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Investigation of a Closed Loop Modulator for Bluetooth Radios

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The frequency regulator is a dynamic system with high complexity. Therefore the investigation has been done with simulators built with Matlab and Simulink. The simulations show that the new idea puts hard requirements upon the phase error and the asymmetry of the transmitted data when reducing the activity of the frequency regulator. The problem with the asymmetrical data is solved with an additional filter that the transmitted data goes trough. But in the case of large phase error, ringing will occur causing drift like problems. No satisfactory solution was found to overcome this problem. However, the work indicates that with careful optimisation of the loop filter and timing as well as with an increased reference frequency to 1 MHz the suggested idea is likely to work if some ringing of the frequency during modulation is allowed.

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1 INTRODUCTION

This rapport investigates the transmitter of the Ericsson Bluetooth radio. The open loop modulation scheme of the existing design is theoretically very simple but difficult to implement with available components. Frequency drift of the carrier is a common result of open loop modulation. This work therefore investigates an idea of frequency regulation where the regulation is active during modulation in order to reduce the frequency drift. Instead of completely opening up the phase locked loop, the rate of activity will be reduced to a level enough to compensate the frequency drift.

The frequency regulator is a dynamic system with high complexity. Therefore the investigation has been done with simulators built with Matlab and Simulink. The simulations show that the new idea puts hard requirements upon the phase error and the asymmetry of the transmitted data when reducing the activity of the frequency regulator. The problem with the asymmetrical data is solved with an additional filter that the transmitted data goes trough. But in the case of large phase error, ringing will occur causing drift like problems. No satisfactory solution was found to overcome this problem. However, the work indicates that with careful optimisation of the loop filter and timing as well as with an increased reference frequency to 1 MHz the suggested idea is likely to work if some ringing of the frequency during modulation is allowed.

1.1 PROBLEM FORMULATION

Map and understand the frequency regulation in the Ericsson Bluetooth and investigate whether the new idea of frequency regulation is a solution of the frequency drift problem.

1.2 EXPERIMENTS

To be able to really understand the function of the frequency regulator models in Simulink and Matlab have to be built. The results of the simulations have been the basis of the analysis. Additional to that, measurements of the real module have been of great importance.

1.3 PREFACE

The rapport starts in Section 2 with the background and what Bluetooth stands for. Section 3 presents an overview of how Bluetooth works. Section 4 describes the Bluetooth radio and how the frequency regulator woks in more detail. It is in the fourth section that the relevant information for this work is presented. Section 2 and 3 are there to give a broader perspective of this investigation and the importance of the radio functions in the Bluetooth technology. Section 5 describes the different simulators and the corresponding code. The section describes how the functions of the real module have been translated to a Simulink model. Section 6 shows the outputs from the Simulink models and further descriptions of how the dynamics in the module works. This section also considers the new potential solution of the frequency regulator. In Section 7 measurements of the real module is illustrated. Here the concordance between the real module and the Simulink model will be observed. Both 6 and 7 are analytical parts and ends in the conclusions of this work. The rapport ends up in Section 8, which deals with possible further studies.

1.4 RESULTS

The result of this work is the mapped frequency regulator and the understanding of the dynamics of the regulator. The new idea of frequency regulation has been investigated and results in the knowledge that two main parameters are of great importance for the new type of module. The parameters are the initial phase error when the charge pump current decreases and the asymmetric data during the modulation. Both will give oscillations as a result.

The conclusion is that the new kind of module probably is a solution of the frequency drift but that a few additional measurements of the real module have to be done to secure this statement. The settling time of the phase error seems to be insufficient. But with suggested improvements the whole problem should be solved.

2 BLUETOOTH

2.1 THE BACKGROUND OF BLUETOOTH

The name Bluetooth refers to a Danish king named Harald Blåtand (Bluetooth). He was the viking warrior who unified Denmark and Norway. That is what Bluetooth technology is all about. The main idea with this technology is to unify the telecom and computing industries. Bluetooth is a technology with a huge potential with big opportunities for many different kinds of applications.

The Bluetooth wireless technology allows users to make wireless and instant connections between various communication devices. It is a method for data communication that uses short-range radiolinks to replace cables between the applications. The need of cables has increased due to the continuously growing degree of computerisation. We now have better opportunities to digitally communicate with for example computers connected to internet and mobile phones. The increased need of this kind of communication also increases the need for cables of varying kinds. Bluetooth with its short-range technology is the ultimate solution for plenty of the products that today require cables. The digitalisation is driven further and further and Bluetooth technology enables continuing development of the user friendliness. The telecom industry is in an economic perspective an exceptional industry because of the fact that many technical innovations are developed before the customers understand their needs. The Bluetooth technology is not a part of that section, it is driven by an actual need.

The idea of wireless short range communication between electrical appliances has been discussed in many companies, but it was Ericsson Mobile Communications that in 1994 finally started a project to accomplish this desire, Bluetooth was born.

Ericsson was the initiator and still is a major player in the development and realisation of Bluetooth. Ericsson had the opportunity to protect the ideas from competitors and try to do it secretly on their own as far as possible. But an open standard will probably achieve greater consumer acceptance and broader market adoption. The companies will create innovative solutions that build on the base of Bluetooth wireless technology to provide interesting and diverse products for many markets.

The Special Interest Group, SIG, was created in 1998 [1]. The Bluetooth Special Interest Group consists of leaders in the telecommunication, computing, and networking industries that are driving development of the Bluetooth technology and bringing it to the market. The first members were IBM, Intel, Nokia, Toshiba and of course Ericsson. The open Bluetooth Specification was released in 1999. Now the Bluetooth SIG is run by nine promoter companies. They are the original 5 companies plus 3Com, Lucent Technologies, Microsoft and Motorola. These are the big companies but they are not even near alone. More and more companies with interest for the Bluetooth technology become Bluetooth adopters. Currently more than two thousand companies have joined. The market is broad and that is also the set of companies. The group of Bluetooth adopters works like a network producing opportunities for companies to create mobility-enhancing devices. Companies have to co-operate with as many other companies they can to become the winner of the economic race.

2.2 THE BLUETOOTH TRADEMARK

“BLUETOOTH” is the trademark [2] you get access to when you sign the Bluetooth Trademark Agreement. Adopter companies are allowed to use “BLUETOOTH” as trademark on their products if they fulfil the Bluetooth Specifications. The “brand goal” and the “brand values” of “BLUETOOTH” are Freedom, Security, Simplicity, Versatility and Reliability. These are the words that explain the strategic aim and goal. Freedom to communicate in a simple, secure and reliable way is what Bluetooth stands for. The purpose of Bluetooth is also to create opportunities for new more flexible ways of interaction between people and machines.

2.3 MARKET

The Bluetooth technology has a great potential and the areas where cable replacement is needed are growing. It is estimated that by 2005 the Bluetooth wireless technology will be a built-in feature in more than 670 million products. The Bluetooth technology is important if we want to come real close to the information technology. This technology seems to be necessary for the e-trading to take off. The GartnerGroup predicts that in year 2004 as much as 40% of all electronic trading will be done using handheld terminals. The creativity around the technology is big and a wide field of applications is available.

The two-in-one phone idea means that you when you come within range of a Bluetooth base station connected to your fixed phone-line, your mobile phone is automatically able to communicate via the fixed line. Consequently it can be used as a cordless phone. Today we use two different systems for that.

The internet bridge offers possibilities to use internet wherever you are and whenever you want.

If you are at work your phone or hand-computer is connected to a computer with Bluetooth technology and access to the web. At home you communicate with your home computer.

Bluetooth also makes it possible with interactive conferences. Information can be transferred between different computers and after the meeting everybody has the information they want in their own computer.

Headset is another application where the need of a cable can be reduced. You can speak wherever you are and at the same time use you hands freely.

Bluetooth enables your applications to be synchronised. Your computer, mobile phone, notebook and so on synchronise automatically to make sure that the information is identical in all devices.

