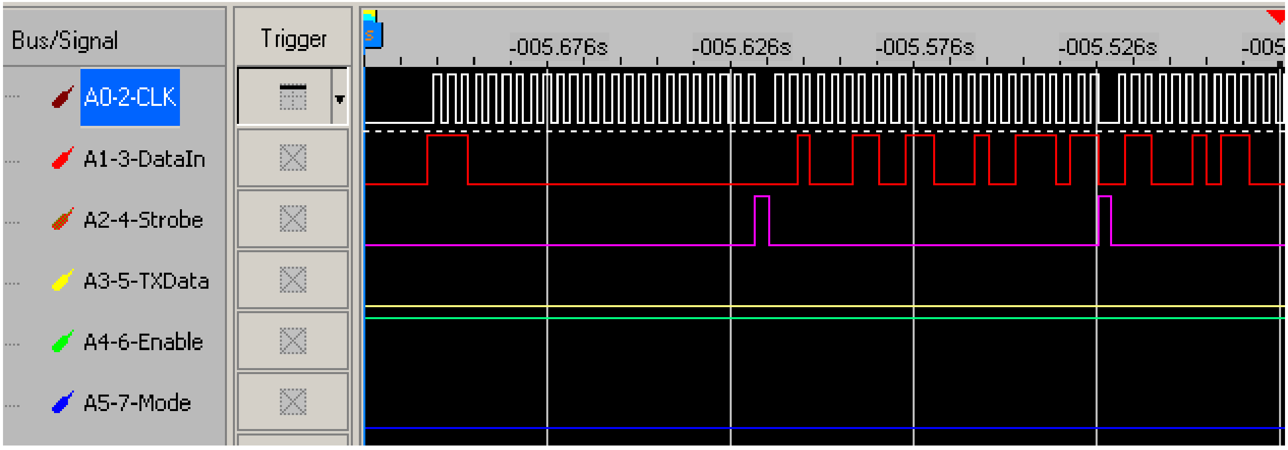

Fig. 3.10: Control signals on parallel port for TRF6900AA transmitter

To achieve the same command signals as above, all inputs to the parallel port should be adjusted to their respective positions, as on first frame of Fig. Fig. 3.11. Clock is important for digital systems synchronization and loading of control signals for TRF6900A transmitter. Since there is no restriction or requirements for clock period for communication between control PC and the transmitter, but stability of the signal during clock's LOW-to-HIGH transition should be enforced for successful load of data bits into registers of the chip. Fig. 3.11 shows how it is achieved in our control system, where for full clock period (Low, High, High, Low), any other signals do not change except the clock signal. Moreover, it was decided to be beneficiary if the codewords are artificially enlengthened by 1 bit („0") each, thus having that logic LOW level when strobe signal is logic HIGH (Fig. 3.11). It is all due to the parallel port communication with the serial interface, which forces a combined binary number representing at instant reading of all input signals. For example, if the interface receives „110010" it is decoded into „clock HIGH, codeword X HIGH, strobe LOW, TX Data 0, enable HIGH, Mode 0"; thus, loading bit 1 into active codeword register. Nothing is loaded into codeword registers if clock is LOW, strobe HIGH changes registers, and TX Data tells if frequency should be modulated.

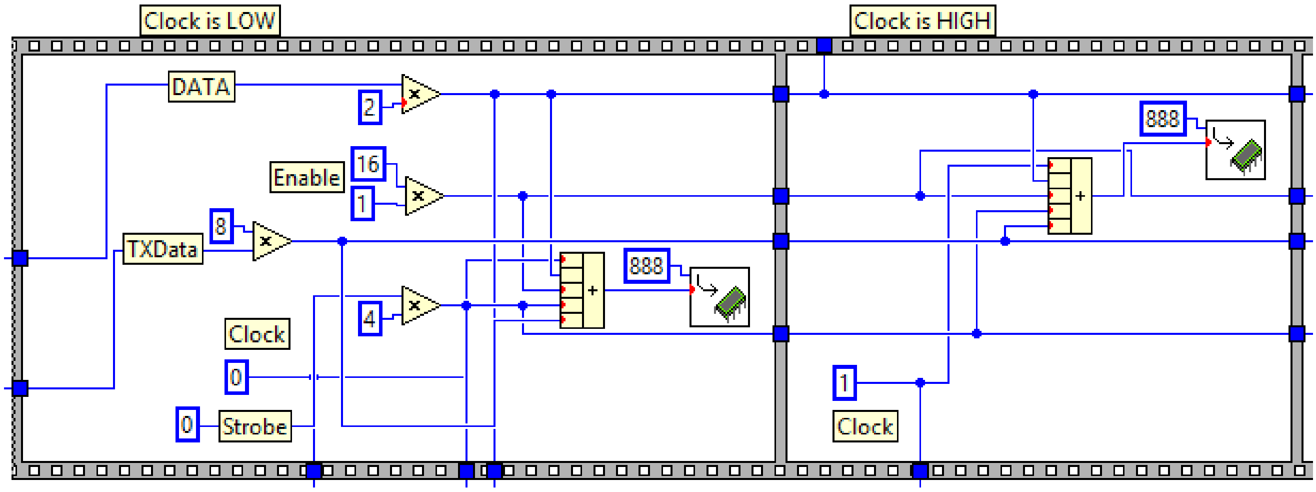

Fig. 3.11: Communication setup for custom control of TRF6900A

4 Testing system

In the automated functional test of the transmitter we are interested in generated frequency and corresponding error, which corresponds to performance evaluation of DDS, PLL and VCO. The error in frequency is due to the frequency accuracy of the reference crystal oscillator used as a clock source. The chip allows three options for the power amplifier (0 dB, 10dB, 20 dB attenuation or OFF), and all four of them should be checked. Last parameter to check is the bandwidth of phase locked loop, which must be equal or greater than modulation rate applied to the synthesizer. If the requirement is not met the output modulation is vanished from spectrum. The advantage of using a DDS-based synthesizer is that as the PLL loop bandwidth is increased for higher data rates, lock time decreases and close-in phase noise performance improves. The trade-off is that spur suppression and rejection of out-of-band phase noise degrade as the PLL loop-filter bandwidth is increased.

Overall testing process for the transmitter is shown on Fig. 4.1. As it can be seen, all important parameters to ensure quality of transmitter are tested, and their numerical values are compared to expected ones.

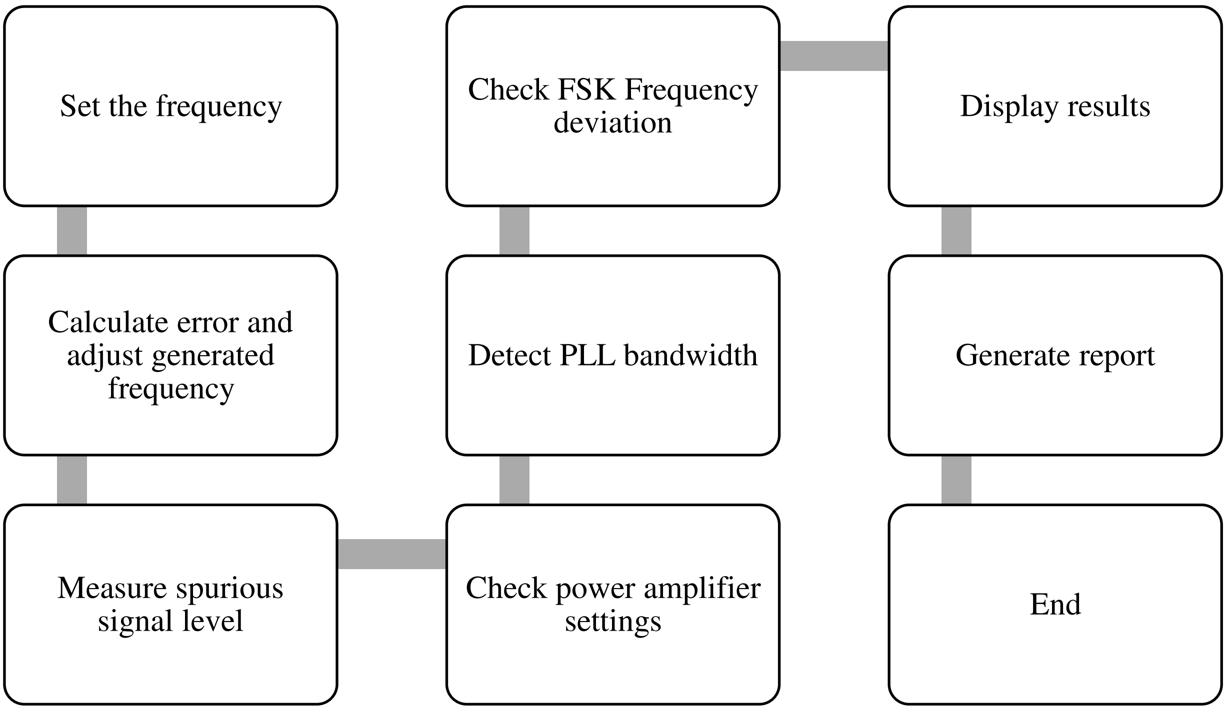

Fig. 4.1: The automated testing system for TRF6900A transmitter

4.1 User interface

For the automated system, a user interface is one of the main blocks, since an operator does not have or have little knowledge of the process involved in the measurements. As it was mentioned before the functionality test is of a black box type, and details of the system under test are not disclosed. Therefore, some indicator of an overall progress of the test should be in place as well as traceability of a later generated report.

There is left to right and top to bottom orientation of all components on the interface, presented on Fig. 4.2. There are only three inputs required from an operator before starting the test. First, name of a current operator should be filled, while date and time information is acquired automatically. Next required inputs are generated signal frequency and frequency deviation for FSK modulation. Other elements of the user interface are informative indicating stages of the automated test system. Right next to the operator's name is "States" indicator, which shows measurements taken during the run of the program from staring the transmitter till report generation. The error output below it is linked to that last state of report generation. If the test program fails to open and modify excel template of the report, this indicator is activated. Send codewords button commands the custom created control of the transmitter to start generating a signal with the frequency setting from the inputs. To ensure that there is data sent to the device separate indicator "Words" follows the button, which shows codewords A, B, C and D and their status. The codewords are generated when the frequency is set, but they are only sent if the "Send codewords" button is pushed. In the lower section of the user interface power spectrum and measurements results are placed. The graph shows the generated signal after frequency error is detected and corrected. After the system carries out the measurements for the test, the values are present in the output indicator in the lower right corner of Fig. 4.2. The same values are copied to the Excel template of a report (Fig. 4.20), and compared to expected limits of the conformity test.

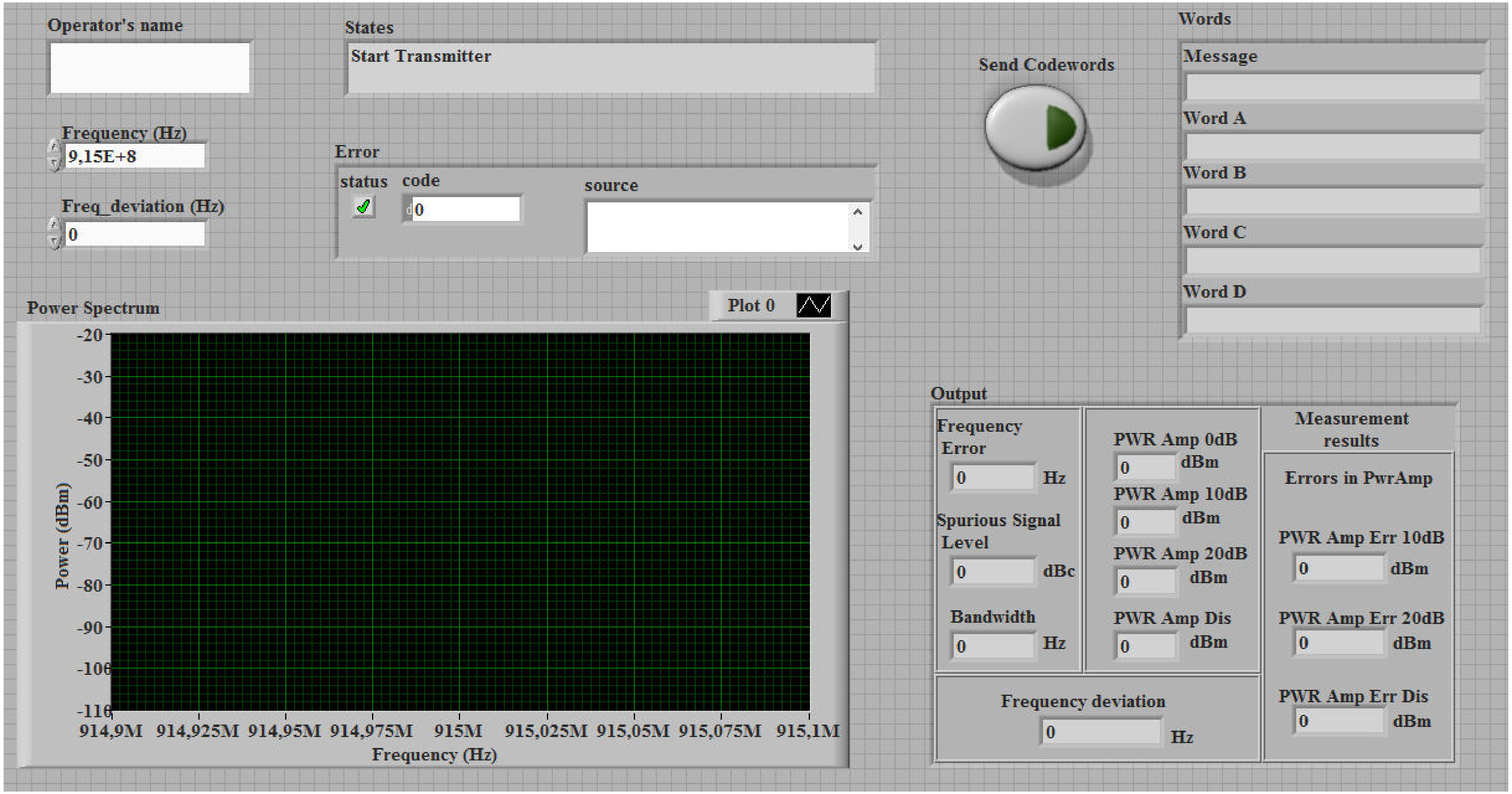

Fig. 4.2: User interface of the automated testing system

4.2 Frequency error

Recalling from 3.3.1 the formula below is used to generate frequency of the output, and the whole process is shown on Fig. 4.3.

$$f_{out} = (N) * \frac{f_{ref} * DDS}{2^{24}}$$

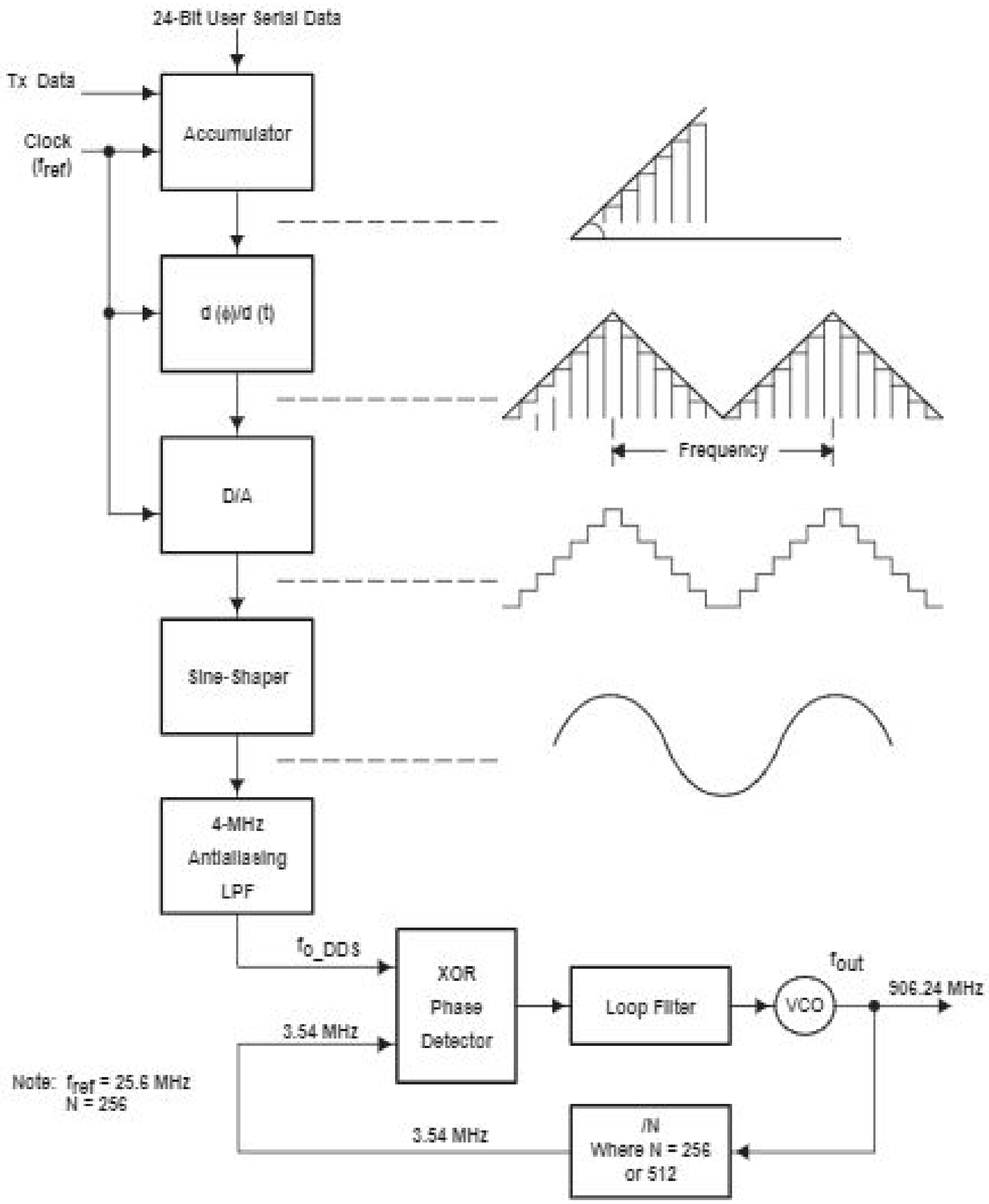

Fig. 4.3: TRF6900A DDS/Synthesizer block diagram

As it can be seen, a 24-bit serial data received starts the frequency generation from accumulator to phase angle computation resulting in ramp waveform. After digital-to-analog conversion and sine shaper the generated signal is low-pass filtered to suppress unwanted spurious responses. The analog output signal is then used as a reference input signal for a phase locked loop. The PLL circuit then multiplies the reference frequency by a predefined factor. Afterwards, the generated sine wave is set up for the frequency specified by codeword A or B. Since output frequency of the chip is set by an operator (Fig. 4.2); the error value can be detected by simple comparison between required and actual output (Fig. 4.4 and Fig. 4.5).

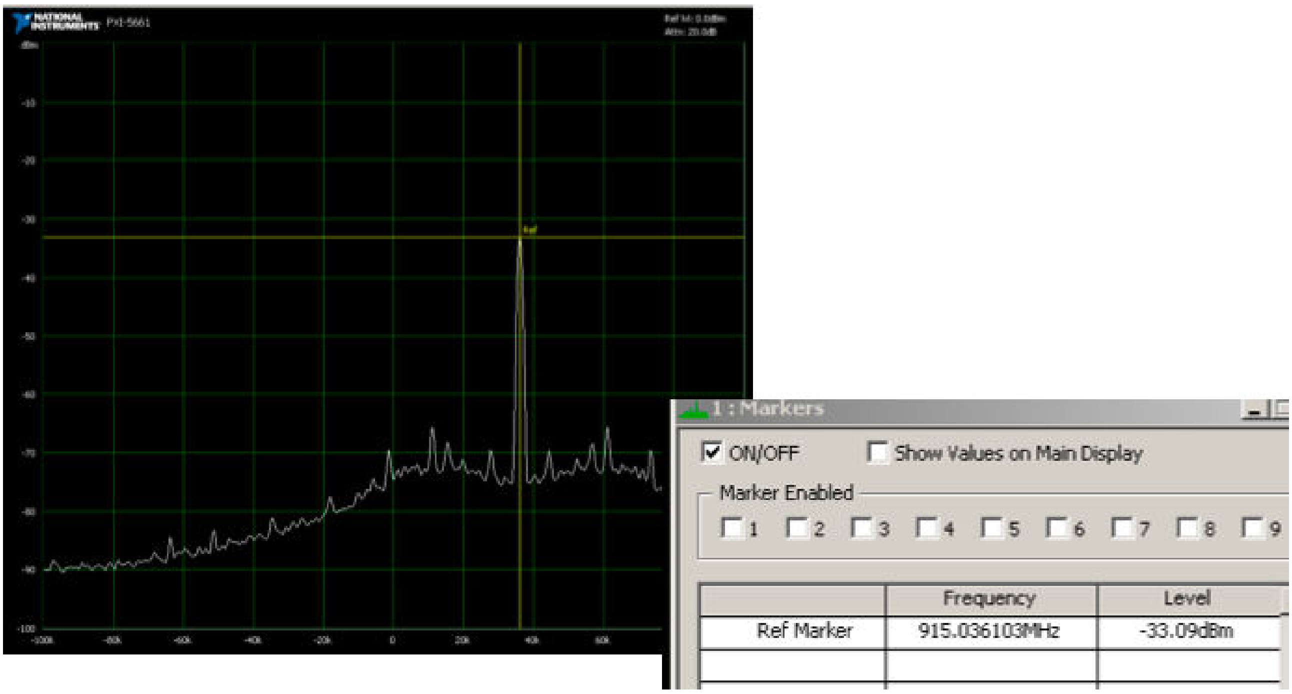

Fig. 4.4 : Power Spectrum of the TRF6900A output signal before correction

However, it is not enough to detect the error, it also should be corrected. First step is to detect the error, by comparing set frequency with the one detected by the PXI unit. After that the difference between frequencies is sent to TRF6900A custom control to adjust generated frequency so that the difference is decreased to step of the DDS. However, detection and correction of the error should be sequential, so that only currently detected error is corrected. These operations are carried out in the block diagram on Fig. 4.6.