All these kind of ideas leads us to possibilities that make our lives easier and more effective in a way that hopefully effects us positively.

Ericsson was first out to study and discuss the idea of a low-power, low-cost radio interface between mobile phones and their accessories. They have led the development and are still holding a strong position.

Ericsson was first to develop modules, first to make live demonstrations and announced the first commercially available product. But it is a very long way to go before the inventions commercialise to innovations and the profits can be achieved. The Bluetooth technology is going to be a very big business but there are many companies that compete. It is not necessary that the leader now will be the winner when the market has grown really big. The engineers of the companies have to solve the technical problems fast and in a cheap and successful way to win. In any case the companies that first access the market have really big values to get. Presently Ericsson still has a god position and it is important that this position is maintained.

3 THE FUNDAMENTALS OF BLUETOOTH

3.1 NETWORKS

Bluetooth units that come within range of each other can set up ad hoc point-to-point and/or point-to-multipoint connections. Units can dynamically be added or disconnected to the network. Two or more Bluetooth units that share a channel form a piconet.

Several piconets can be established and linked together in, so called, ad hoc “scatternets”. This allows communication and data exchange in flexible configurations. If several piconets are within range they each work independently and each have access to full bandwidth. Each piconet is established by a different frequency hopping sequence. All users participating in the same piconet are synchronised to this hop pattern. Unlike infrared devices, Bluetooth units are not limited to line-of-sight communication.

To regulate traffic in the piconet, one of the participating units becomes a master of the piconet, while all other units become slaves. With the current Bluetooth Specification up to seven slaves can actively communicate with one master. However, there can be almost an unlimited number of units virtually attached to a master being able to start communication instantly.

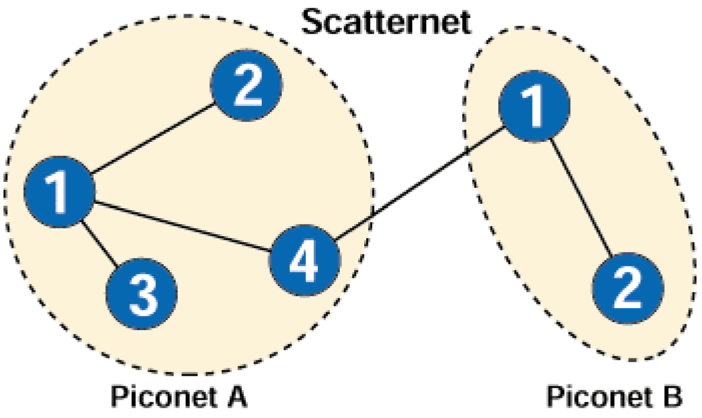

Figure 3.1 *Devices are grouped into piconets consisting of one master and up to seven slaves. Several piconets can in turn be connected to form a scatternet since each device can be active in more than one piconet.*

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3.2 CONNECTION PROCEDURE

The connection procedure for a non-existent piconet is initiated by any of the devices, which then becomes master of the piconet thus created. A connection is made by a PAGE message being sent if the address is already known, or by an INQUIRY message followed by a subsequent PAGE message if the address is unknown.

In the initial PAGE state, the master unit will send a train of 16 identical page messages on 16 different hop frequencies defined for the device to be paged. If there is no response, the master transmits a train on the remaining 16 hop frequencies in the wake-up sequence. The maximum delay before the master reaches the slave is twice the wakeup period, i.e. 2.56 s, while the average delay is half the wakeup period, i.e. 0.64 s.

The INQUIRY message is typically used for finding Bluetooth devices, e.g. public printers, fax machines and similar devices with an unknown address. The INQUIRY message is very similar to the page message, but may require one additional train period to collect all the responses.

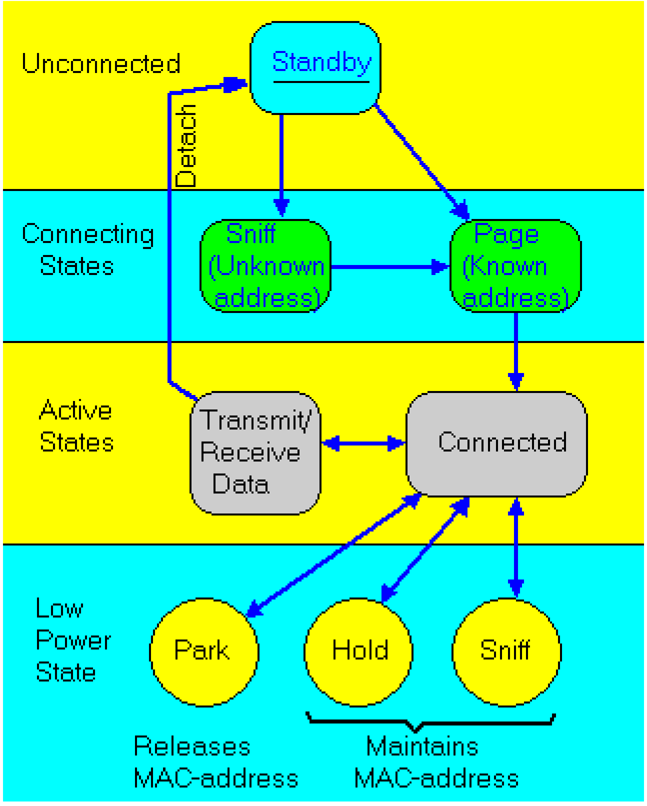


Figure 3.2 *The four states that a Bluetooth unit can exist in.*

A power saving mode can be used for connected units in a piconet if no data needs to be transmitted.

The master unit can put slave units into HOLD mode showed in fig. 3.2, where only an internal timer is running. Slave units can also demand to be put into HOLD mode. Data transfer restarts instantly when units transition out of HOLD mode. The HOLD is used when connecting several piconets or managing a low power device such as a temperature sensor.

In the SNIFF mode, a slave device listens to the piconet at reduced rate, thus reducing its duty cycle. The SNIFF interval is programmable and depends on the application.

In the PARK mode, a device is still synchronised to the piconet but does not participate in the traffic. Parked devices have given up their address in the piconet and only occasionally listen to the traffic of the master to re-synchronise and check on broadcast messages.

3.3 SECURITY

In the line of the “Bluetooth brand” security is of high priority. Security can mean two things in this context:

- We want to be sure that transmitted data arrives in un-corrupted condition to the receiver.
- We also want to be sure that this data has not been eavesdropped by parties for whom it is not intended.

Are transmissions secure in a business and home environment? Yes, they are supposed to be quite reliable. Bluetooth has built in sufficient encryption and authentication and is thus very secure in any environment. In addition to this, a frequency-hopping scheme with 1600 hops/sec. is employed. This is far quicker than any other competing system. This, together with an automatic output power adoption to reduce the range exactly to requirement, makes the system difficult to eavesdrop.

3.4 FREQUENCY HOPPING

Bluetooth has been designed to operate in noisy radio frequency environments and therefore uses a fast acknowledgement and frequency-hopping scheme to make the link robust. Bluetooth radio modules avoid interference from other signals by hopping to a new frequency after transmitting or receiving a packet.

Compared to other systems operating in the same frequency band, the Bluetooth radio is typically hopping faster and uses shorter packets. This is because short packets and fast hopping limit the impact of microwave ovens and other narrow-band sources of disturbances. Furthermore, the use of Forward Error Correction (FEC) limits the impact of random noise on long-distance links.

3.5 TECHNOLOGY

The Bluetooth Specification defines three classes of radios. Class 1 devices have output powers up to +20 dBm and a range of approximately 100 m. Class 2 devices have -6 to +4 dBm of output power and a range of 10 m. Class 3 devices have less than 0 dBm of output power. The definition of the data packages is identical for all three classes with voice capabilities and data transmission up to a maximum capacity of 720 Kb/s per piconet.

Radio frequency operation is in the unlicensed Industrial, Scientific and Medical (ISM) band at 2.402 to 2.480 GHz, using a spread spectrum, frequency hopping, full-duplex signal at up to 1600 hops/sec. The signal hops among 79 frequencies at 1 MHz intervals to give a high degree of interference immunity. RF output power in the Ericsson Bluetooth is specified as 0 dBm (1 mW) in the 10m-range version and -30 to +20 dBm (100 mW) in the longer range version.

3.6 VOICE

Up to three simultaneous synchronous voice channels are used, or a channel which simultaneously supports asynchronous data and synchronous voice. Each voice channel supports a 64 kb/s synchronous (voice) channel in each direction.

3.7 DATA

The asynchronous data channel can support maximal 723.2 kb/s asymmetric (and still up to 57.6 kb/s in the return direction), or 433.9 kb/s symmetric. A master can share an asynchronous channel with up to seven simultaneously active slaves in a piconet. By swapping active and parked slaves out respectively in the piconet, 255 slaves can be virtually connected. A parked device can participate again within 2 ms.

3.8 MODULATION

The information is sent in packets carried by a certain frequency, the channel. The packets are sent over the air in timeslots with a nominal length of 625 µs. The packet can be extended to a maximum of five ordinary timeslots. The same RF channel is used for the entire packet independent of its length. The channel bandwidth is 1 MHz and the frequency deviation is between 140 and 175 kHz. The frequency deviation is measured by

$$f_{\mathrm{mod}} = \frac{(f_{\mathrm{mod}1} - f_{\mathrm{mod}0})}{2}, \qquad (1)$$

where $f_{\mathrm{mod}1}$ is the frequency for a logic one and $f_{\mathrm{mod}0}$ is the frequency for a logic zero.

The implemented modulation technique is Gaussian Frequency Shift Keying, GFSK, with a BT product of 0.5.

4 THE PRESENT MODULE

This section describes the function of the now existing module there the phase locked loop is open during the modulation.

4.1 IMPLEMENTATION OF THE PRESENT MODULE

The hardware and firmware parts in the Ericsson Bluetooth module are shown in Fig. 4.1 below. The module transforms digital information from the host into radiowaves, which are possible to send through the air. The same thing happens but in the opposite direction when the module is receiving information.

The Bluetooth module handles several tasks that the host never has to be aware of. These tasks are handled by the firmware which consists of the Host Controller Interface (HCI) and the Link Manager (LM). The firmware resides in a flash memory and is available in object code format. The primary task for the Host Controller Interface is to handle the communication with the transport layers of the host. The HCI connection between the host and the Bluetooth application makes it possible for the two parts to understand each other. The Bluetooth specification regulates what standards the HCI have to satisfy.

The Link manager handles hardware related and time critical tasks like link-set-up, security, control and power savings. The link manager uses information produced by the baseband and sends relevant information trough the HCI to the host.

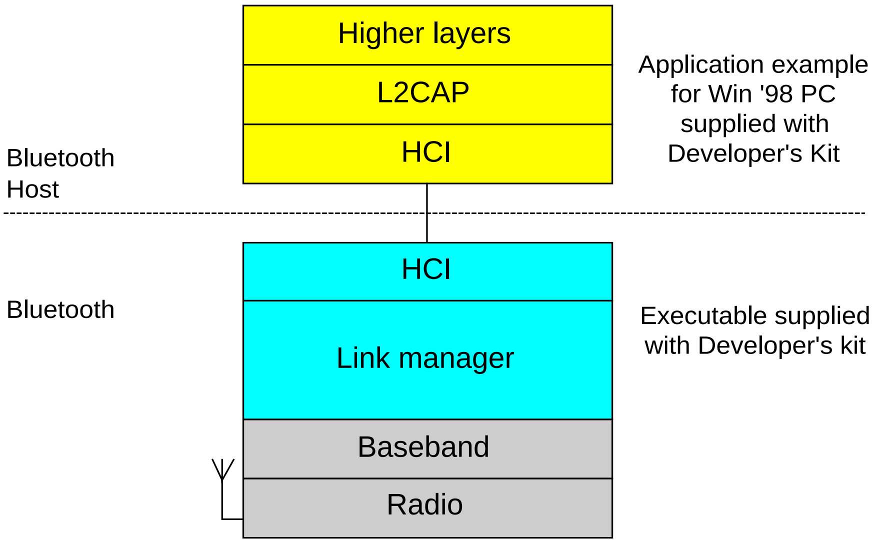


Figure 4.1 *The HW-FW stack and the interaction between the host and the Bluetooth unit.*

The hardware consists of both a radio and a baseband. The baseband provides the link-set-up and control routines for the layers above. Furthermore, the baseband also provides Bluetooth security like encryption, authentication and key management. Figure 4.2 is a simplified picture of the Ericsson Bluetooth module. The main parts are the baseband, the flash memory and the radio.

It is necessary for the module to have a non volatile flash memory in which the operative information, like firmware and control constants, can be stored. The device address is one example of this such information.

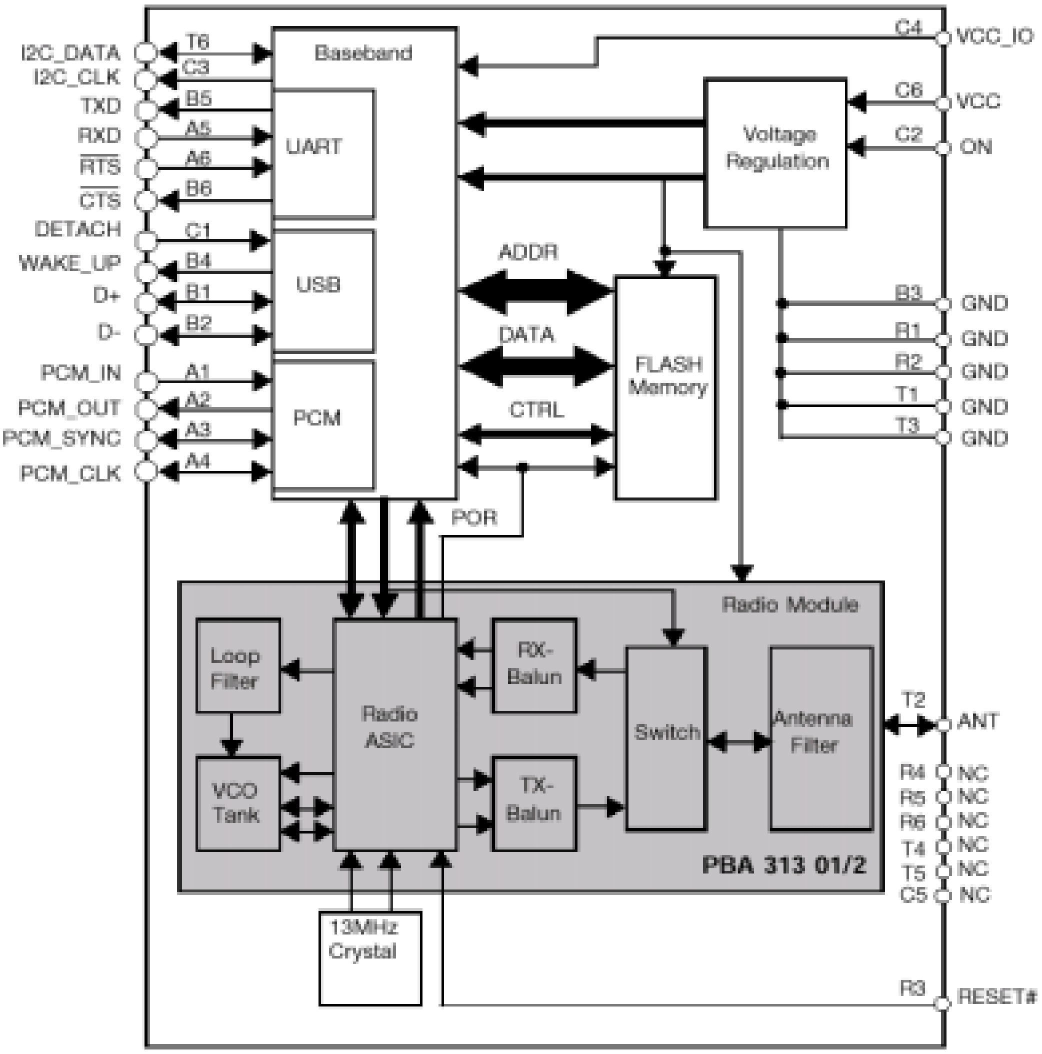


Figure 4.2 *Block diagram of the Bluetooth module. The radio parts of the module are marked by a shadowed square. Flash memory, baseband and voltage regulation are shown with their connections to each other, the radio and to the host.*

The baseband controls the operation of the radio transceiver. The baseband controls everything that happens in the radio. What and when the radio is supposed to perform a certain function is decided by the baseband. Examples are if the radio is going to receive or send information and when the modulation is going to start. The baseband also decides which channel the radio is supposed to send on.