4.3 Spurious signal level

On the power spectrum of the TRF6900A signal (Fig. 4.5), there is a clear peak at set frequency (915MHz) corrected by previous step. However, before moving from frequency generation to other elements of the transmitter chip, power level of unwanted frequencies should be accessed. Here, peaks after the greatest one come to consideration. Visually it is very easy to identify secondary peaks but setting the PXI unit to the same task can be tricky.

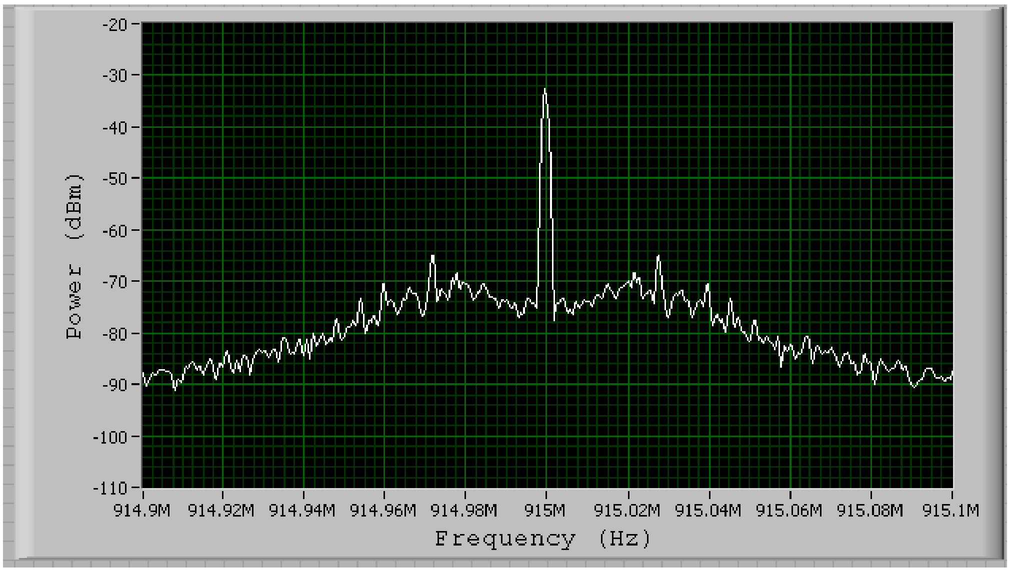

Fig. 4.5: Power Spectrum of TRF6900A output signal with corrected frequency

Documentation of a power amplifier in the chip states typical values for harmonics compared with base peak to be -30dBc [8]. Given that carrier peak value is about -35 dBm, the threshold for PXI should be set at about -65dBm (Fig. 4.7). However, to simplify comparison PXI should find exactly 3 peaks: base one and 2 worst spurs. After several trials -66dBm proved to be the most suitable value for threshold. After acquiring 3 highest points of the power spectrum, we should identify the worst spur and compare it to base peak (Fig. 4.7). First of all, we create array of the peak values and find the first highest and the second highest values. It is known that the highest value corresponds to peak at the set frequency, so the biggest value of the remaining two is the worst spur. Since array is used for comparison, all that is needed are indexes of the base peak and the worst spur. The difference between the values at these indexes is spurious signal level.

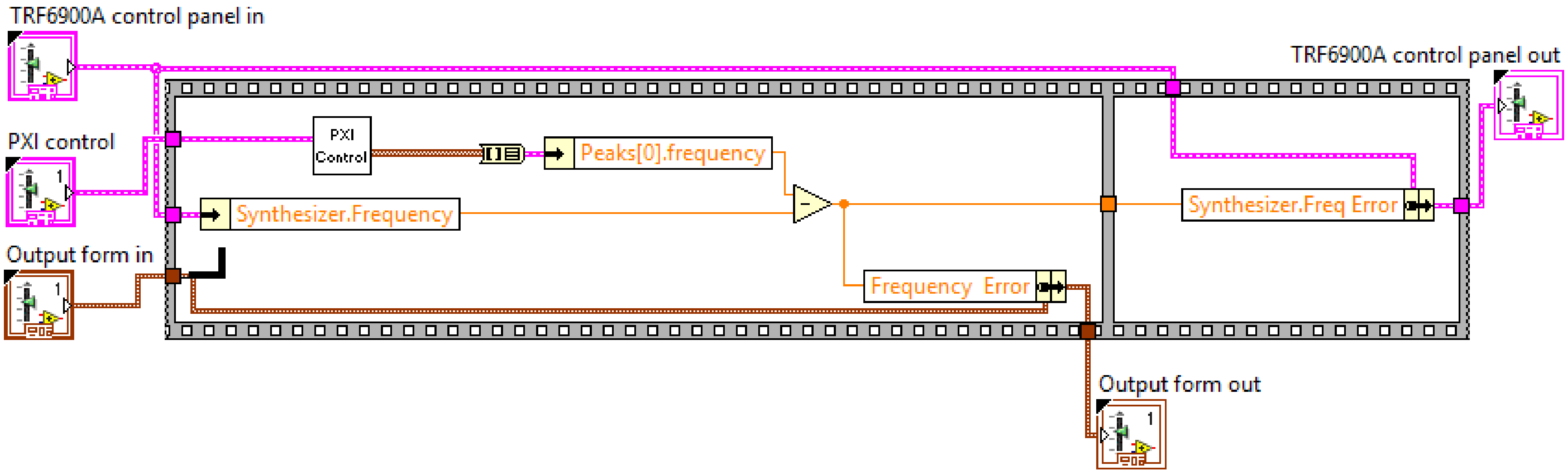

Fig. 4.6: Error detection and correction

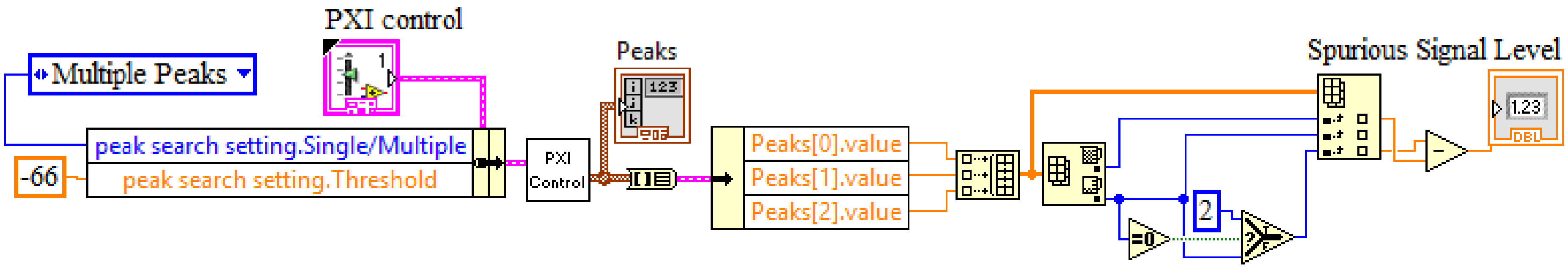

Fig. 4.7: Spurious signal level detection

4.4 PLL bandwidth

Another characteristic of generated signal which is easier to define visually is determined by the PLL bandwidth. On Fig. 4.5 of the power spectrum it can be defined as steady rise and fall at around -75 dBm and around 80 kHz of RF bandwidth. (full bandwidth). Since key for the bandwidth is rise and fall of the power spectrum graph derivative approach seems to be the most suitable.

In the LabVIEW environment derivative is calculated as follows. The differentiation $f(t)$ of a function $X(t)$ is defined as

$$f(t) = \frac{d}{dt}X(t)$$

Let Y represent the sample output sequence dX/dt. There are 4 option for derivative to choose: second order central, forth order central, forward and backward. In second order central derivative method used for the PLL bandwidth measurement Y is given by

$$\boldsymbol{Y_i = \frac{1}{2dt}(x_{i+1} - x_{i-1}) \qquad for\ i = 0, 1, 2, \dots, n-1} \tag{4.1}$$

where n is number of samples of a function X, x_{-1} and x_n are first and final conditions. Without both conditions defined, the derivative function results in false peaks for the first and last samples of $X(t)$, and consequent error in PLL bandwidth calculation.

On the Fig. 4.8 it can be seen how derivatives of the power spectrum correspond to the signal levels. Zigzag shaped derivative values in the middle of the figure below correspond to the base signal at 915MHz, while secondary peaks on the same graph could be spurious signals or edges of the PLL full bandwidth.

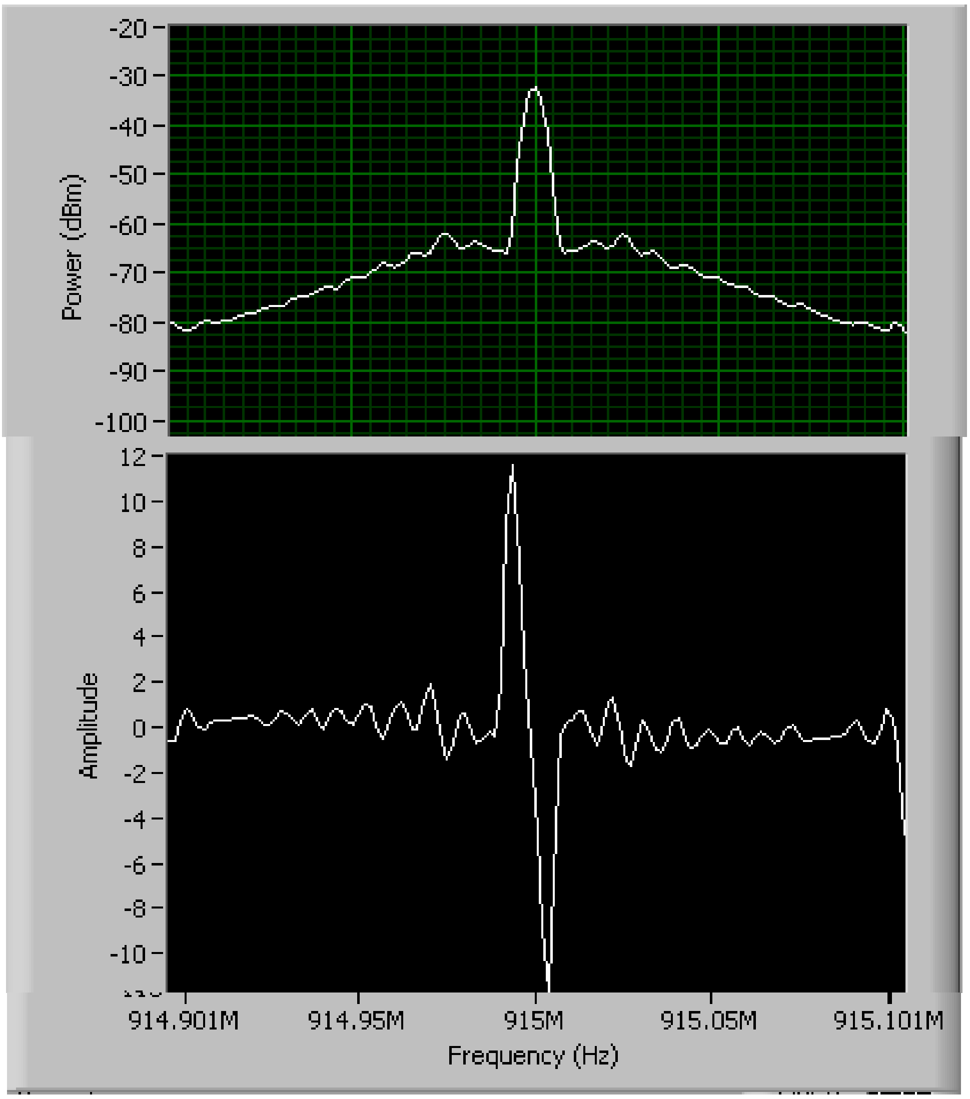

Fig. 4.8: Signal power spectrum and its derivative

However, using the derivative values introduces uncertainty to the bandwidth estimation therefore adjustment mechanism should be in place. Fig. 4.9 shows how the bandwidth is calculated in the proposed testing system. Similarly to spurious signal levels, the highest derivative of the power spectrum corresponds to the peak value at 915MHz, our test frequency. Therefore, it is discarded, and next peaks are searched for. As it was mentioned before, the worst spurious signals are next peaks, but they do not indicate end of the PLL bandwidth, but more of harmonics suppression. Thus, they are also discarded, and next peak is considered as the bandwidth's edge signal. In addition, to present the bandwidth in hertz, index of the edge detector peak should be multiplied by step of the power spectrum, resulting in half bandwidth of the PLL. At last, the result of the calculation is compared to the defined limits, and in case of mismatch the whole process of peak search is repeated.

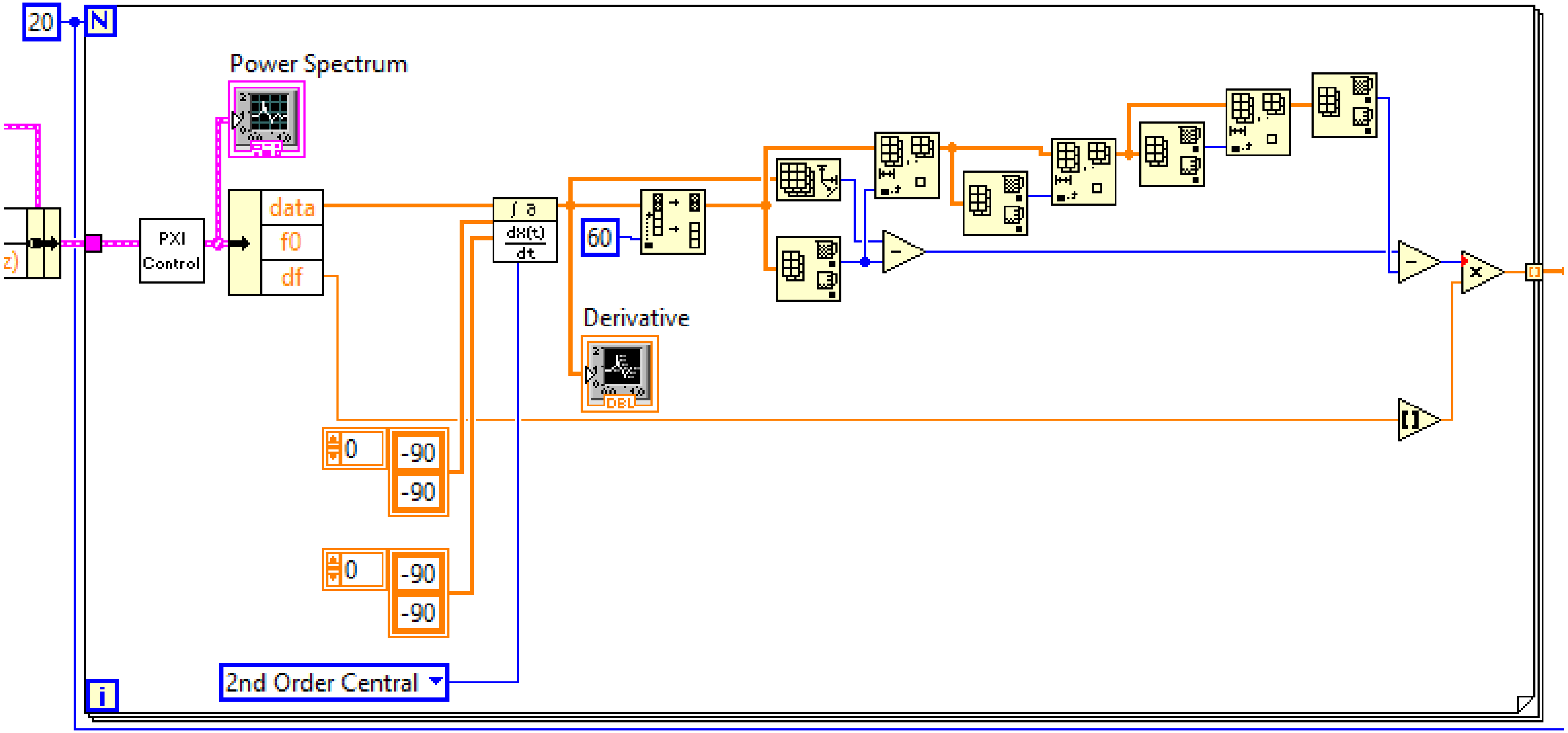

Fig. 4.9: PLL bandwidth block diagram

4.5 Power attenuation levels

Depending on applications of the transmitter chip, a level of the output signal should be controlled in order not to drive the receiver part into saturation and also the necessary signal level has to be provided for normal operation of the receiver. The TRF6900A board uses built-in power amplifier to accomplish this task. The device is IC with the certain characteristics, so the signal outputs corresponding to different setting can be compared with designed ones. To access the performance of the attenuation every state of the hardware should be tested and resulted values should be compared to the existing limits. Adding complexity is that there are 4 characteristics to test, not just one as was in error detection and correction. Solution is within LabVIEW logic, where all operations in a state should be fulfilled before next state of the state machines starts. Thus, signal value at the current settings can be measured while settings for next power amplifier level are sent to the TRF6900A control. Next states repeat that process until all 4 measurements are acquired (Fig. 4.10). Because of the difference in response time of both TRF6900A and PXI and processing time of the dedicated LabVIEW virtual instrument, we can be sure in sequential readings of the signal levels.

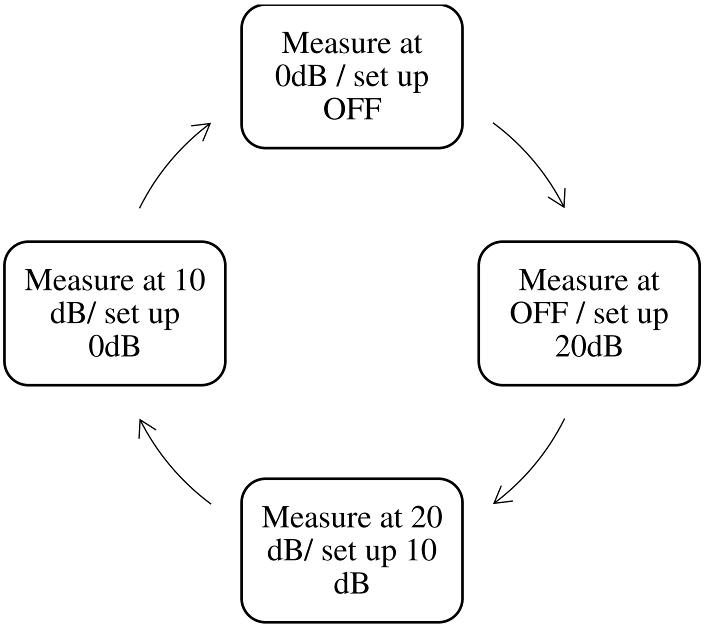

Fig. 4.10: Measurement states for power amlifier settings

The process realization in LabVIEW is shown in Fig. 4.11, where in 20 dB state signal level at attenuation OFF setting is measured and stored, while 20dB attenuation is set and ready to be sent to the TRF6900A board. As it can be seen after all operations in the state are finished new setting are sent to TRF6900A custom control, so that signal with new attenuation level can be generated.