The voltage regulator stabilises and filters the supply voltage. It generates two different voltages, 2.2 V for the baseband and 2.8 V for the radio. The supply to the radio is in turn split into two. One voltage for the VCO, that generates the radio frequencies, and one for the remaining radio circuitry.

The 13 MHz crystal is driven by a crystal oscillator to generate a high quality reference frequency required by the radio.

A detailed functional description of the radio transceiver can be found in Fig. 4.3. below.

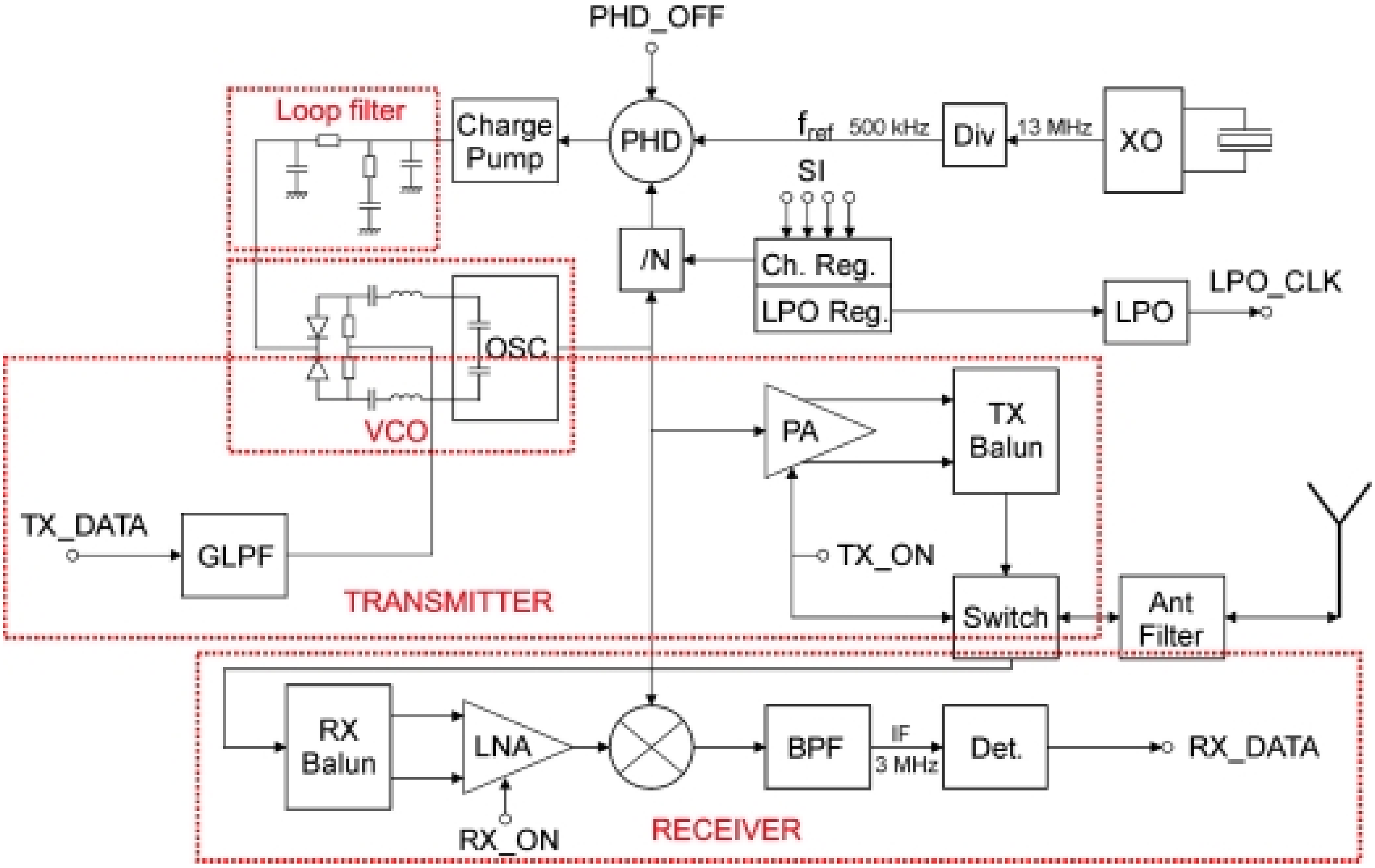


Figure 4.3 *Functional description of the radio.*

The electromagnetic waves are transmitted and received by the antenna. The antenna filter suppresses unwanted frequencies that otherwise could interfere with the transmission. Most critical are frequencies used by different mobile phone systems, e.g. GSM at 900 and 1800 MHz.

The switch directs the power either from the antenna filter to the receive ports or from the radio controller output ports to the antenna filter. These are the receiving and transmitting modes of the radio, respectively.

When the radio is receiving, the signal goes into the RX-balun where the incoming signal is converted from single ended to balanced. The balanced signal consists of two parts with a 180 degrees phase difference. Balanced signals are preferred on-chip due to there high common mode rejection.

The received signal is mixed with a 3 MHz lower frequency generated by the local oscillator, i.e. the synthesiser in the module. The resulting 3 MHz Intermediate Frequency (IF) signal is then filtered and passed to the detector that interprets the signal into a digital signal, the received data (RX_DATA).

When transmitting, the control signal TX_ON is taken high. This turns on the power amplifier in the chip as well as it opens the switch. Modulation starts when the phase comparator is turned off by setting PHD_OFF high. The modulation is done directly in the VCO. From the local oscillator the signal, goes through the power amplifier, the TX-balun and then further to the antenna filter and to the antenna.

To avoid noise and to manage to create an information secure link between two applications the Bluetooth specification states that the radio has to hop among 79 different frequency channels with 1600 hops per second. This fact puts tough requirements upon the radio. The radio has therefore a synthesiser and a frequency divider, which are controlled by the baseband via registers in the radio.

The synthesiser is a frequency regulator that makes it possible for the radio to change channel at the demanded rate.

The synthesiser consists of a voltage controlled oscillator (VCO), a frequency divider (/N), a phase detector (PHD), a charge pump and a loop filter. A 13 MHz crystal, which is possible to trim with the XO-trim register, is driven by the crystal oscillator (XO) and the resulting signal is divided down to a 500 kHz reference frequency that the phase detector uses.

The voltage controlled oscillator transforms an input voltage to an output frequency. The frequency is set by the resonator which is normally referred to as the VCO-tank. The VCO generates the required frequency of the carrier which is the channel frequency. Because of the heavy demands upon accuracy, the VCO-tank is a very sensitive part of the radio. To ensure high performance the working point of the VCO is laser trimmed.

The information is modulated directly in the VCO-tank. The transmitting signal goes from the TX_DATA input through the Gaussian low pass filter (GLPF) to the VCO. When the synthesiser is locked it normally reacts very fast on phase differences between the generated signal and the reference. In the present module the phase locked loop has to be open during modulation. That means that the synthesiser is not active and the PHD_OFF is high.