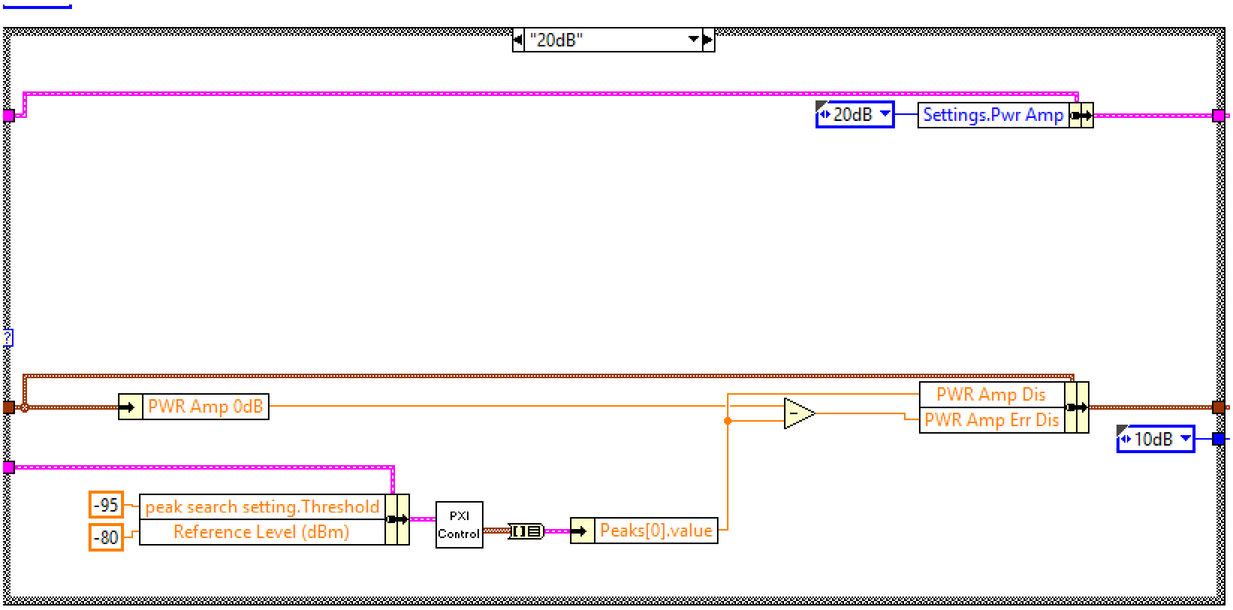

Fig. 4.11: Measure at OFF/ set 20dB state of power attenuation level measurements

After reading all signal levels for the attenuation settings of the power amplifier, we can compare if the acquired signal levels correspond to the ones in documentation of the device. The 0 dB attenuation signal level is used as a reference, and according to the specifications 10dB and 20dB should result in level drop of minimum 5dB and 14dB correspondingly. As it can be seen in Fig. 4.2 a difference between the refence and current signal level is stored in the output custom control for later transfer to a report and display on the user interface of the automated testing system.

4.6 TX Data Frequency deviation

Frequency Shift Keying (FSK) is a digital modulation technique in which frequency of the carrier signal changes according to the digital signal value. High frequency corresponds to binary high and low frequency to a binary low; the pair is called Mark and Space frequencies. The Fig. 4.12 illustrates the frequency modulation principle.

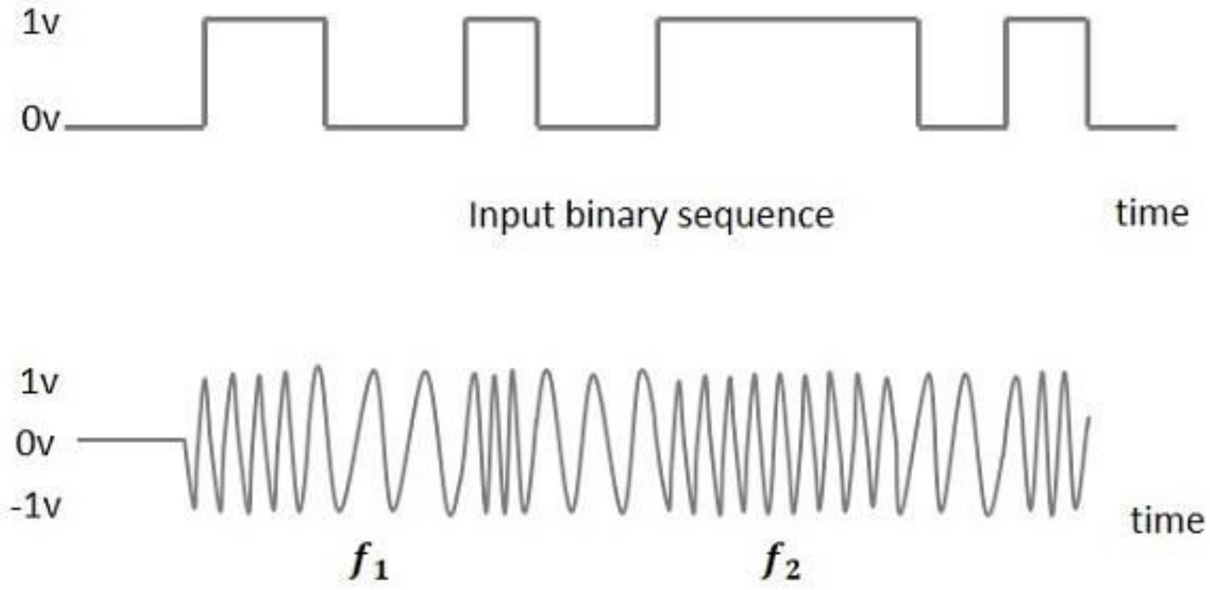

Fig. 4.12: FSK modulated output wave

The TRF6900A transmitter supports binary FSK and allows to set a deviation frequency between high and low outputs of the modulation. However, it should be noted that original control software of the TRF6900A transmitter does not allow setting a carrier frequency and deviation from it. The signal frequency which is stored in codeword A is a frequency corresponding to logic LOW of FSK modulation, and frequency for the HIGH logic is calculated as $f_{LOW} + f_{deviation}$. In other words, the deviation register contains $2 * FSK_{deviation}$ frequency, and average of LOW and HIGH frequencies is the carrier frequency. To simplify user interaction with the device under test the custom control of the TRF6900A was adjusted to allow setting the carrier frequency and binary FSK deviation value, $FSK_{deviation}$. Before converting the frequencies to binary format of the codewords, carrier one is decreased by set deviation, while second value is multiplied by two. Thus, the custom control is intuitive for a user, but also follows logic of the TRF6900A.

It should be noted that the base frequency is encoded in codeword A, but the deviation level is stored in bits 14-21 of codeword D. One difference between base frequency and deviation conversions is in the number of bits involved, i.e. base frequency uses 24, while deviation calculations involve only 22. But, in the codeword D only 8 bits are dedicated to deviation value, because only last 8 bits of the deviation result in slight changes of the original base frequency of codeword A (Fig. 4.13). Other than that, transformation of the frequency deviation value from decimal to binary is same as base frequency one, discussed in detail in section 3.3.1.

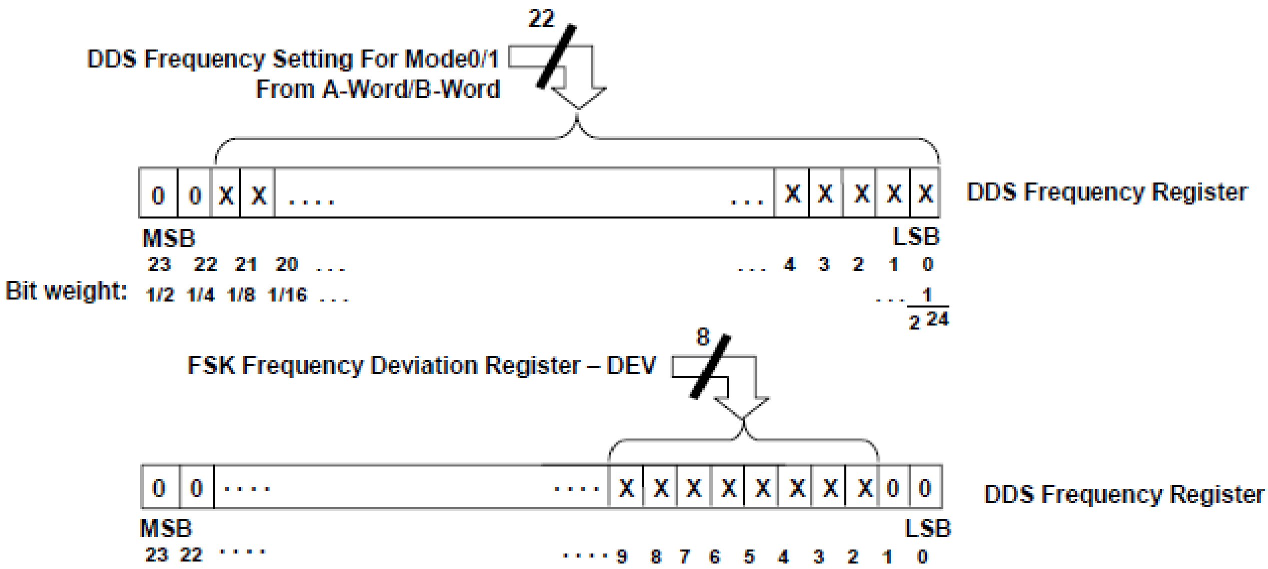

Fig. 4.13: Implementation of the DDS frequency and FSK deviation in the DDS frequency register

Fig. 4.14 shows conversion process, and also how the resulting bits are inserted into D codeword.

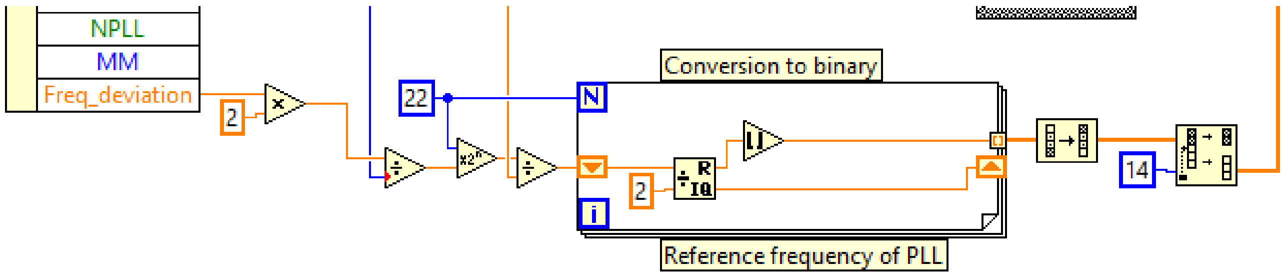

Fig. 4.14: Conversion of the frequency deviation to binary in codeword D

However, the modulation output itself is not controlled by the codewords, but rather with a separate input to the serial interface of the TRF6900A transmitter. On the Fig. 4.15 dedicated pins of the parallel port are indicated. There are three signals (clock, data input and strobe) discussed before, and TX data input, which represent the actual data the device should transmit.

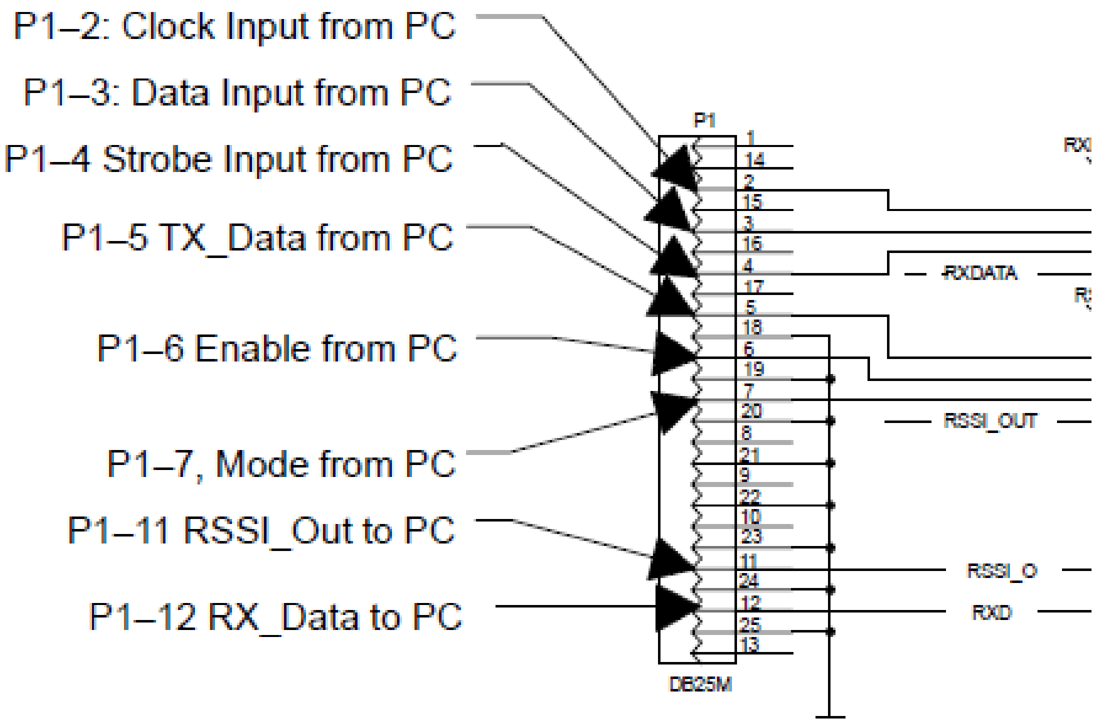

Fig. 4.15: Parallel port pins used for serial interface of TRF6900AA control

Depending of the logic LOW and HIGH values from TX data corresponding frequencies with previously defined deviation are generated by the TRF6900A. Therefore, the values of the TX input should be changed by the custom control to check the frequencies for logic LOW and HIGH. Then, difference between these frequencies should be equal to twice of the deviation value. As it can be seen on Fig. 4.16 the TX data should be sent to the TRF6900A, and then the PXI unit analyzes power spectrum of the output signal. Lastly, the set carrier frequency signal and generated modulated signal values should be compared to each other to obtain the deviation value.

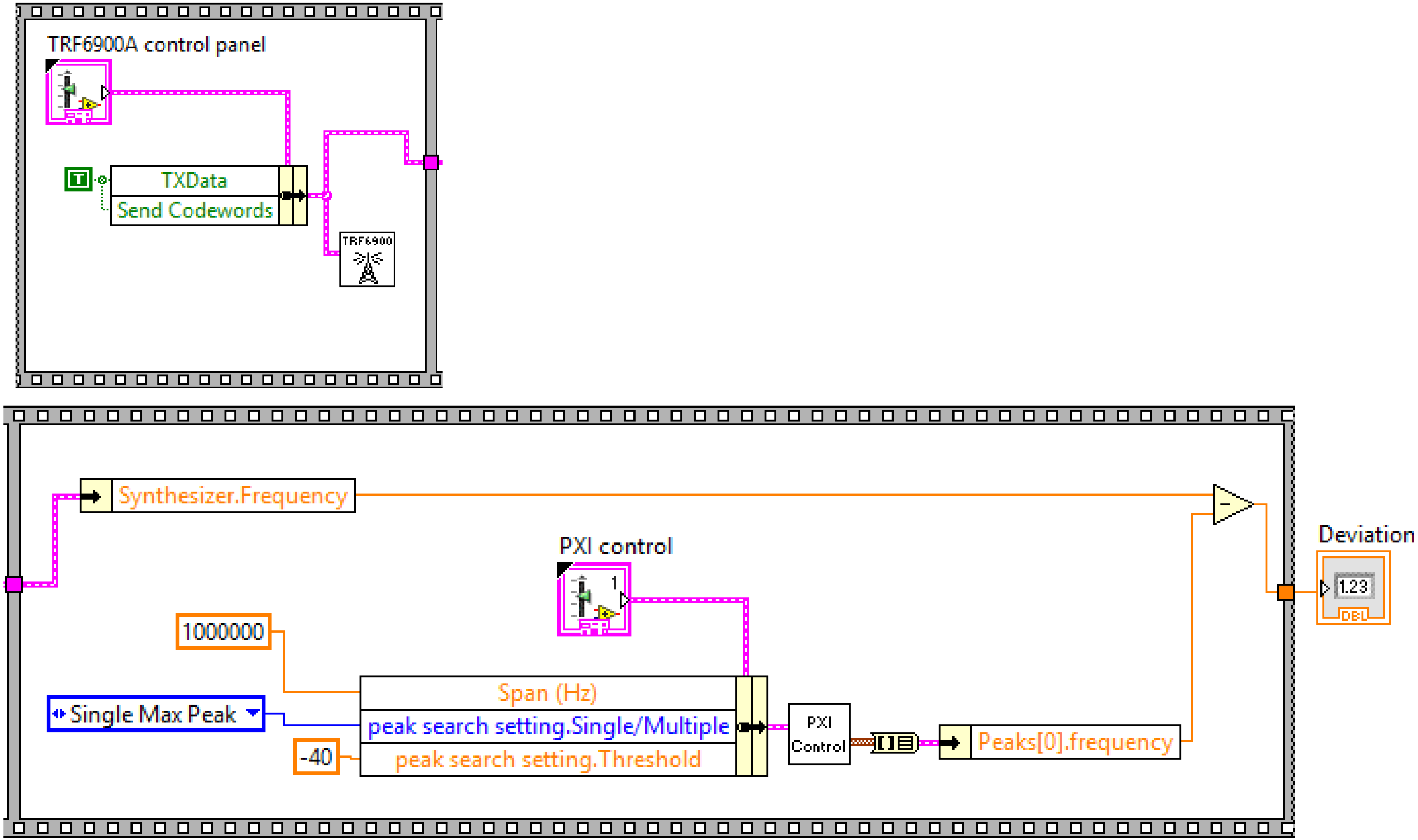

Fig. 4.16: FSK frequency deviation block diagram

4.7 Report generation

Finally, after all measurements are taken and saved they should be reported in an appropriate format. For the automated system Excel was chosen for formatting since Microsoft Suite is highly popular and wide spread. However, till recently the LabVIEW did not have a driver to interact with MS Excel directly and for the purpose of report generation a custom access driver has created. The LabVIEW supports ActiveX framework, which allows access to other applications directly from the workbench. There are two types of nodes, invoke and property, which can be used to create the custom control. First of all, there is a template generated in Excel format, so that necessary measurement data can be filled in corresponding cell of the spreadsheet. The overall idea of modifying the template into actual report is represented on Fig. 4.17. The process is represented in layers, and to transfer from one to other the invoke node is used, while to access properties in each layer the property node is used. Other than that, the report generation is fairly simple and straight forward.

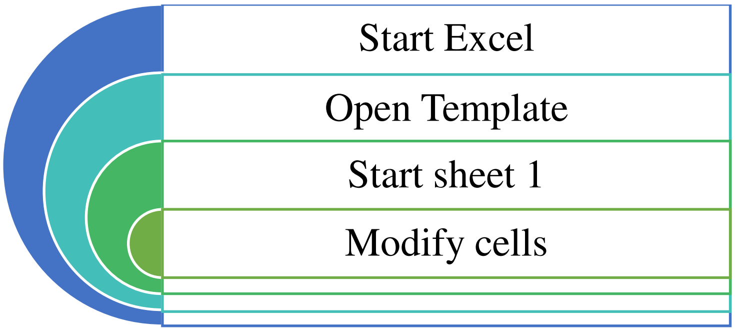

Fig. 4.17: Report generation via ActiveX in LabVIEW

Since we have a set template for every report generated, every measurement value should be stored in its' designated cell in Excel spreadsheet. As it can be seen in the Fig. 4.18 there are invoke node to access active worksheet and property node to modify value of a cell. Both cell index and value are defined by user, or other custom control.