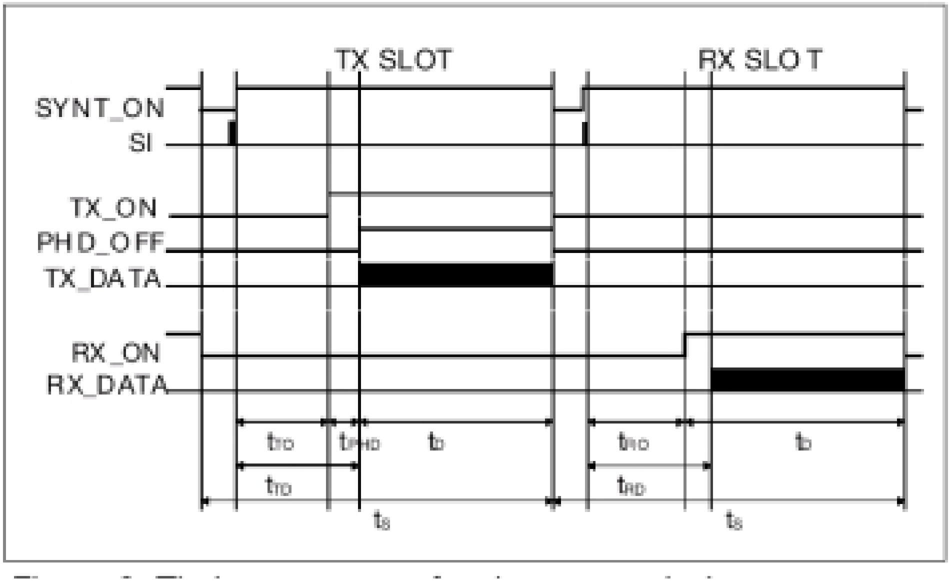
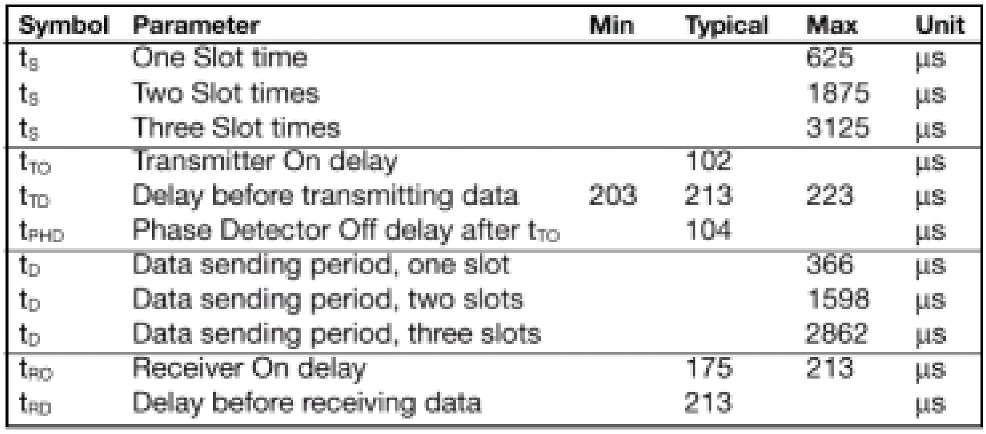


Figure 4.4 *Timing sequence for data transmission.*

Table 4.1 *Timing requirements for data transmission.*



Symbol	Parameter	Min	Typical	Max	Unit
t_S	One Slot time			625	µs
t_S	Two Slot times			1875	µs
t_S	Three Slot times			3125	µs
t_{TO}	Transmitter On delay		102		µs
t_{TD}	Delay before transmitting data	203	213	223	µs
t_{PHD}	Phase Detector Off delay after t_{TO}		104		µs
t_D	Data sending period, one slot			366	µs
t_D	Data sending period, two slots			1598	µs
t_D	Data sending period, three slots			2862	µs
t_{RO}	Receiver On delay		175	213	µs
t_{RD}	Delay before receiving data		213		µs

When the phase locked loop is closed and the synthesiser regulates towards the carrier frequency the output frequency from the CVO has to be divided to a range where it can be compared to the reference frequency of 500 kHz. When the required frequency is obtained the divided frequency should be the same as the reference of 500 kHz. If you for example want the carrier at channel 50, which represents 2450 MHz the N value should be set to 4900.

In the phase detector (PHD) the phase of the down scaled carrier and the phase of the reference is compared. Observe that the frequency is compared in an indirect way. Even if the frequency is right the synthesiser will regulate from this frequency if the phase difference is not zero. Both the differences of frequency and phase have to be zero. The PHD compares the positive slopes of the waves. The output of the PHD is a signal with constant amplitude and a width proportional to the phase difference. The phase difference can be $+/-2\pi$ and the longest time of a single output current pulse is 2 µs. The amplitude is positive or negative depending on if the phase difference is positive or negative. If the down scaled carrier is after the reference wave then the carrier has to accumulate phase faster, which means that the frequency has to be higher. To make this happen the amplitude of the PHD output has to be positive. In the other case the opposite relation is the fact.

The charge pump just scales the output from the PhD to a current with the same duration as the PhD output. It is 1000 µA when the synthesiser is active in the present module.

The loop filter is an important part of the regulator. Much of the regulating qualities depend on the design of the loop filter. It transforms the pulses from the charge pump into voltages, which is the input to the CVO where the carrier is generated. If suitable values are selected of the components in the loop filter, then the settling times will be short. A practical problem is the tolerance of the components. Capacitors typically have 10% tolerance and resistors 5%. However, 1% resistors are available at a slightly higher cost. The tolerances can make a big difference on the performance of the loop filter. The loop filter is further described in section 5.5 where the Laplace function of the filter is derived.

When transmitting information the baseband controls the radio as described in Fig. 4.4 and Table 4.1. First of all RX_ON is set low. That is because the radio is not going to receive information in the coming time slot.

In the detailed view of the radio transceiver you can se the serial interface (SI). SI consists of three 1-bit digital inputs (SI_CDI, SI_CMS and SI_CLK) and one digital output (SI_CDO). With the signal SI_CMS and SI_CLK it is possible to step from one state to another in the state machine. Different states are used to clock in data to instruction registers and data registers. The data written to the registers are clocked in using SI_CDI. When registers are read the data appears on SI_CDO.

When the registers are set the radio knows what to do. One of the registers is the channel register that is used to set the desired carrier frequency. From this register the appropriate N-value for the prescaler can be derived. Other registers are the RSSI-register, the XO-trim register and the ID register. The RSSI register indicates what strength the received signal had. This helps to prevent the Bluetooth applications to “scream” to each other i.e. use too large output power. The XO-trim register sets the value for the internal capacitor load of the crystal. The value of this register is set once in production and it is required to secure the accuracy of the 13 MHz clock. The ID register reveals the chip ID and revision.

After the registers have been set, the SYNT_ON is set high. When this signal is high the VCO is powered up and the synthesiser regulates towards the required channel. The locking after a frequency hop is illustrated in Fig. 4.5.

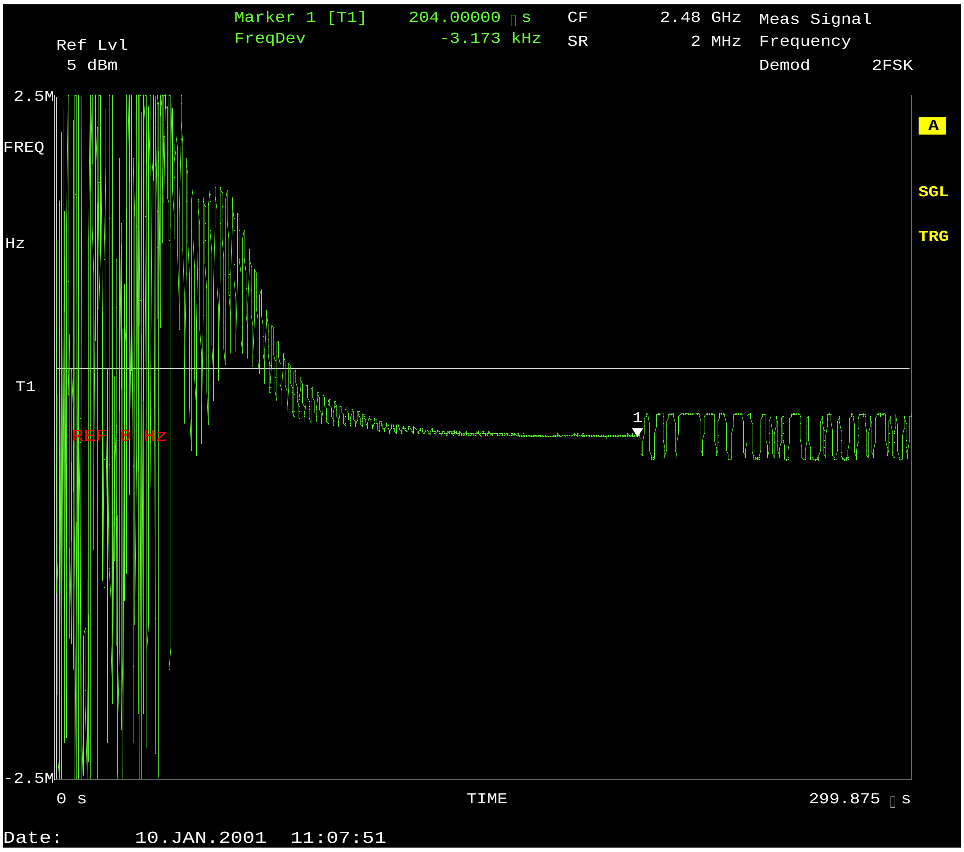


Figure 4.5 *Measurements on an actual device showing the frequency settling after a hop from 2402 MHz to 2480 MHz. Initially the frequency is outside the bandwidth of the instrument. From marker 1 and onwards the carrier is modulated with random data.*

The transmit-on (TX_ON) is activated 102 µs after SYNT_ON has been set high. This turns the power amplifier on and the switch opens to direct the power from the radio controller output ports to the antenna filter. When TX_ON is set high the VCO is to some degree disturbed and it requires time to reach the right frequency. That is the reason why TX_ON is activated before the start of the transmission of data. However, the transmit-on cannot be set too earlier because then the power would be turned on before the carrier is within the selected 1 MHz channel and you would break trough to neighbour channels and disturb them with your radio.

PHD_OFF is set high and the phase detector is turned off 104 µs after TX_ON is set high. Simultaneously the data on the TX_DATA is transmitted. PHD_OFF has to remain high during modulation of the carrier. Otherwise the information is going to be destroyed by the synthesiser. Data consists of logical ones and zeros represented by +/-160 kHz shifts of the carrier frequency. The duration of one bit is 1 µs. If the phase detector would be active the synthesiser would try to regulate the output from the VCO towards the specified channel frequency which means that the synthesiser considers the data as a frequency error that has to be corrected. When the data is transmitted and the transmitting slot is finished then everything is turned off. The next slot will be a receiving slot.

4.2 DRIFT ISSUES OF THE PRESENT MODULE

In the present radio the phase locked loop is opened when the radio is transmitting data. The regulation is stopped and the initial conditions remain constant, see Fig. 4.6. The initial frequency error and of course also the phase error remain ideally constant trough the modulation. The problem is that when the regulation is stopped anything causing the tuning voltage of the VCO to change will consequently also change the carrier frequency with frequency drift as fact.

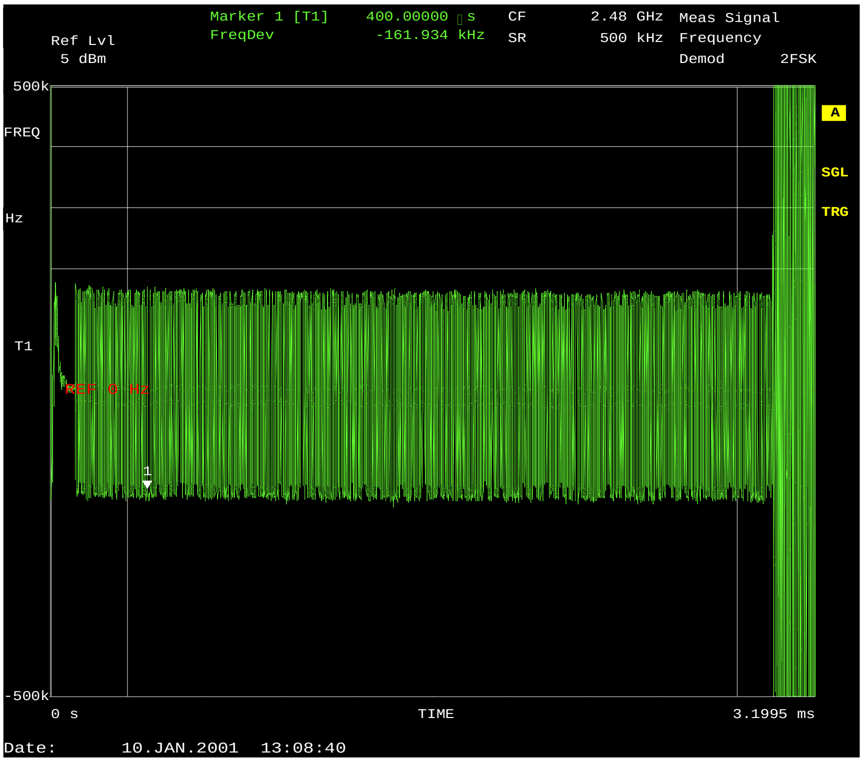


Figure 4.6 *Measurement illustrating the settling and modulation using a module with negligible frequency drift. The time of modulation corresponds to a 5-slot packet.*

There are three main things that cause this effect. The first is a memory effect of the capacitors in the loop filter that tends to remember the voltage associated with the previous channel. The memory effect therefore always causes the frequency to drift towards the frequency it came from. The memory effect is the result of dielectric absorbtion in the capacitors. This can be modelled by adding a resistance and a capacitance in series in parallel to the main capacitance. The largest capacitor in the loop filter in the present module is 2.7 nF. For this capacitor simulations indicate that the additional resistance should be around 500 MΩ and that the capacitance should be 2 pF in order to model the memory effect of physical capacitors from poor batches. In the model for the imperfect loop filter it is not in equilibrium when the phase locked loop opens up. Due to the different time constants of the RC-networks, current continues to flow between the capacitors after the phase detector has been disabled and that affects the output voltage from the loop filter. The memory effect causes an exponentially decaying frequency drift, i.e. the drift is largest just as the loop is opened up and then reduces to eventually nothing. Figure 4.7 illustrates the result of extreme memory effect.