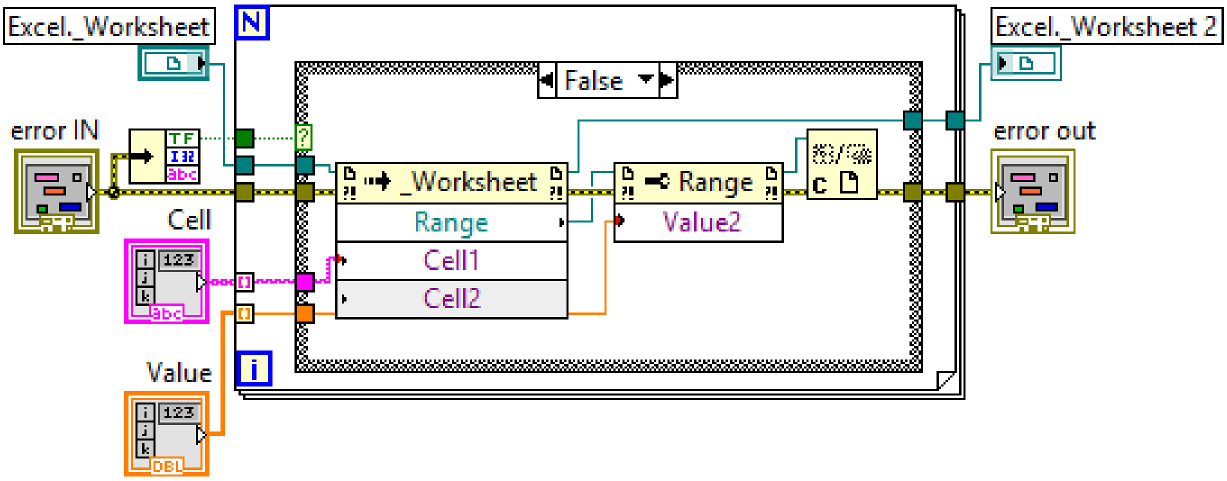

Fig. 4.18: Cell modification for test report

In addition to showing test results and measured values the report should also provide some means for traceability, which are, in our case, date and time of the test fulfillment and name of the operator who supervised it. However, since both of the required inputs differ from numerical values a separate control was created especially for them (Fig. 4.19). It is quite similar to the cell modification and follows the same logic.

After all of the editing and modification Excel report looks like one on the Fig. 4.20, with all measurements of the device under test. As it can be seen all the parameters discussed in details earlier are listed with corresponding limits and readings. It should be noted that the limits are derived from Texas Instruments documentation on the TRF6900A transmitter. In addition to supporting the template for the report, Excel is used to compare values in reading column to the ones in minimum and maximum. In case measured value is within the limits, pass cell is colored green, otherwise red.

After measuring parameters of interest and saving test results our automated system routine stops, waiting for the next run.

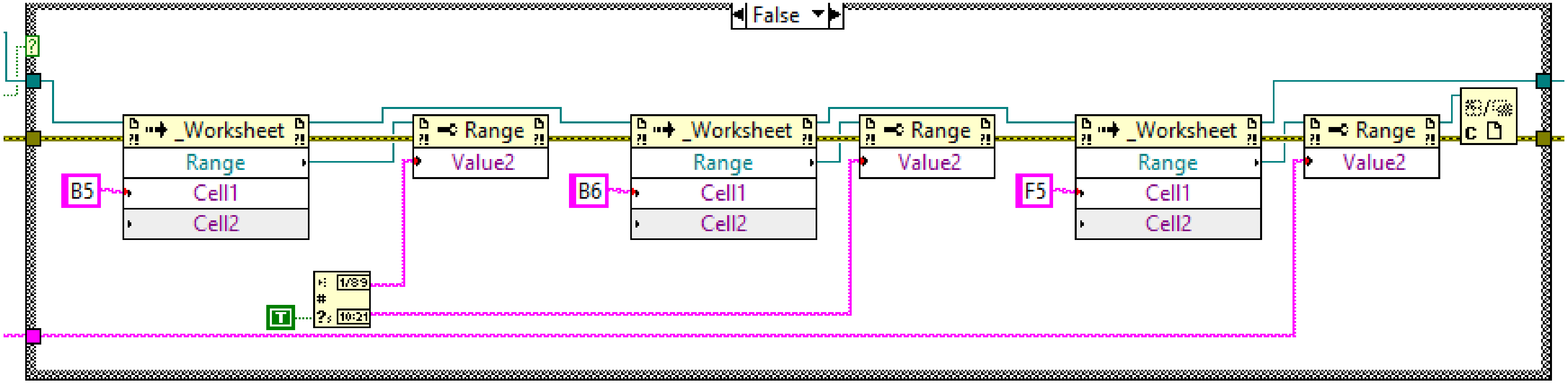

Fig. 4.19: Name, date and time inputs for the test report.

M Ű E G Y E T E M 1 7 8 2

Test Date: 27/03/2019 Operator: Beisenbay

Time: 0,74186 sec

Equipment name: NI TRF6900A Tranciever

Measurements						
Name	Set	Reading	Minimum	Maximum	Difference	Pass
Frequency error (Hz)	9,15E+08	35756,27	0,00	36000,00		
PLL Bandwidth (Hz)	n/a	36633,00	32000,00	45000,00		
FSK Frequency deviation (Hz)		30094,98	28438,00	31562,00		
Spurious Signal level (dBc)	n/a	-32,78	-13,00	-40,00		
Signal attenuation for 0dB (dBm)*	n/a	-32,89	-35,00	-10,00		
for 10dB (dBm)	10	-41,72	5,00	10,00	8,830167	
for 20dB (dBm)	20	-49,09	14,00	20,00	16,1988	
for OFF state (dBm)		-91,74	56,00	60,00	58,85773	
Overall				PASS only if all green		

* reference

Fig. 4.20: Report of the automated testing system

5 Conclusion

Overall, the proposed automated testing system for wireless embedded transmitter checks all main components for their performance and generates traceable report. However, it would not be possible without throughout understanding of the device under test, the TRF6900A. It was discussed in details how transmitter test software was designed and how commands from the control computer are interpreted by the embedded chip. Even though, the TRF6900A board has a serial interface to process commands, parallel (printer) port is used to transmit them to the device allowing parallel controls signals to be sent. However, the codewords, which are used for setting up the transmitter during operation are combined serially and sent through 1 pin on the port. In addition, other control signals like clock, strobe, enable, TX data, and mode are combined to 6-bit binary number, which is transmitter through 6-pins of the parallel port. It was discovered that for the successful communication all signals should be stable during LOW-to-HIGH transition of the clock.

Main blocks to be tested in the transmitter are direct digital synthesizers, phase locked loop with voltage controlled oscillator and power attenuator. Two of them generate signal to be transmitter and the last one can modify signal strength. For accessing overall performance of the transmitter, each of these components should be tested and evaluated. To accomplish that testing routine for every parameter linked to the components is designed, namely frequency error and deviation, spurious signal level, PLL bandwidth and power attenuation. Next, all of the routines are combined into one autonomous testing system, which requires only name of user, test frequency and the value of deviation of FSK modulation inputs. Finally, all of the measurements are stored in a customized report template in Excel also autonomously.

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Annex

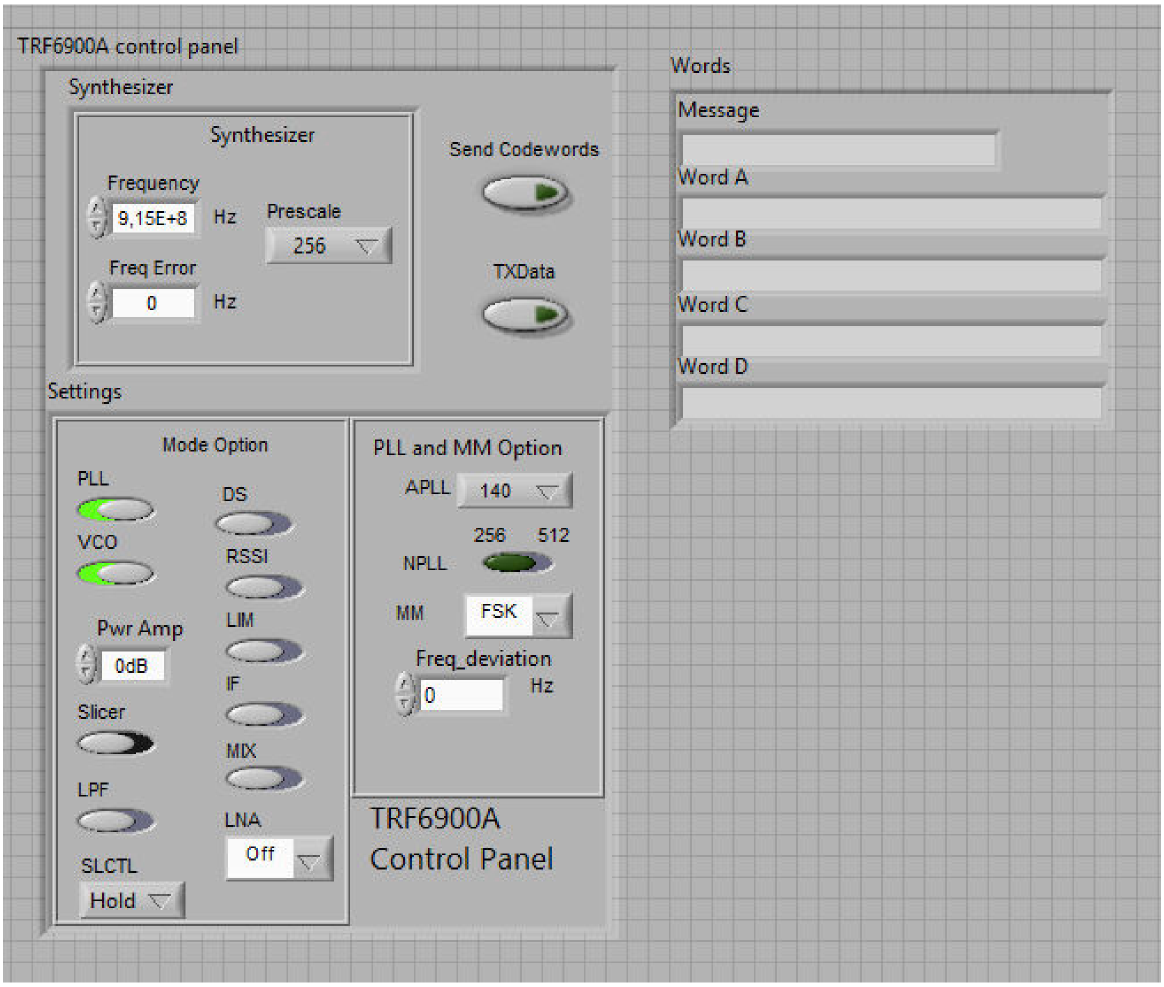


Fig. 0.1: User interface for TRF6900A custom control

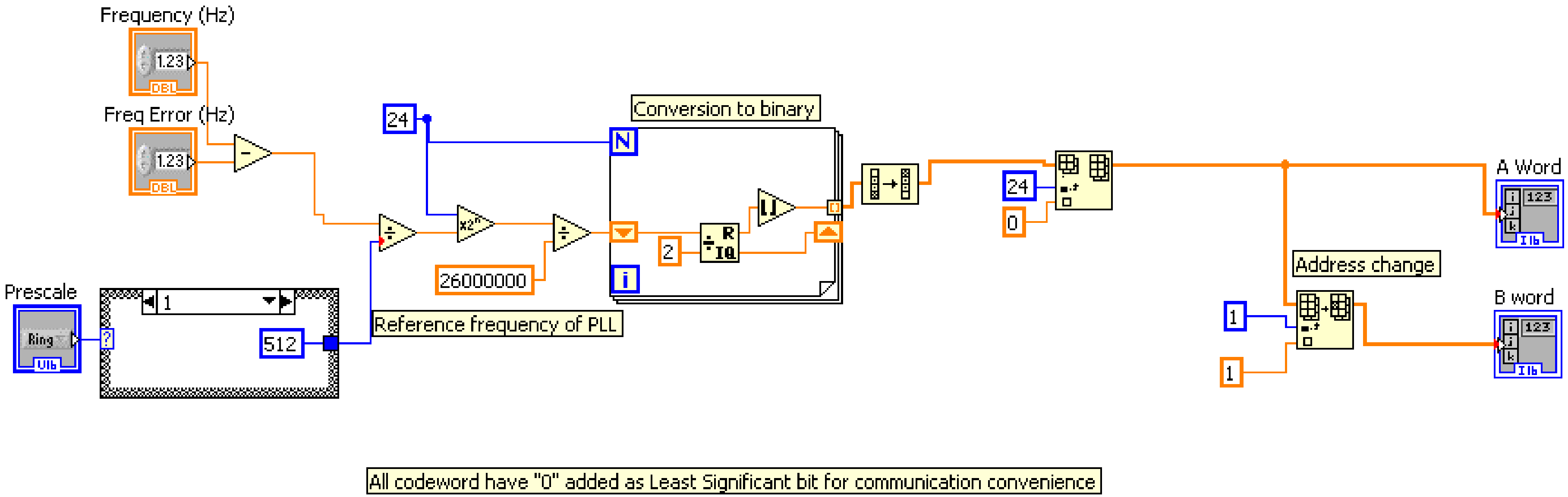


Fig. 0.2: Codeword A and B block diagram

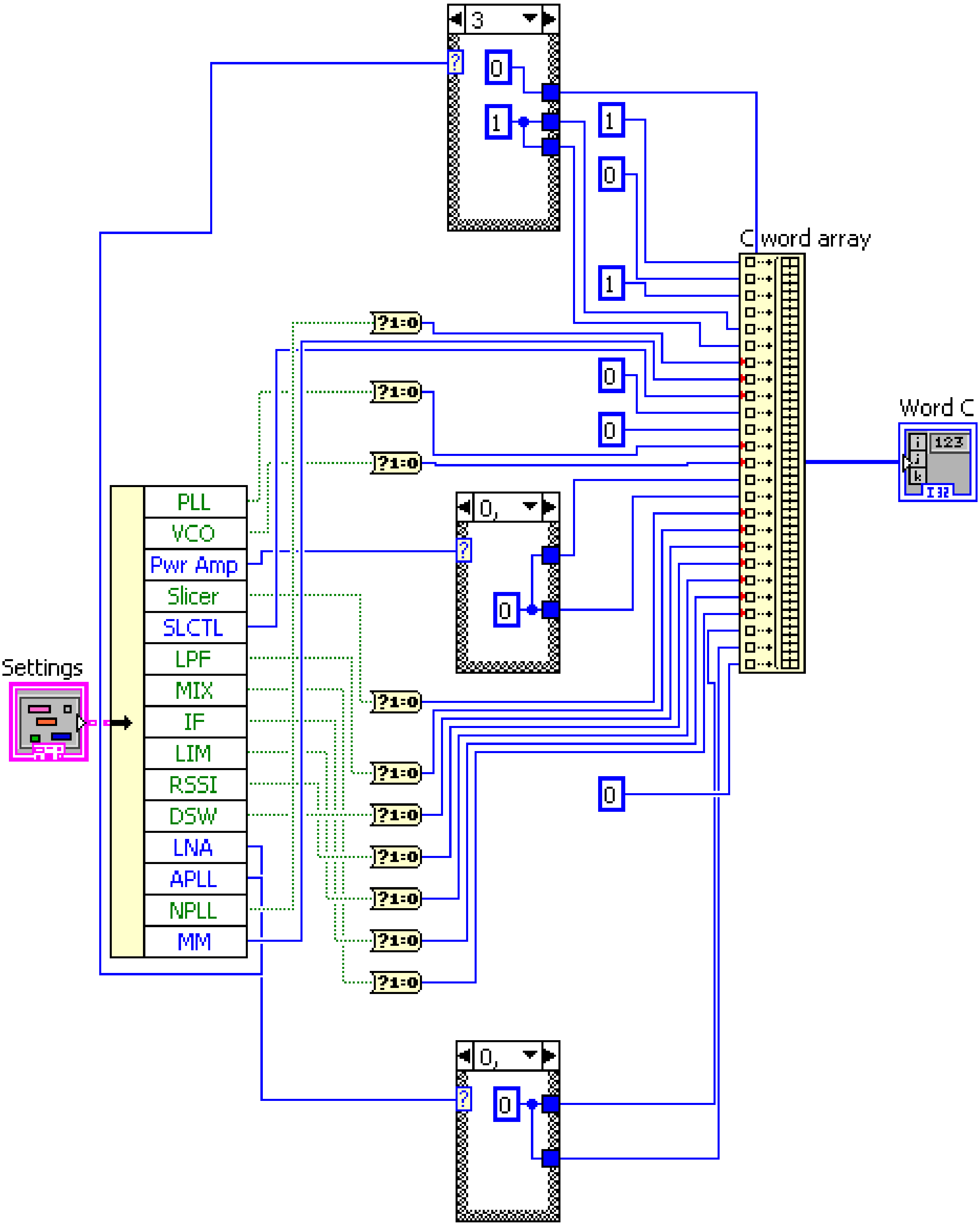


Fig. 0.3: Block diagram for codeword C

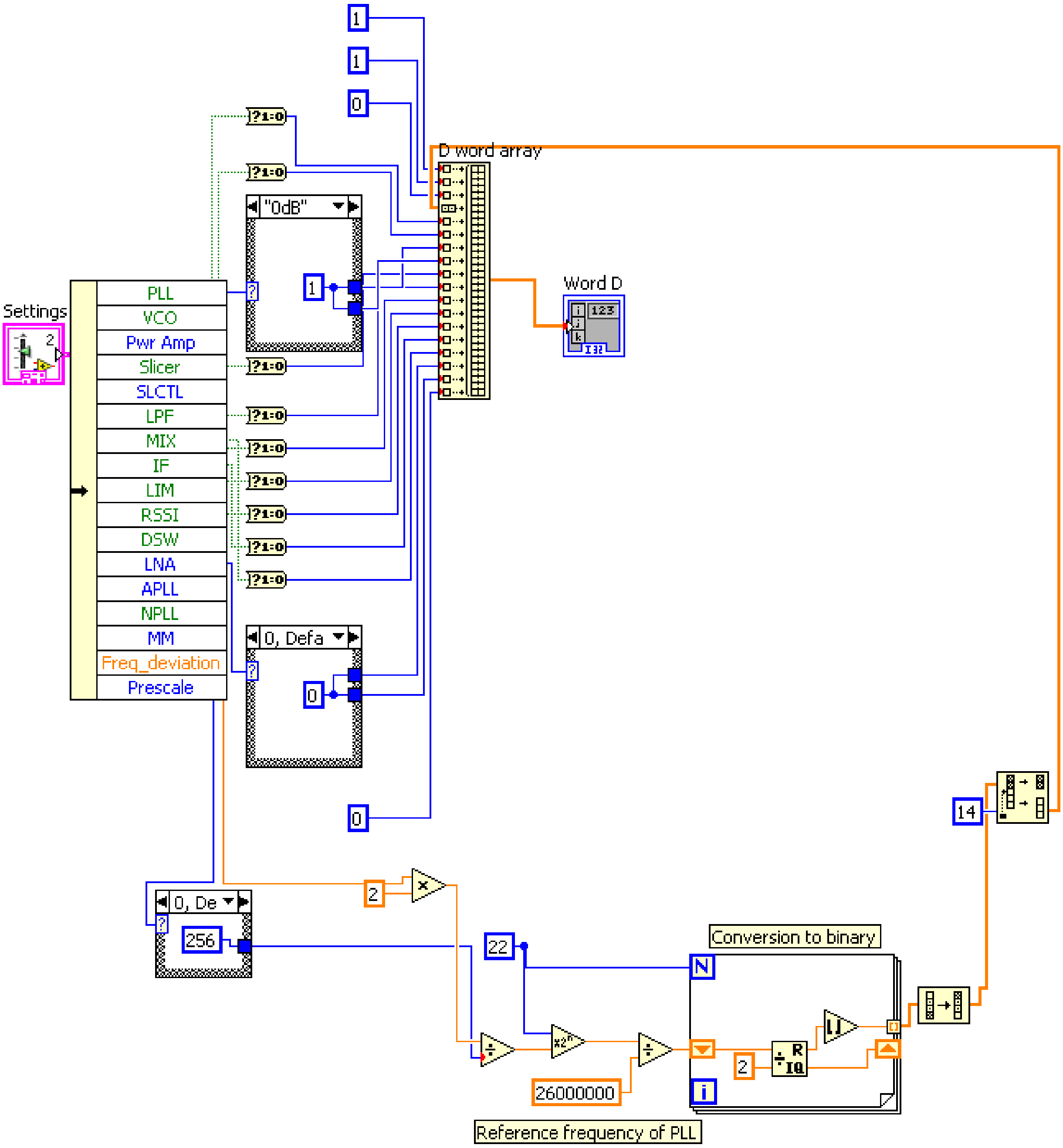


Fig. 0.4: Block diagram for codeword D

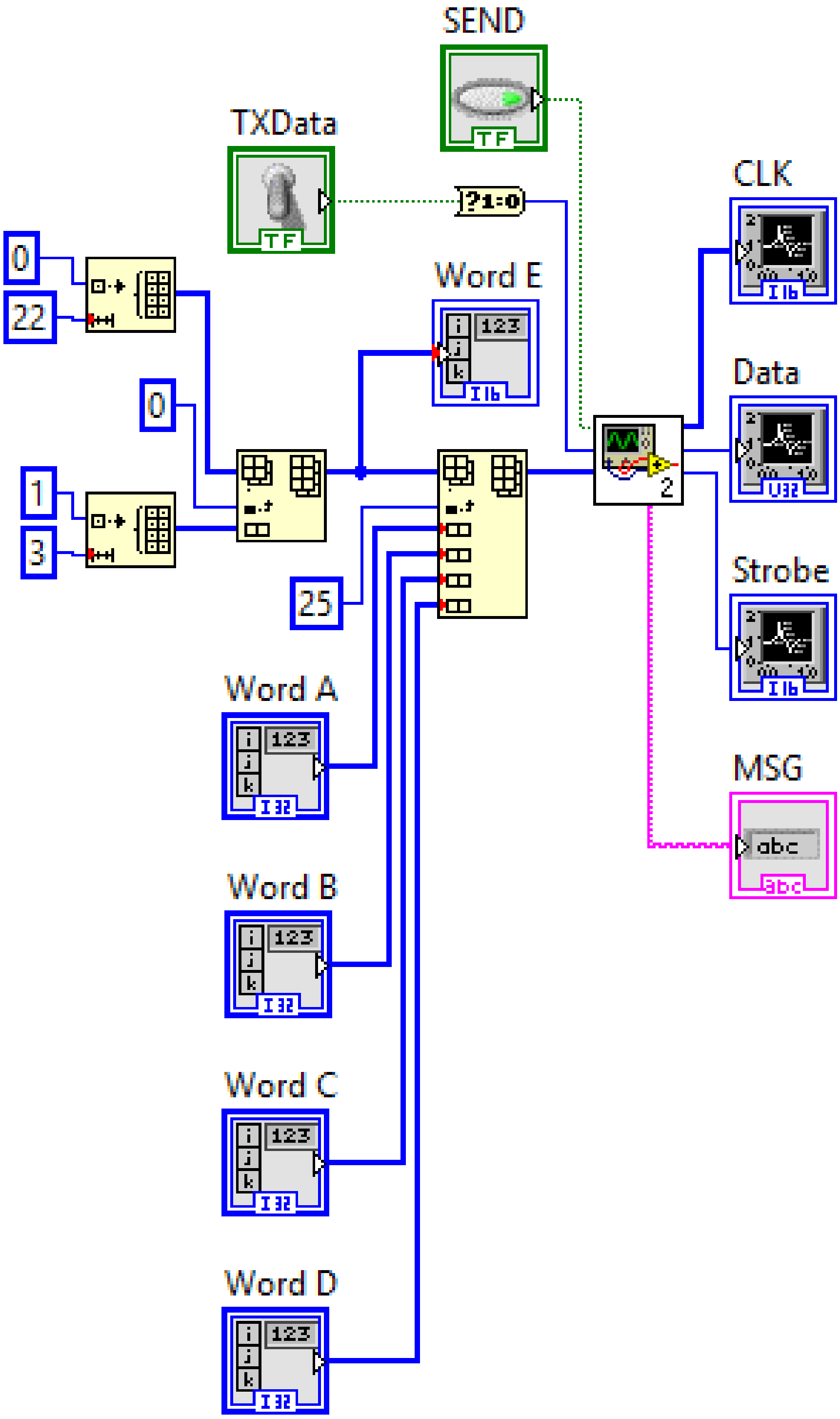
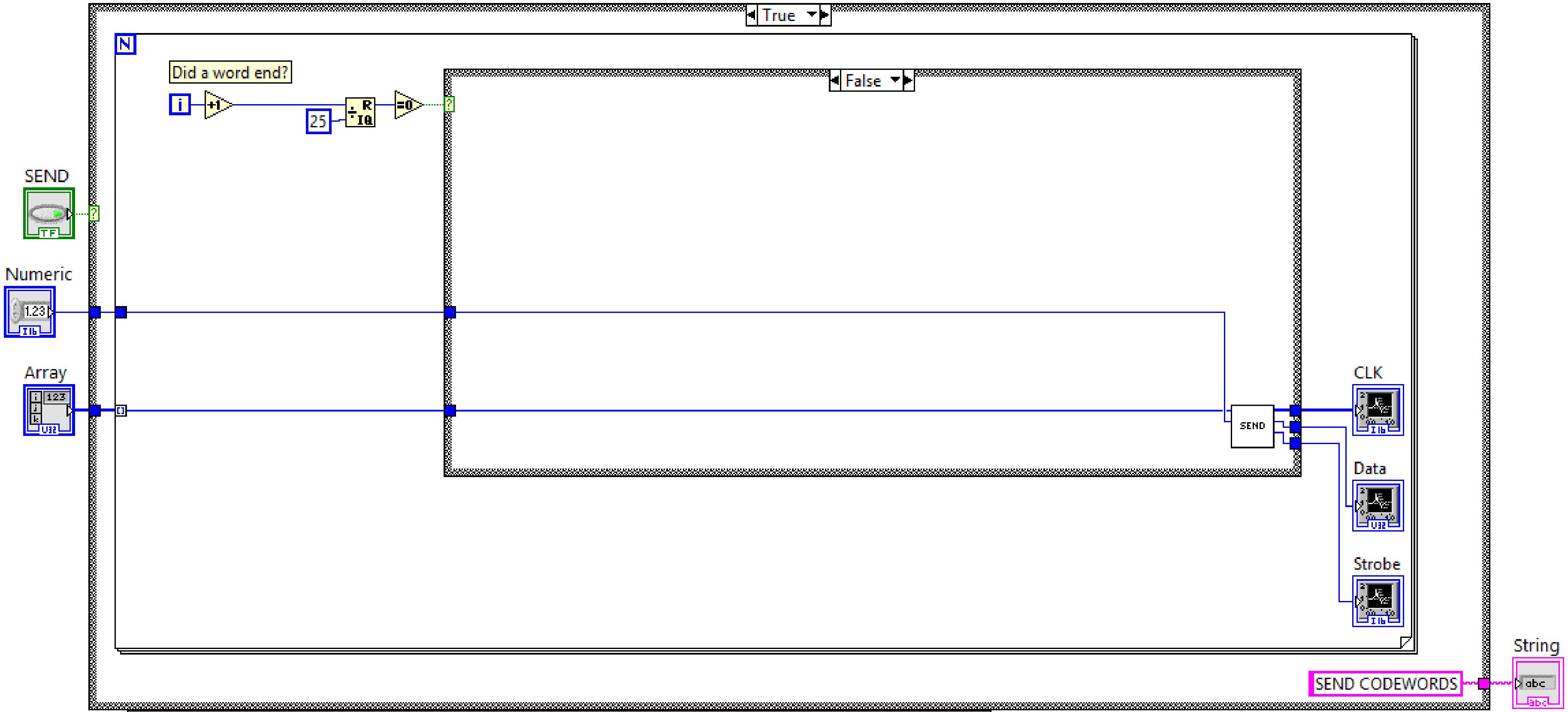


Fig. 0.5: Block diagram for TRF6900AA communication



Opearion:
1. Enable is always 1, and mode is always 0.
2. When answer for "Did a word end?" is true, the strobe signal is set to 1, and rest of the signals are zero, except enable. The added zeros in Least Significant bit of each word is transmitted now.
3. If a word is loaded, for each bit of it is transmitter 4 times at corresponding clock levels (Low, high, high, low).
4. Above opearions are execured only if "Send Codewords" button was pressed
5. Stacked sequence is used to ensure stability of the data signals at rising edge of the clock.
6. Word E is not defined by user, it is used to clear all register before new data is loaded

Fig. 0.6: Arranging data to be sent to TRF6900AA

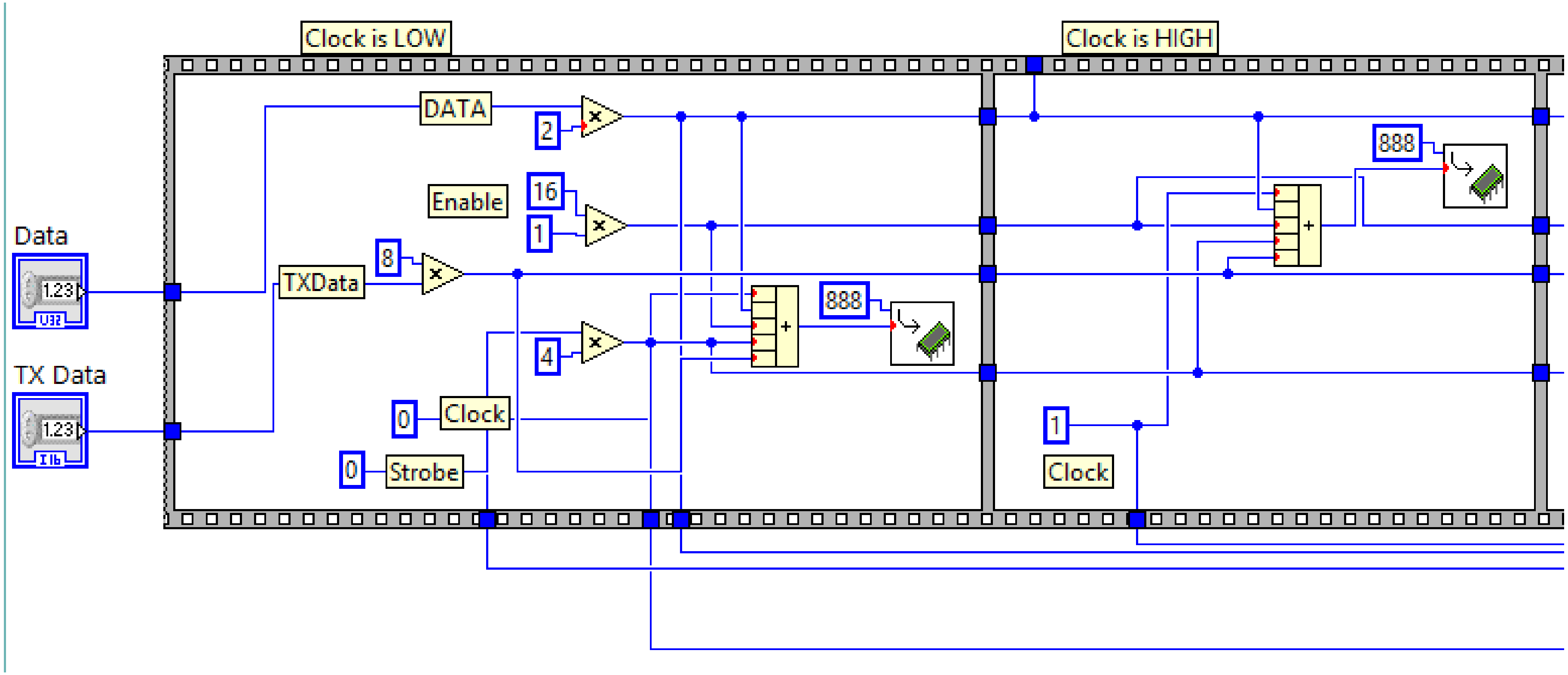


Fig. 0.7: Codeword sending state with clock Low-High-High-Low (part a)

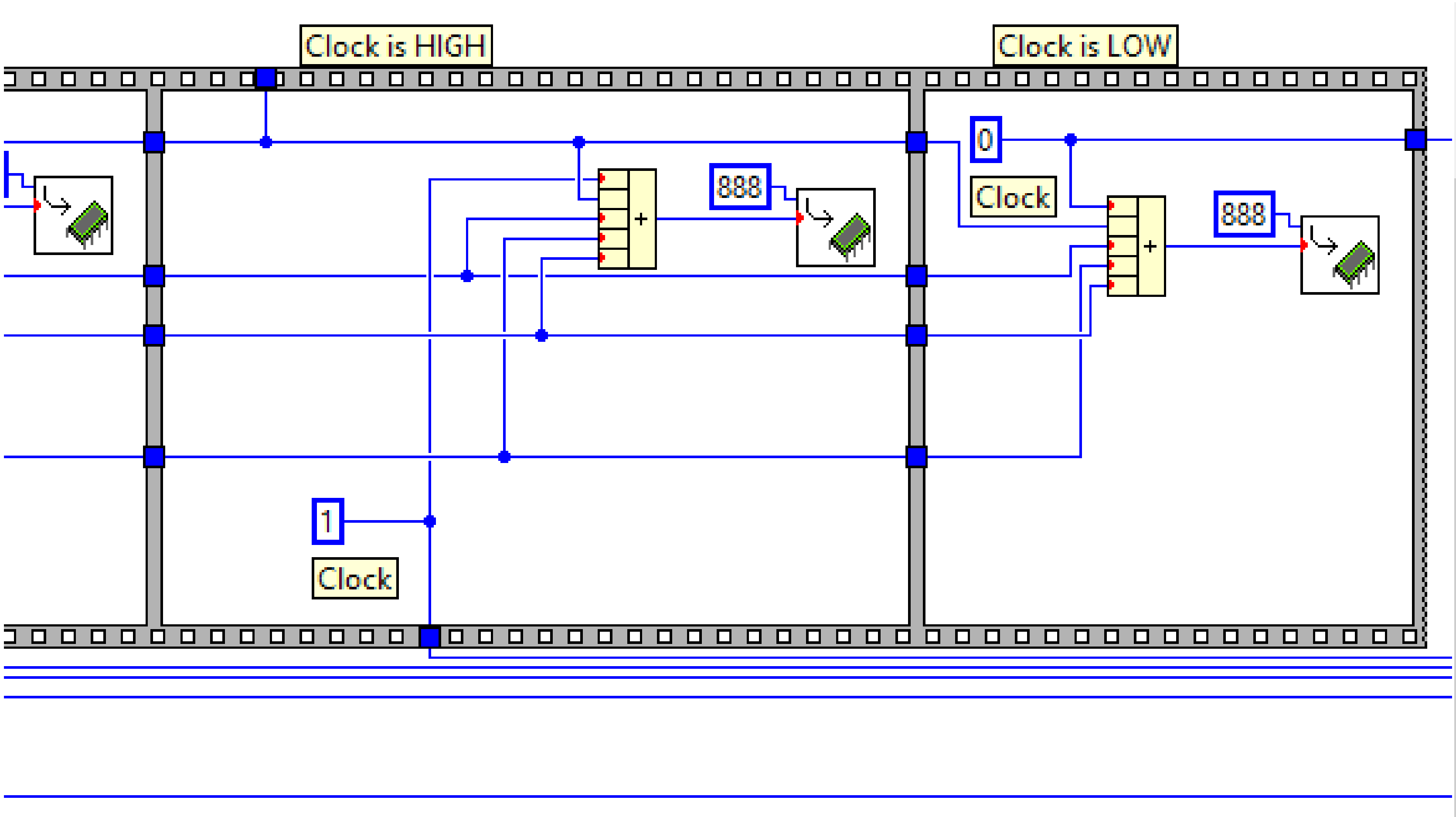


Fig. 0.8: Codeword sending state with clock Low-High-High-Low (part b)