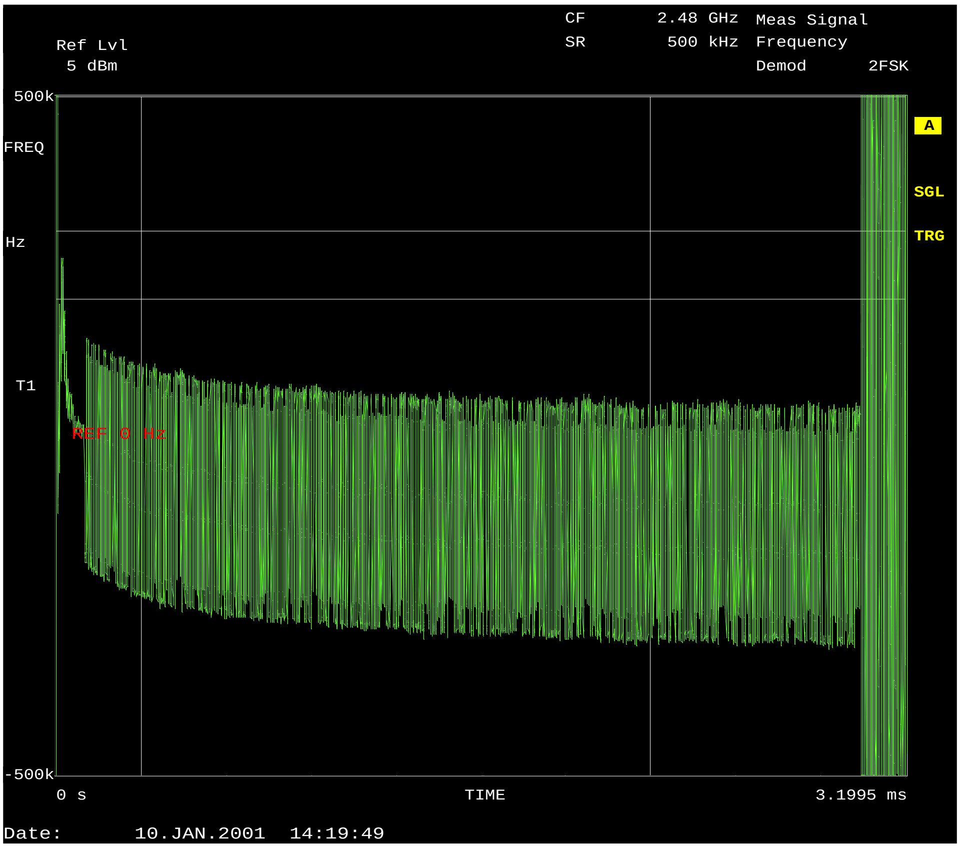


Figure 4.7 *This picture shows frequency drift of a device with extreme memory effect and with the phase detector disabled during modulation. The time of modulation corresponds to a 5-slot packet.*

The second thing is leakage current in the varactor diodes, the charge pumps and in the loop filter. Leakage causes a frequency drift with constant derivative, i.e. the frequency error grows linearly with time. However, the drift rate is exponentially dependent on temperature. At room temperature it is negligible but starts do become noticeable at 55 or 75ºC.

The third thing that can cause frequency error is punch through of digital signals and unstable supplies. Very low frequency disturbance cause drift-like phenomena. This can be resolved by proper layout of the module.

4.3 POTENTIAL SOLUTION TO THE FREQUENCY DRIFT

To prevent frequency drift the idea is to let the phase locked loop be closed but with a much slower regulation during modulation. Instead of a charge pump current of 1000 µA the charge pump current could be reduced to tens of microamps instead. A low charge pump current could potentially correct frequency drifts without destroying the information. The scope of this work is to investigate the feasibility of this.

5 THE SIMULATOR

One way to study this dynamic system is to create a model in a simulation program. I have chosen Simulink and Matlab. The simulator consists of two parts. One m-file and one Simulink file. I am going to describe the different sections in the model and in the code. I have three different models. One where I have approximated the phase detector and there I need to have access to a program which is only available at LTH (5.3+5.4). A second model similar to the first but which is not able to do everything that is demanded (5.3). That model has the advantage that only Matlab and Simulink is required. The third model is a simulator that not considers everything but instead it has phase detector description that closely resembles the physical implementation (5.1).

5.1 DESCRIPTION OF THE SIMULATOR WITHOUT THE APPROXIMATED PHASE DETECTOR

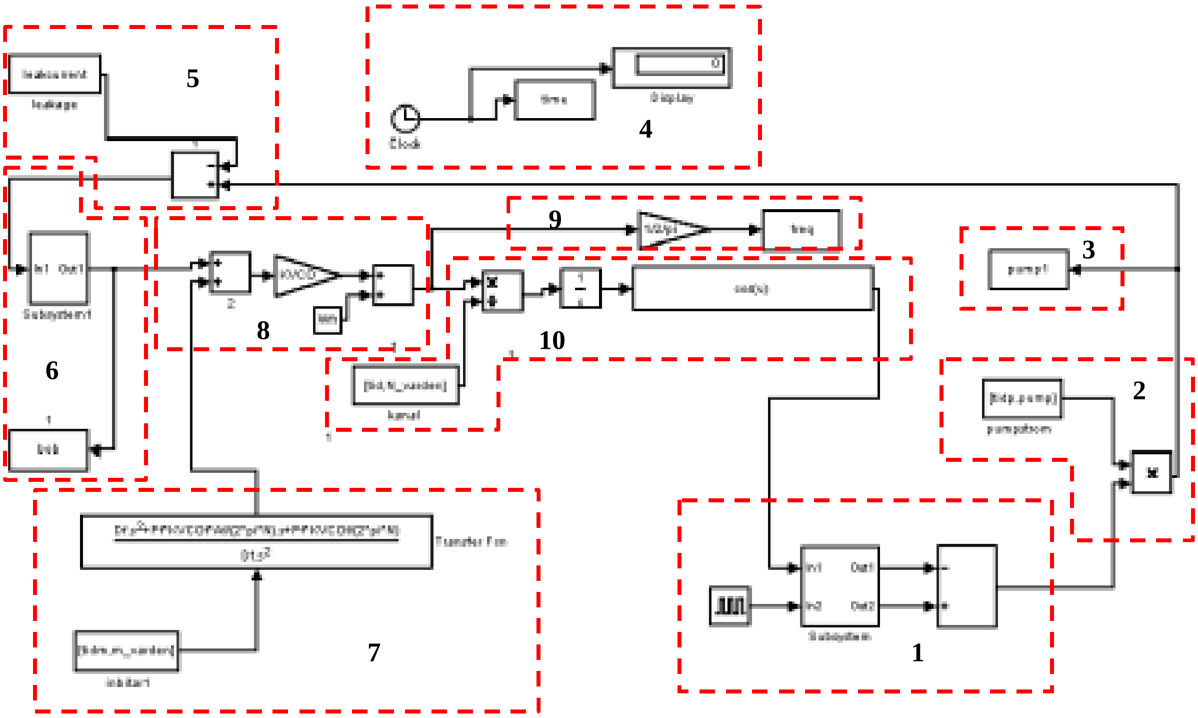


Figure 5.1 *The Simulink model without the approximated phase detector.*

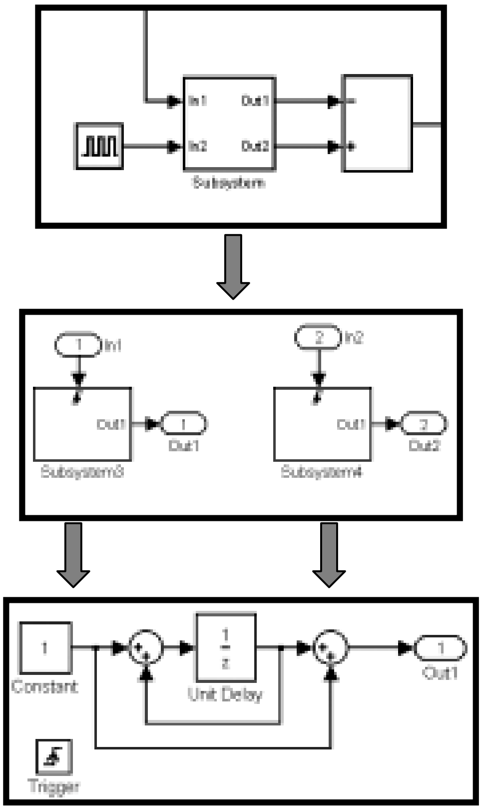


Figure 5.2 *The hidden layers of the subsystem in square 1.*

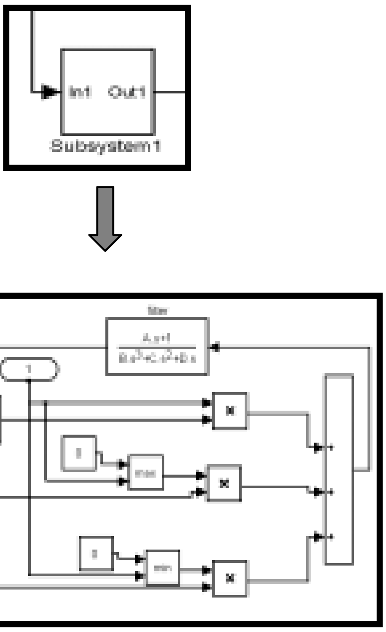


Figure 5.3 *The subsystem containing the Laplace function of the loop filter and the saturation realisation.*