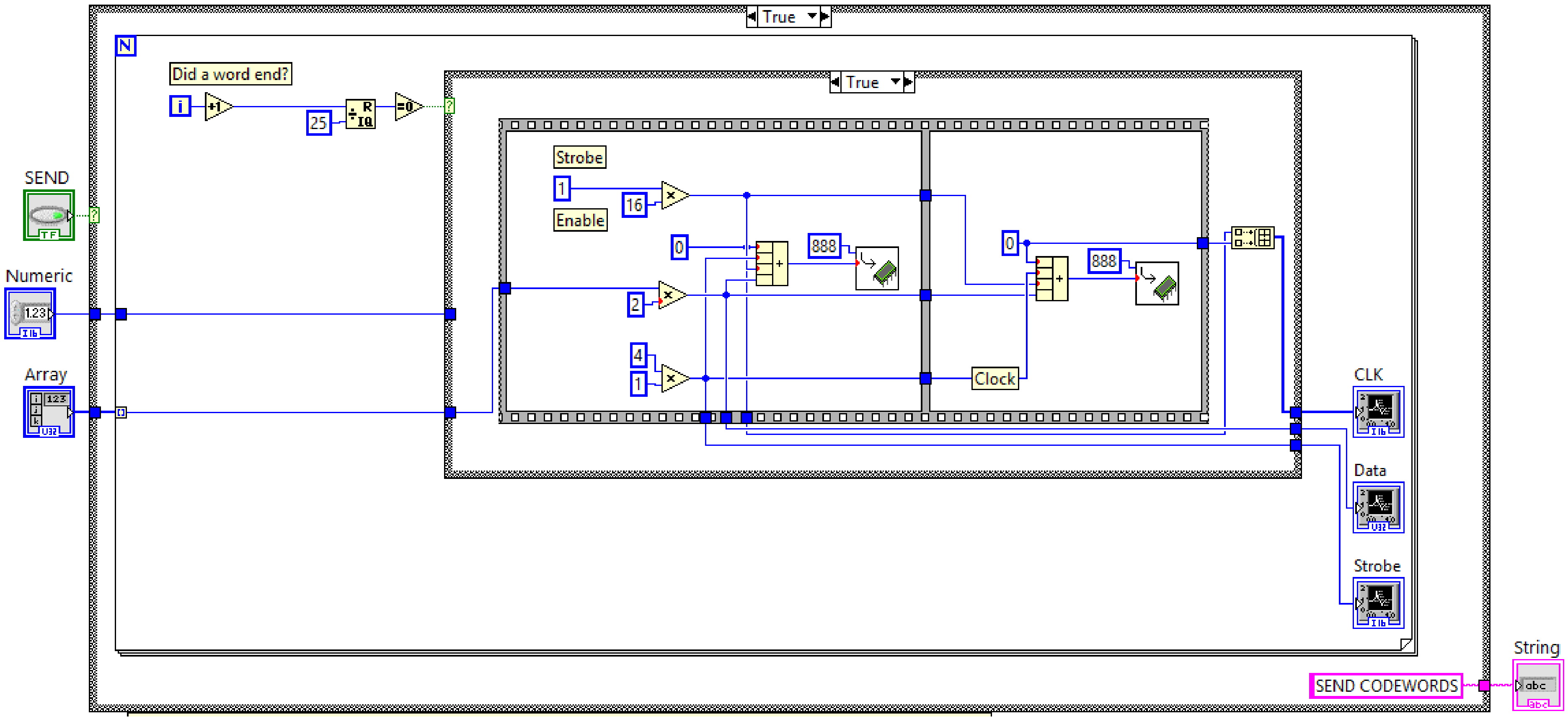


Fig. 0.9: Codeword finished state

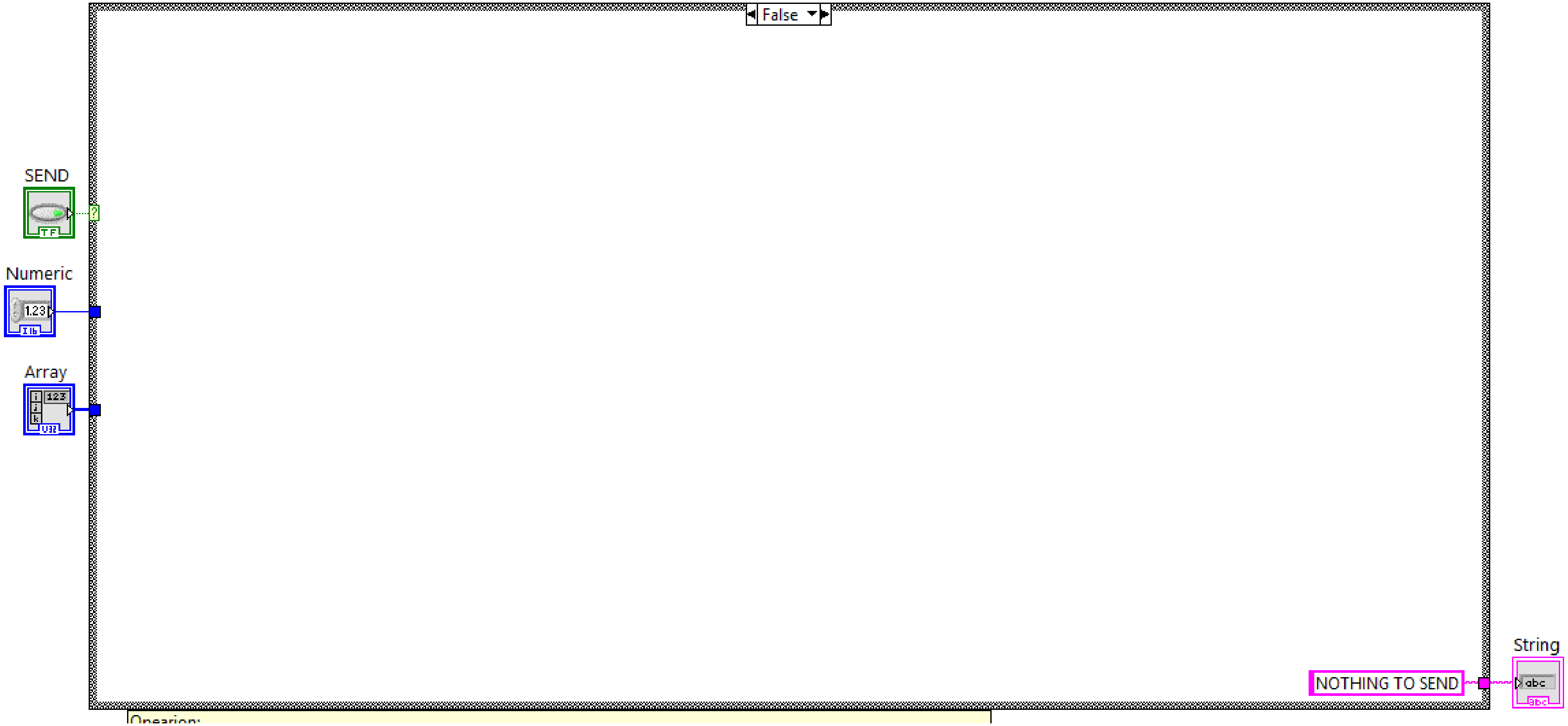


Fig. 0.10: Not sending codewords state

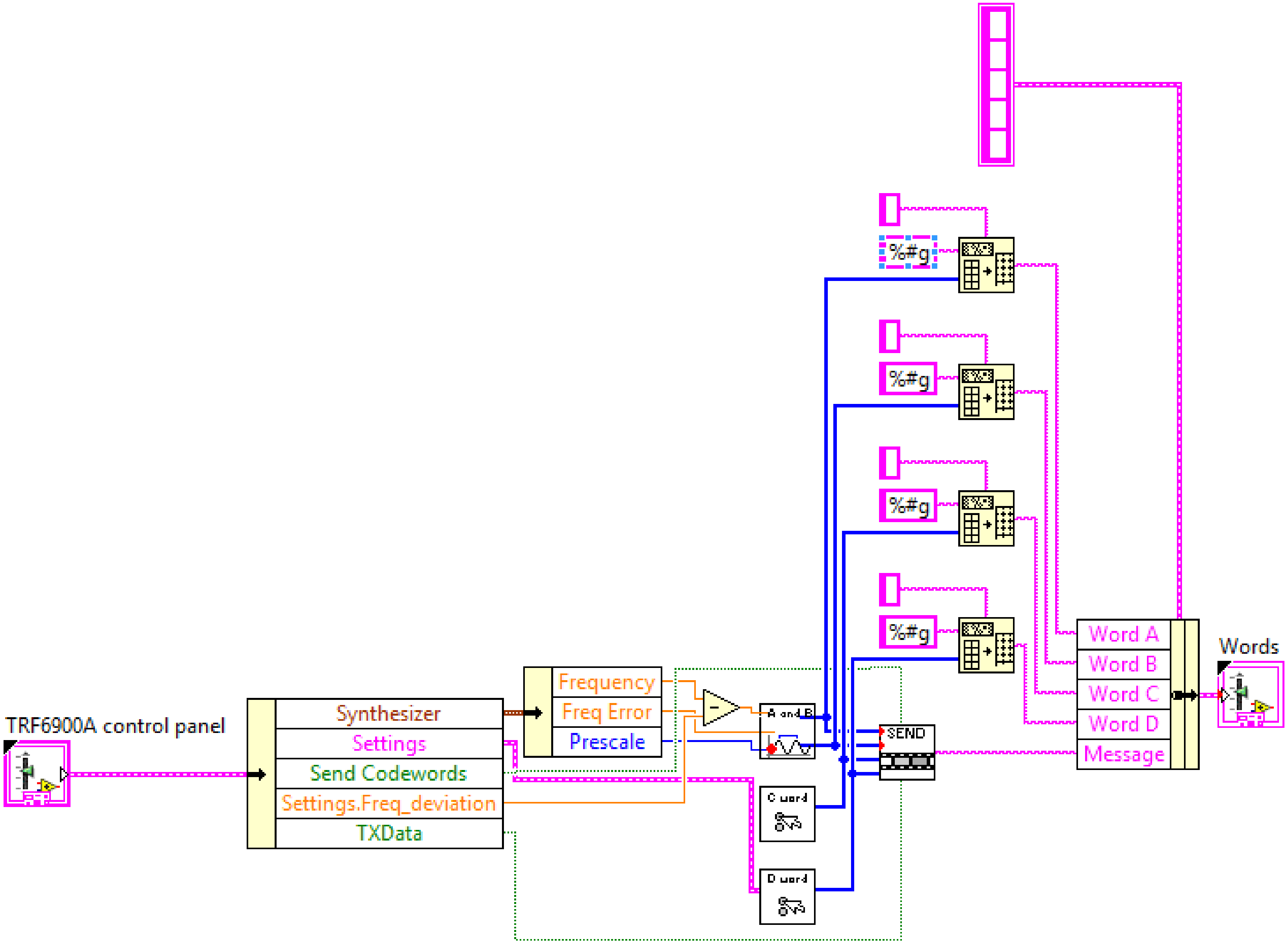

TRF6900A control panel
Synthesizer
Settings
Send Codewords
Settings.Freq_deviation
TXData
Frequency
Freq Error
Prescale
A and B
C word
D word
SEND
%#g
%#g
%#g
%#g
Word A
Word B
Word C
Word D
Message
Words

Fig. 0.11: TRF6900A control block diagram

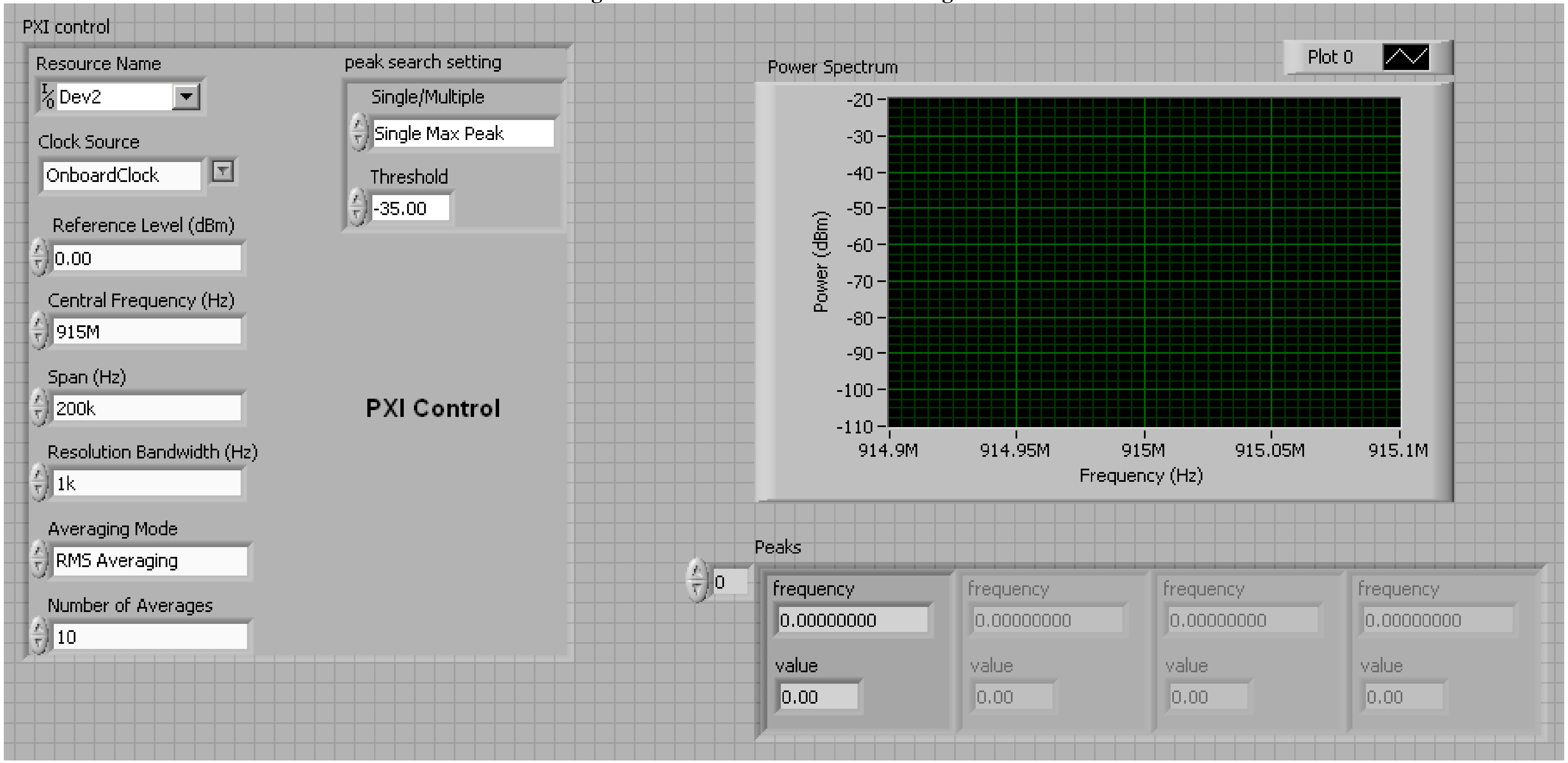


Fig. 0.12: PXI control interface

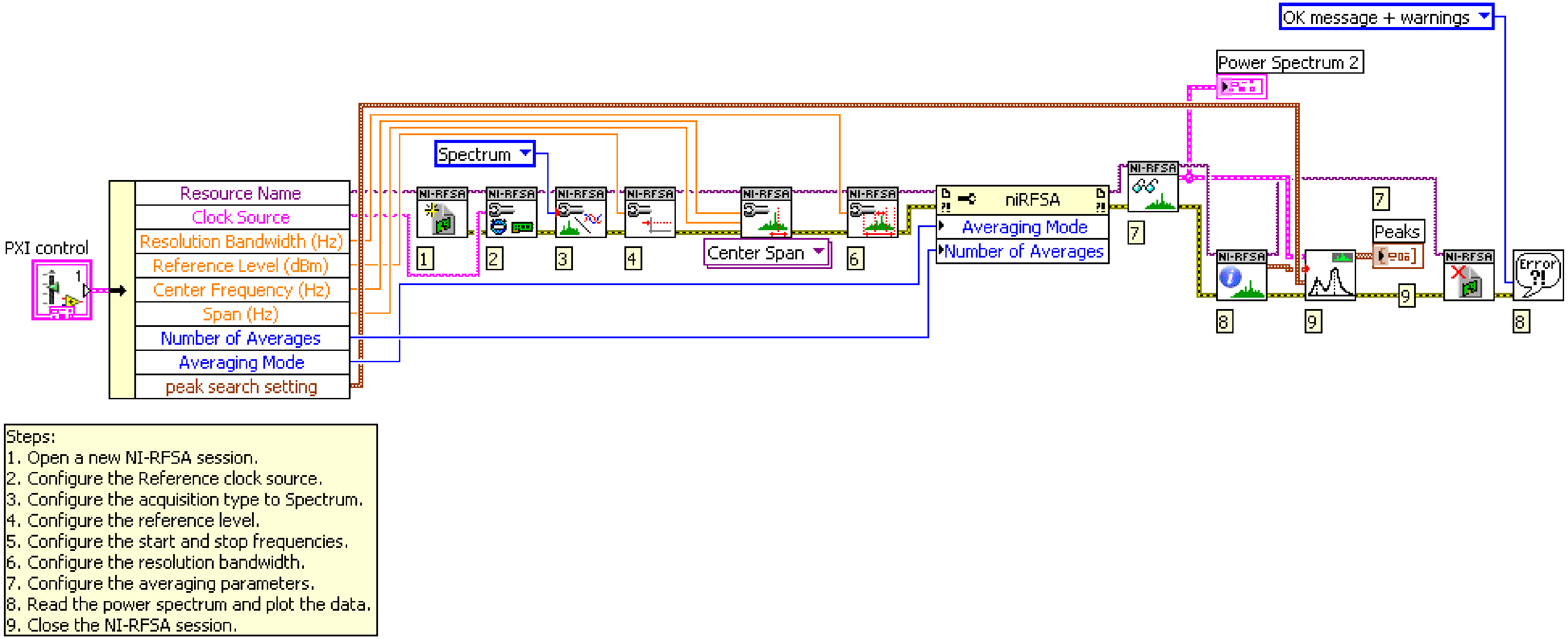


Fig. 0.13: PXI control block diagram

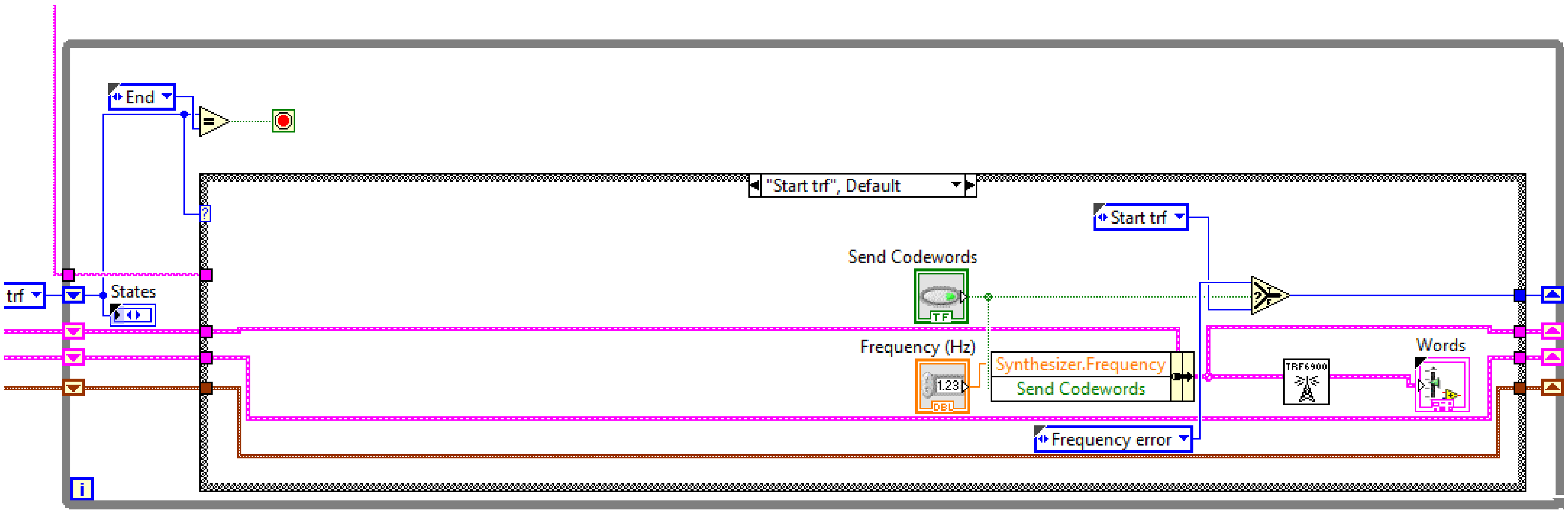


Fig. 0.14: Start state of the automated testing system

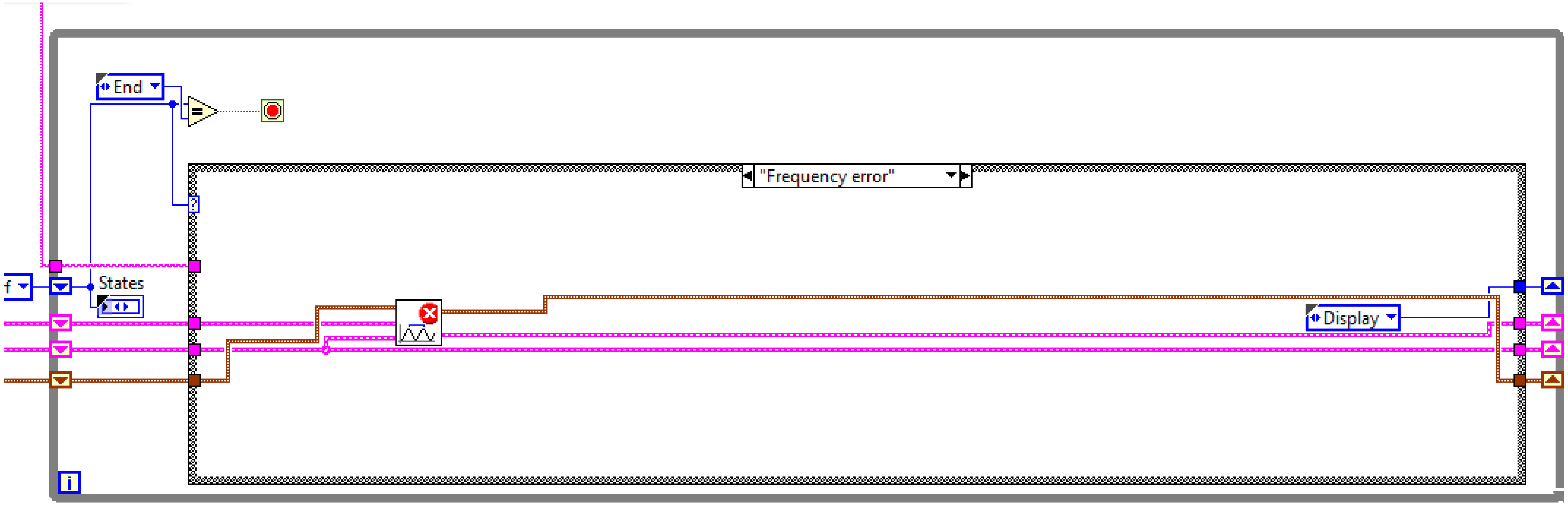


Fig. 0.15: Frequency error and correction state in the automated testing system

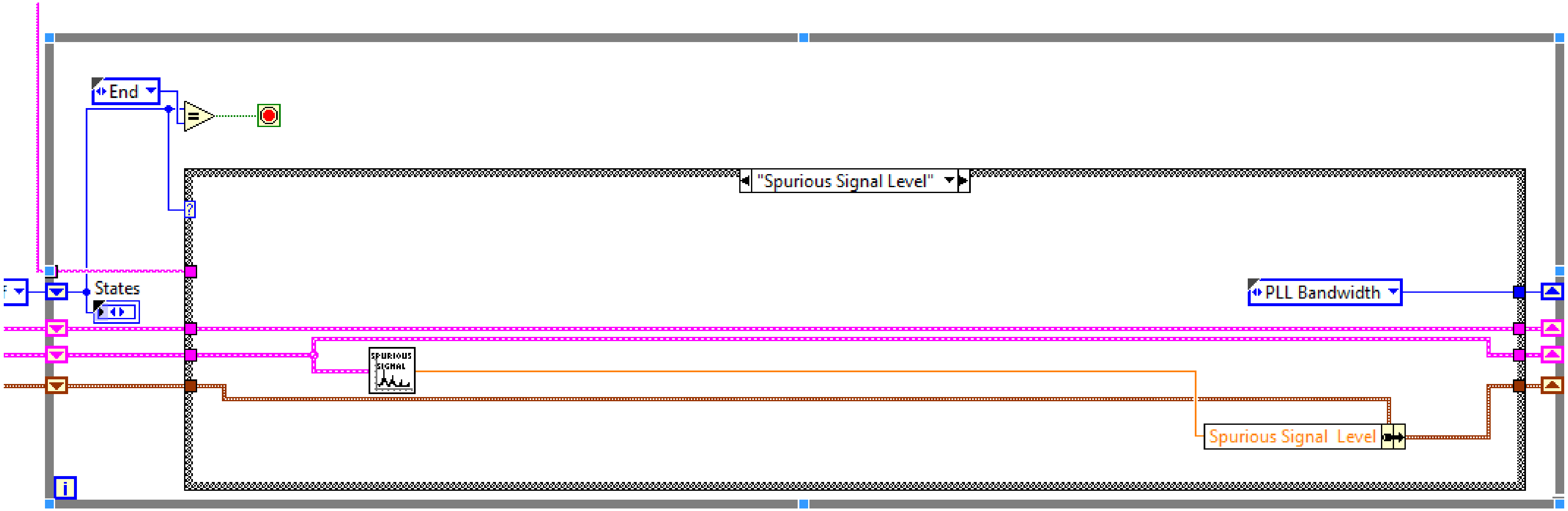


Fig. 0.16: Spurious signal level state in the automated testing system

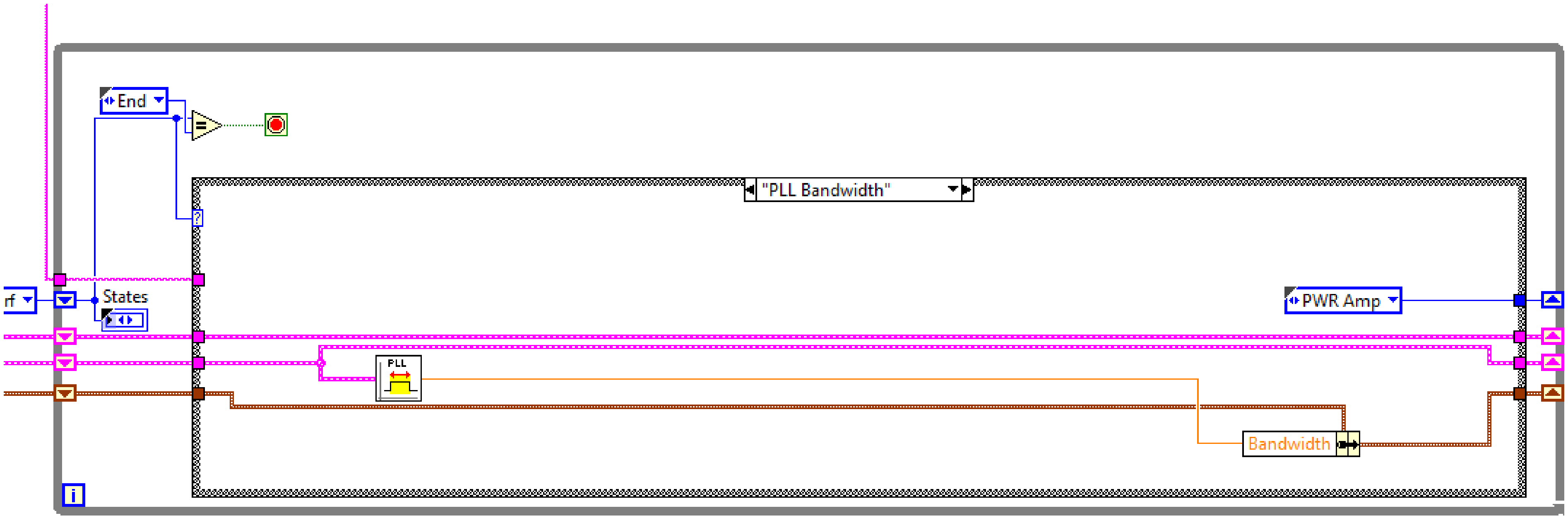


Fig. 0.17: PLL bandwidth state in the automated testing system

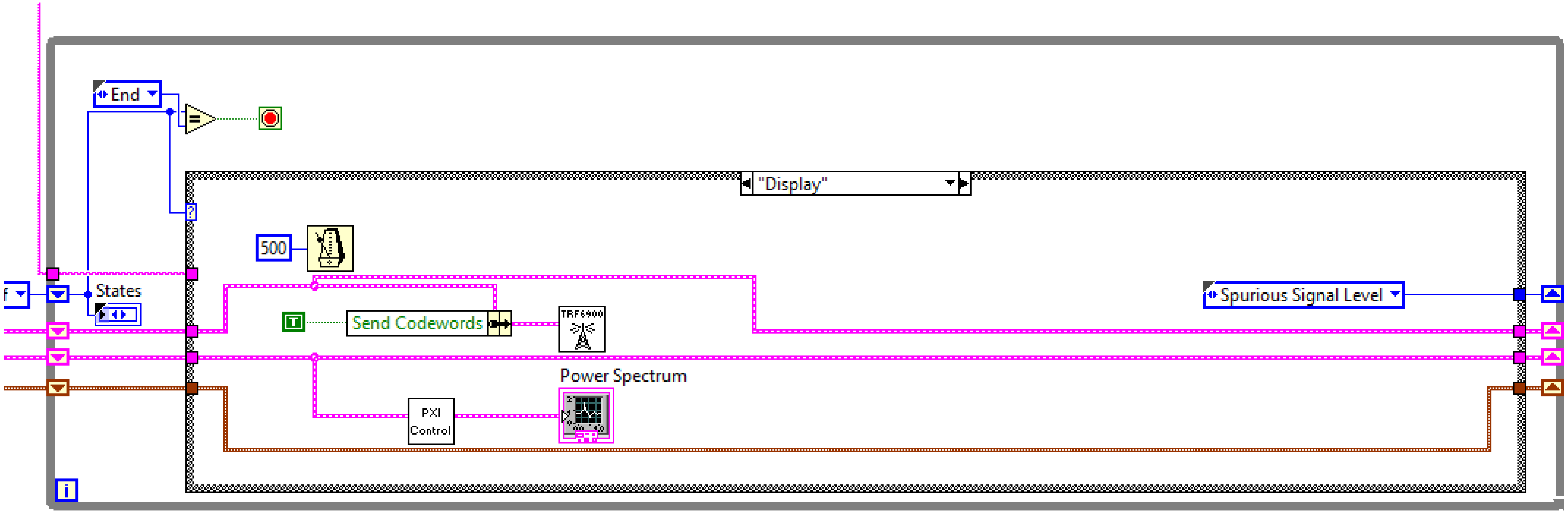


Fig. 0.18: Display state in the automated testing system

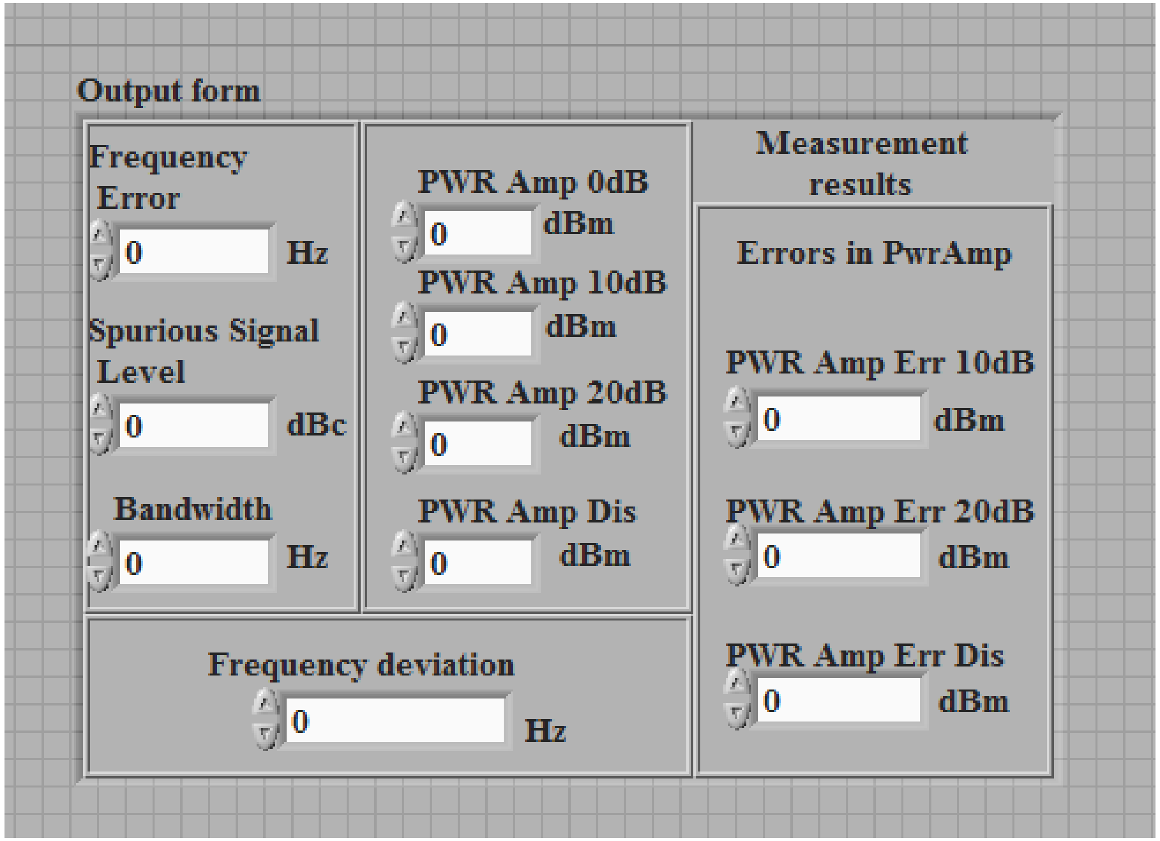


Fig. 0.19: Output of display state in the automated testing system

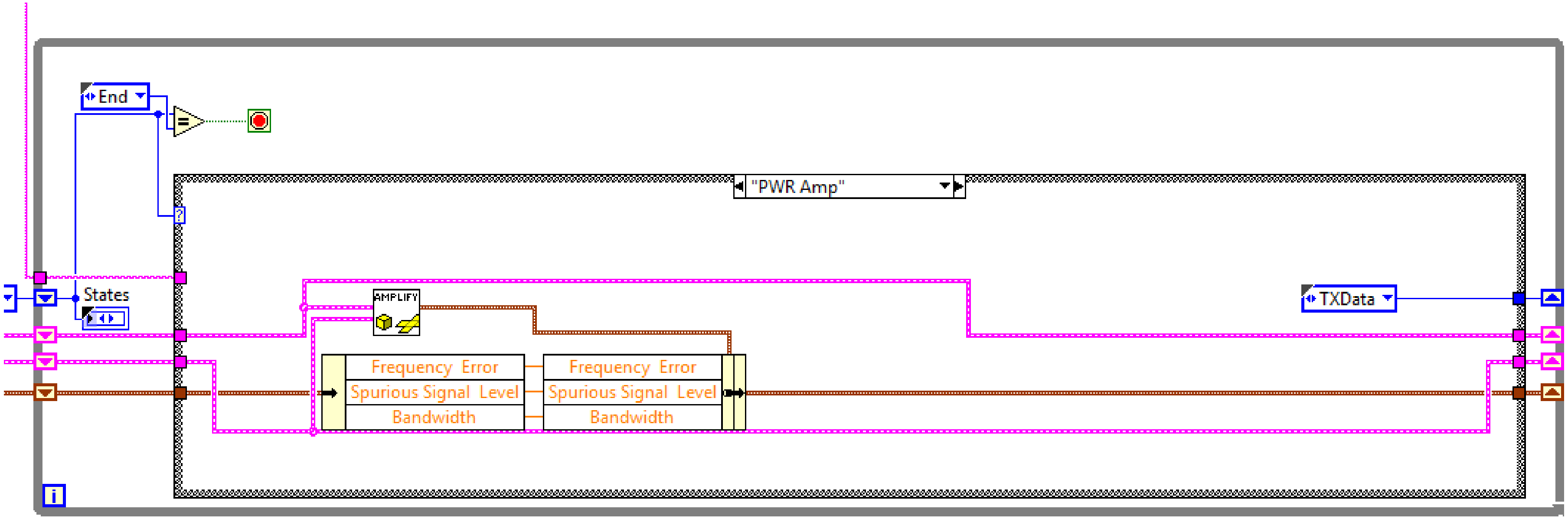


Fig. 0.20: Power amplifier state in the automated testing system

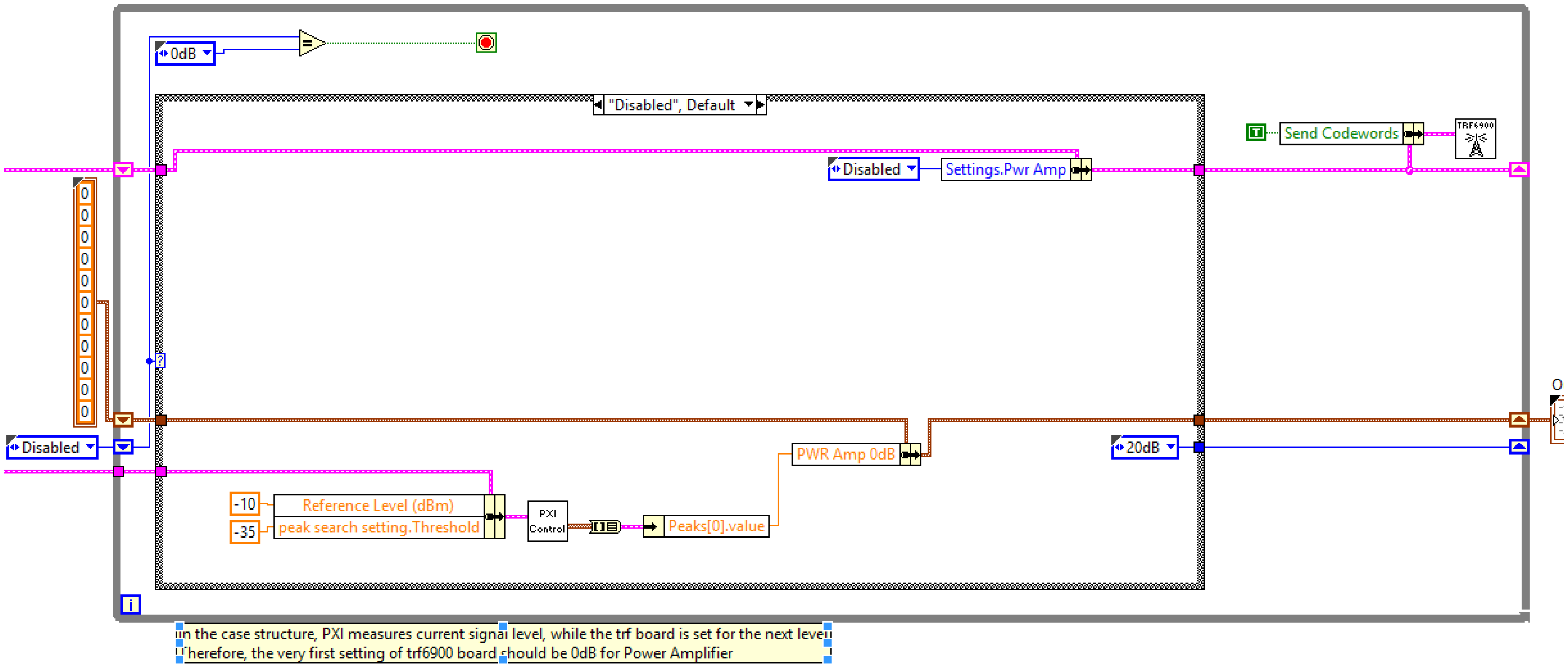


Fig. 0.21: "Disabled" state in power amplifier measurement

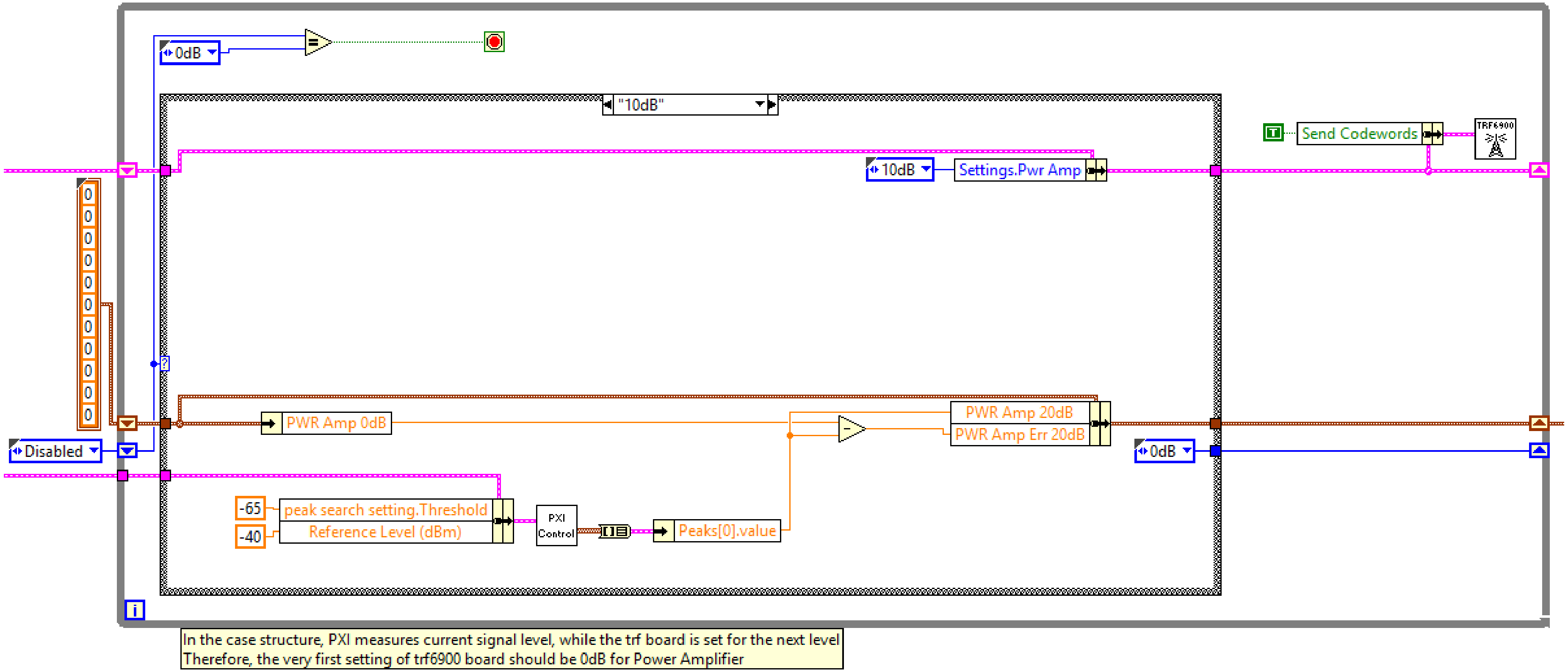


Fig. 0.22:"20dB" state in power amplifier measurement

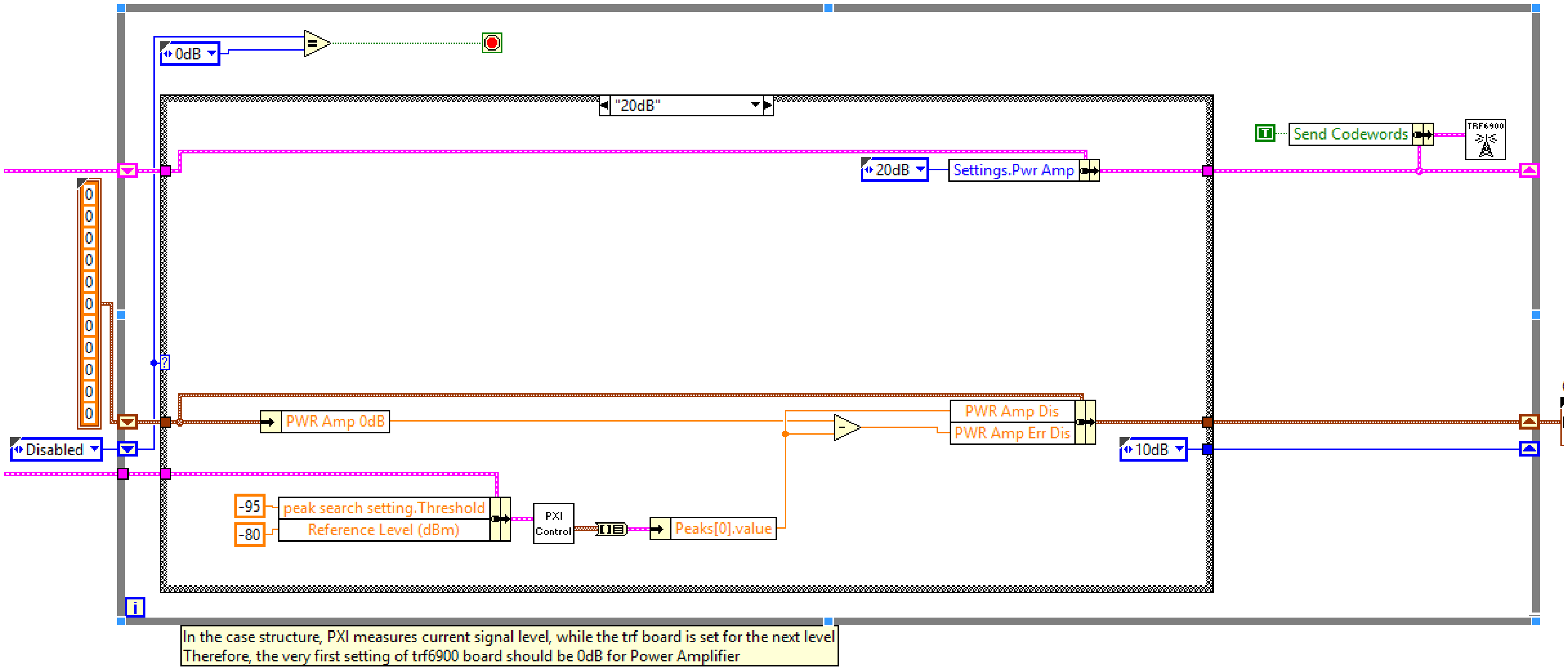


Fig. 0.23:"10dB" state in power amplifier measurement

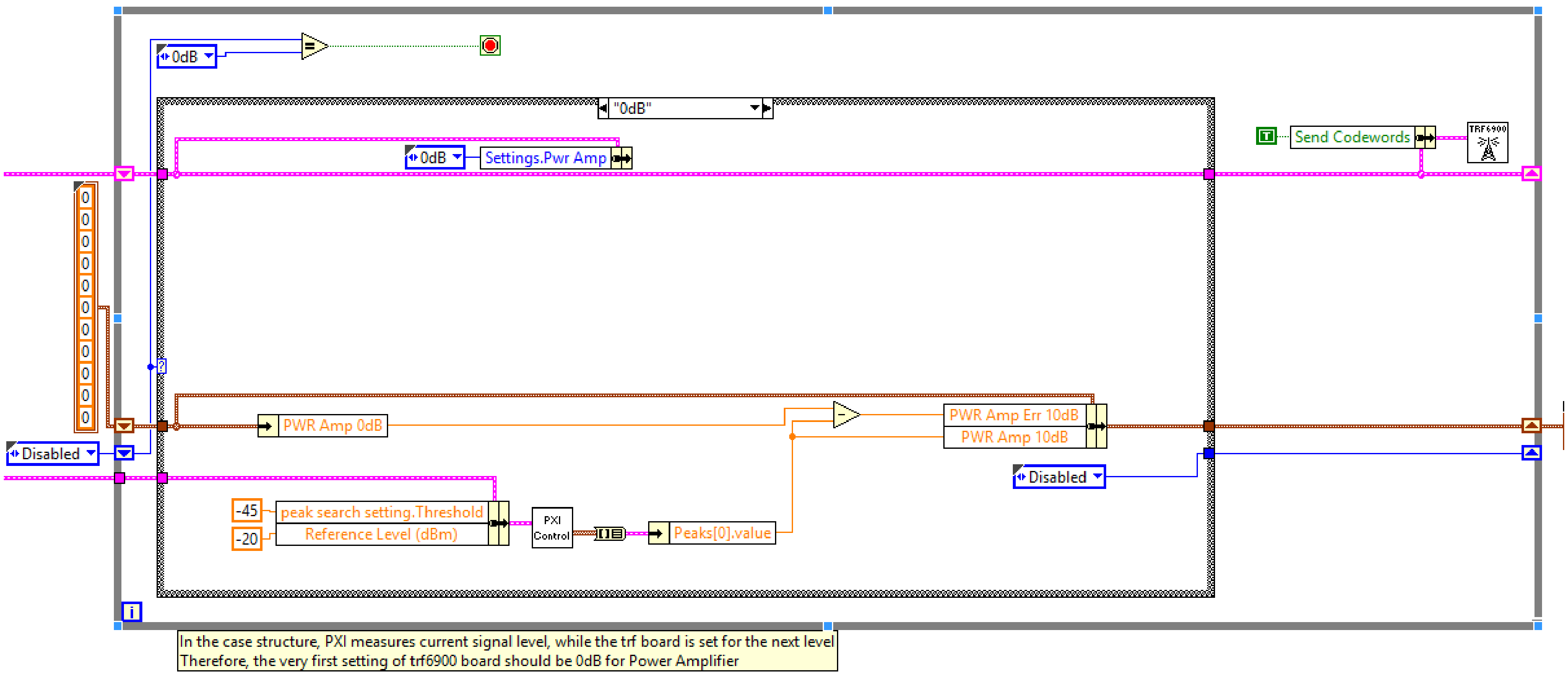


Fig. 0.24: “0dB” state in power amplifier measurement

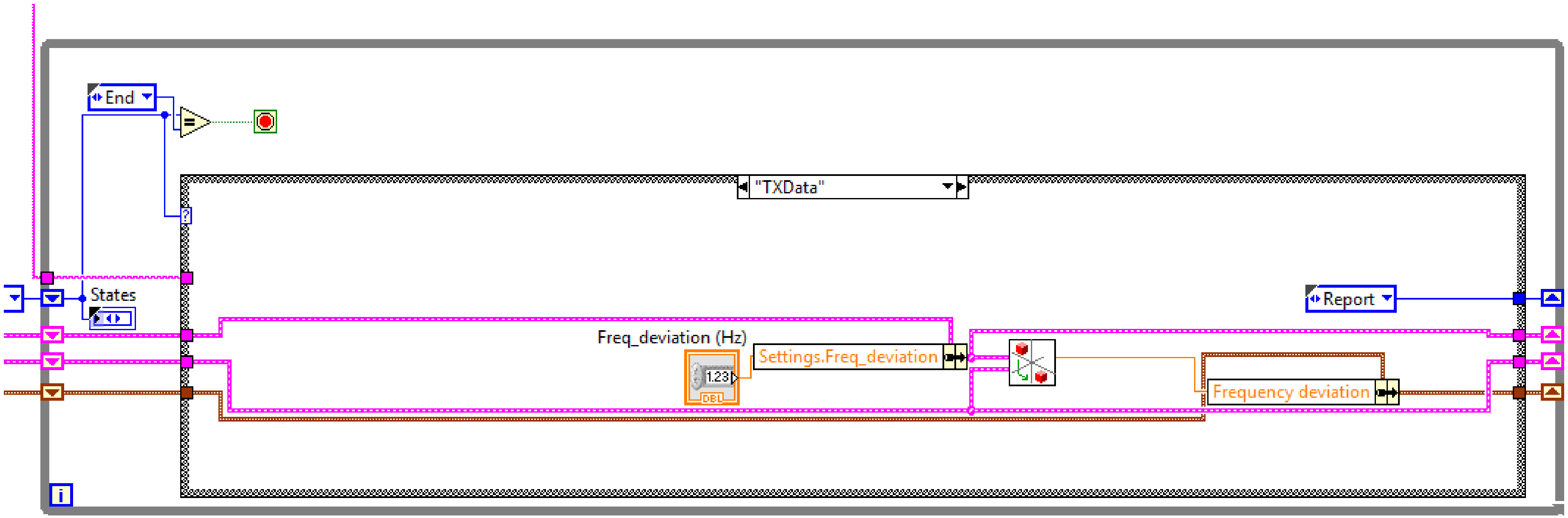


Fig. 0.25: TXData state of the automated testing system

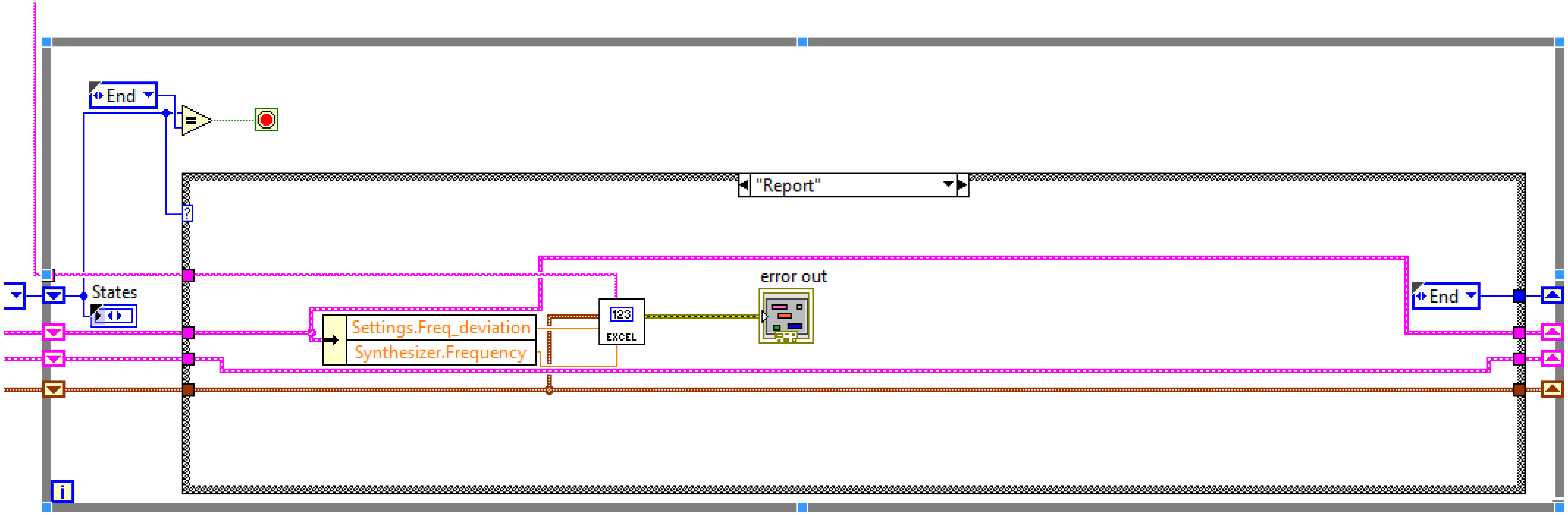


Fig. 0.26: Report state of the automated testing system

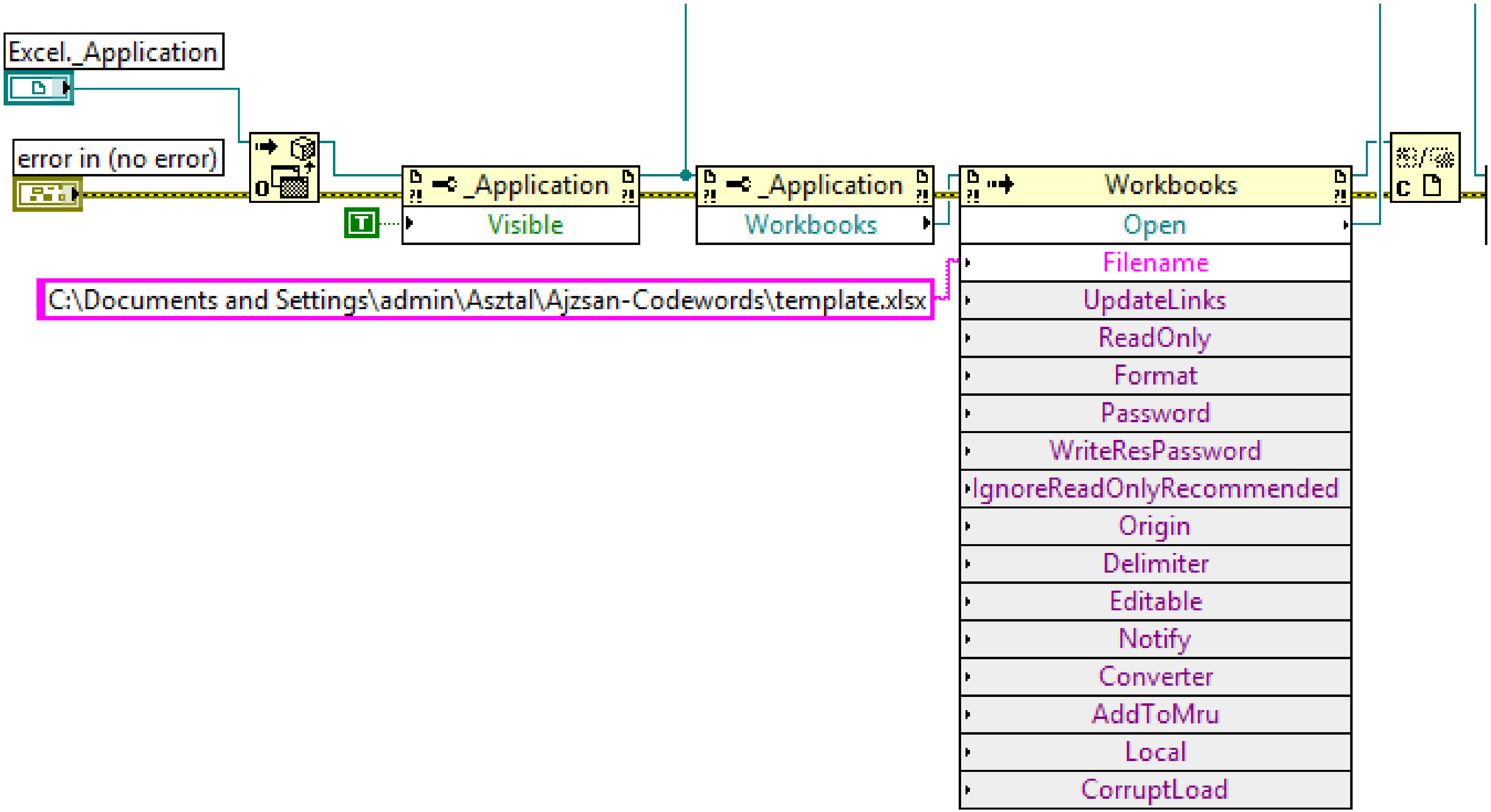


Fig. 0.27: Block diagram for report generation (part a: open the template)

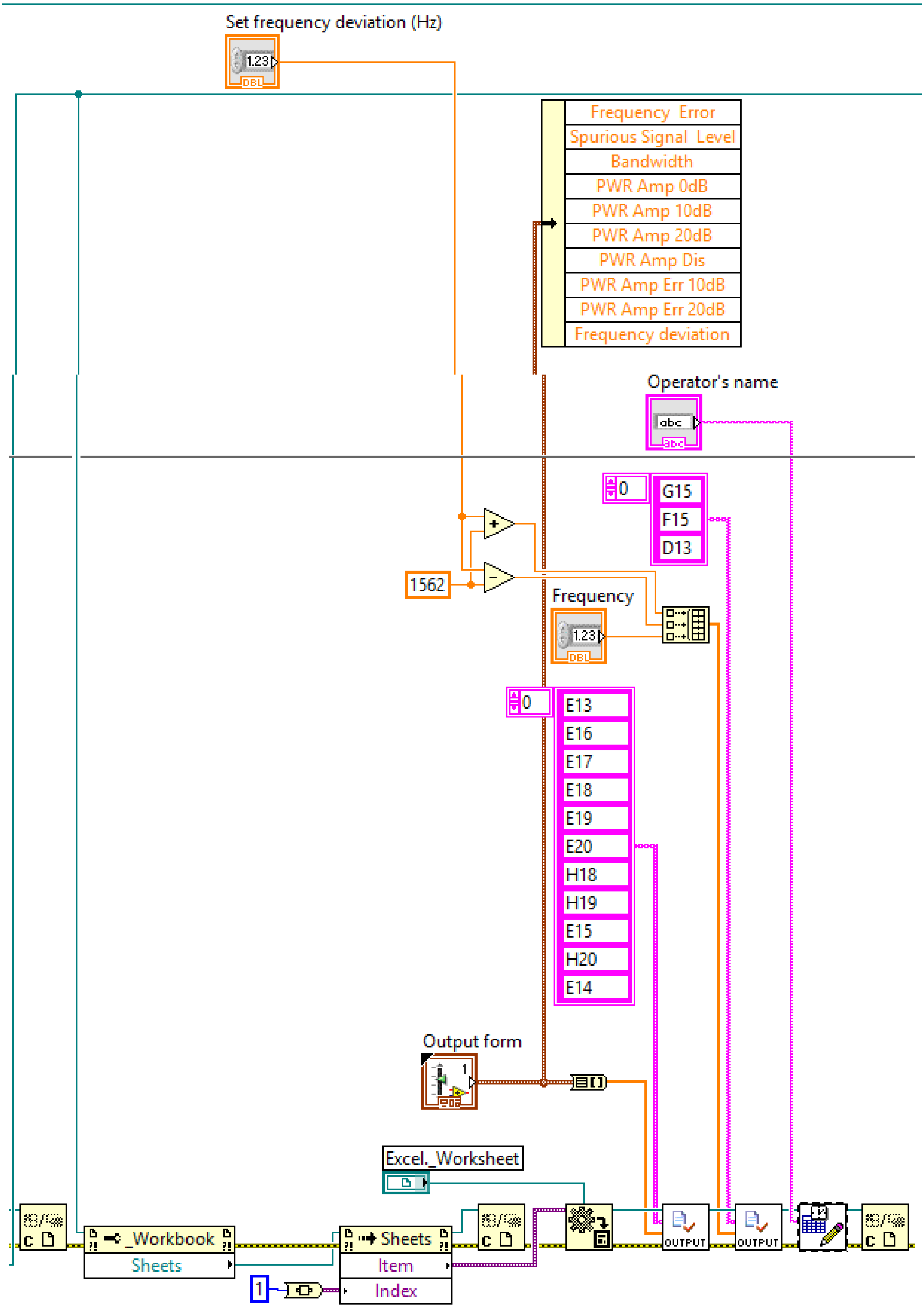


Fig. 0.28: Block diagram for report generation (part b: modify the template)

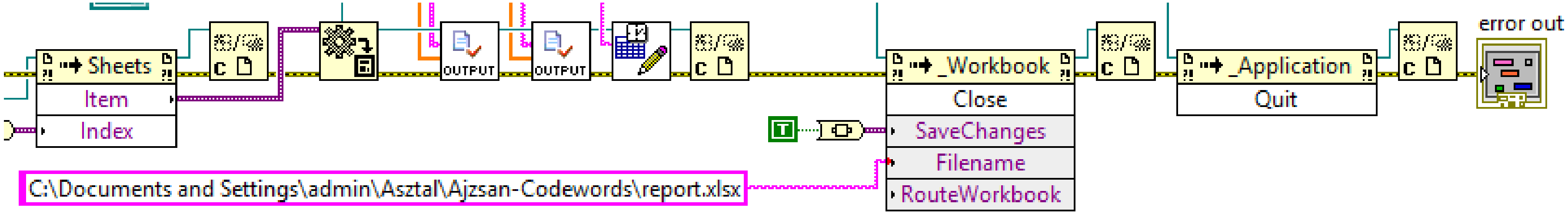


Fig. 0.29: Block diagram for report generation (part c: save the report and close Excel application)

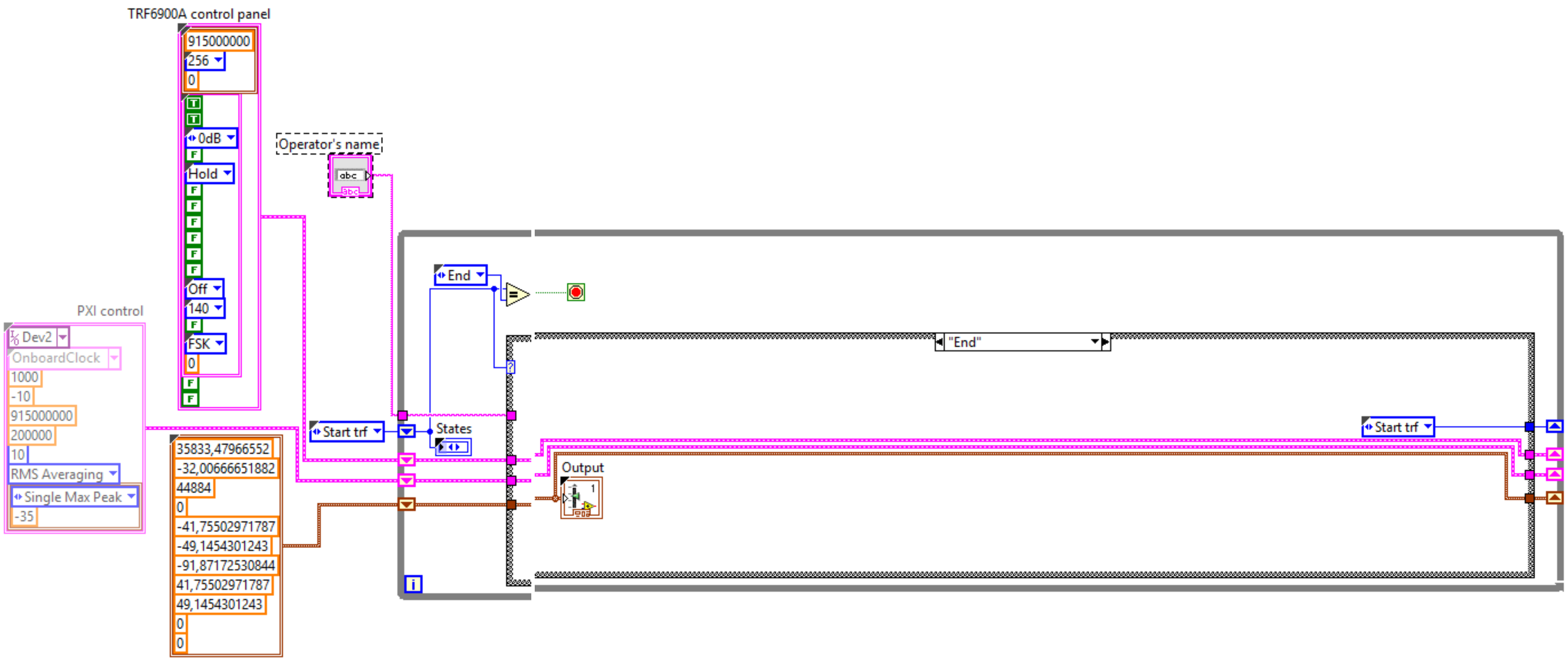


Fig. 0.30: Automated testing system block diagram in end state