1) The first square is the phase detector. You can see the reference wave as input 2 of the subsystem. Input 1 is the downscaled carrier. The phase of these two waves are compered to each other and results in a pulse with a width proportional to the phase difference and an amplitude of one unit. Figure 5.2 shows the levels in the subsystem. Output 1 is the transformed pulse from the current wave. This pulse is always positive. The trigger makes the system 1 tick up one step every time a positive slope is detected. The same thing happens with system 2 but with the reference wave instead. This model of the phase detector is not entirely correct. The real phase detector slips back to zero phase error when the phase difference passes +/-2π but this model does not. This is not really a problem when the initial phase error is not very big. To make the phase detector slip the initial phase error almost has to be +/-2π otherwise the problem will not arise. Problems can also come up if the initial frequency is too low because of the much longer period. The pulses subtract and that means that if the next positive slope does not come within one period of the reference pulse the output 2 will be too large and the phase detector not reliable. Actually this effect is impossible when the simulator is built like this. If the initial output from the loop filter is zero the frequency will be 2302.5 MHz. This frequency is far from half the required channel frequency no matter what channel.

   If the positive slope from the down scaled carrier comes first, then the phase is generated to fast in the phase locked loop and the frequency has to be reduced. In the opposite case the frequency has to be higher to ensure that phase is generated faster and makes the phase difference smaller. Observe that the phase detector only measures the phase difference, not the frequency. This means that the frequency can be exactly the one you want but because of a phase difference the regulator could still regulate from the required frequency. The phase detector is not satisfied before the phase error is zero. This can only happen when the frequency error also is zero. Accordingly, the correct frequency is assured in an indirect way.

2) Here the charge pump current is set. That is the amplitude of the pulses. In the present module the current is 1000 μA when the regulator is active and zero when the radio is modulating. The code that controls the charge pump can be found in Fig. 5.5 square 5.

3) The charge pump current is stored into Matlab workspace as *pump1*.

4) The display shows the time through the simulation and is stored into Matlab workspace as *time*.

5) As mentioned the frequency drift depends on leakage currents, which are simulated with the constant *leakcurrent.* The leakage current is now a constant that can be set in the m-file.

6) This is the loop filter, which is represented by its Laplace function. Figure 5.3 shows what is in the subsystem. I am not able to build a simulator consisting of capacitors and resistors without transforming it to a Laplace function. Therefore I am not able to set initial conditions in the loop filter either. It is possible but not in any simple way. When the output voltage of the charge pumps approaches the supply voltage or ground, i.e. 2.77 V or 0 V, they can no longer supply a constant current and no pulses are generated. The voltage is measured on the output of the loop filter and will be limited within the range [0,2.77] volt. I have access to a program at LTH that makes it possible to create a model consisting of capacitors and resistors but plots show that an approximation where the voltage is measured on the output instead of the input gives almost identical results. In the code square 3 gives the connection between the constants in the loop filter and the values of the capacitors and resistors.

7) This square consists of the input of the transmitting data, which represents number 6 in the code and a Laplace function that will be described later. This function compensates for the corruption of the transmitting data that will arise when it goes through the regulator. The corruption only arises when the charge pump is active. Accordingly, it is not implemented in the present module.

8) The regulating contribution sums up with the modulation frequency. The KVCO is the constant that in the real module gives the connection between output voltage from the loop filter and the output frequency from the VCO. The VCO responds so fast on differences in the input voltage that a constant like KVCO is a very good approximation.

   Then Wfr sums up as well. Wfr together with the regulating contribution gives 2441 MHz, which is the middle of the frequency range when the output from the loop filter is 2.77/2=1.385 volt. The regulator should have the same potential to regulate up and down and therefore the middle channel has to coincide with the middle voltage.

9) The frequency is stored into Matlab workspace in the variable *freq*.

10) This square consists of a divider and an integrator. The carrier frequency is scaled down and converted into a time varying phase which in turn is transformed into a frequency.

    The mathematical expression is

$$\cos\left(\int \frac{\omega_{tot}}{N} dt\right). \tag{2}$$

It is obvious that the phase varies much slower than the frequency.

5.2 DESCRIPTION OF THE CODE

The Matlab code that controls the simulator is described below. All variables have to be set before the calculations in the Simulink model can start.

1

```
% close all
% clear
% clf
color = 'b';
% for delta=0:0.2:0.8
% for kanal=2:77:79
% for litenpumpstrom=1e-6:10e-6:61e-6
% diffkanal=79-kanal;
 diffkanal=0;
```

2

```
leakcurrent=1e-9          %6e-9;
uppervolt=2.77;
initialoutput=uppervolt/2;
initialoutput=0;
KVCO=100e6*2*pi;
Wfr=2441e6*2*pi-uppervolt/2*KVCO;
period1= 2e-6;
kstart=160;
time0=0;
time1=3*625e-6;
kanal=79;
storpumpstrom=1000e-6
litenpumpstrom=20e-6;
antbit=1*625-kstart;
delta=0;
```

3

```
R1=7.5e3;
R2=1.5e3;
C1=220e-12;
C2=2700e-12;
C3=220e-12;

R1f=R1;
R2f=R2;
C1f=C1;
C2f=C2;
C3f=C3;

A=R1f*C2f;
B=R1f*R2f*C1f*C2f*C3f;
C=R2f*C2f*C3f+R1f*C2f*C3f+R1f*C1f*C2f+R2f*C1f*C3f;
D=C1f+C2f+C3f;
```

Figure 5.4 *The first part of the code which controls the simulator.*

```
P=litenpumpstrom;
N=2*2441;


Af=A;
Bf=B;
Cf=C;
Df=D;
Pf=1*P;
KVCOf=KVCO;
```

4

```
tid=[0  time1]';
freq_varden=kanal+[2400 2400]';
N_varden=freq_varden*2;
```

5

```
%pump=[ storpumpstrom*[1 1] litenpumpstrom*[1 1]]';
%tidp=[  0     kstart-100    kstart time1*1e6]'*1e-6;

pump=[ storpumpstrom*[1 1] litenpumpstrom*[1 1]]';
tidp=[  0     kstart  kstart time1*1e6]'*1e-6;
```

6

```
tidm=[];
m_varden=[];
rand('state',5);
v=round(rand(1,antbit));
p=0;
for n=1:antbit
   if v(n)==1
      m_varden(n+p)=1;
      m_varden(n+p+1)=1;
   else
      m_varden(n+p)=-1;
      m_varden(n+p+1)=-1;
   end
   p=p+1;
end
m_varden(1:2)=0;
m_varden(end-1:end)=0;
```

Figure 5.5 *The second part of the code which controls the simulator.*

1) Code for varying the channel, charge pump current and initial phase error.

2) These are the initial states that concern the simulator. The constant *leakcurrent* sets the constant that generates the frequency drift. The parameter *uppervolt* is set to 2.77 volts and is the upper limit for the output voltage from the loop filter. It is not possible to set the initial state of the loop filter in this model and therefore this simulator does not use the *initialoutput*. *KVCO* is the connection between input voltage and output frequency from the VCO. A difference of one volt means a difference of 100 MHz. *Wfr* is the constant, which together with the regulating voltage

from the loop filter gives the middle of the frequency range when the output voltage from the loop filter is 1.385 volt. *period1* is the period time of the reference wave, in this case corresponding to 500 kHz. *kstart* is the time when the simulator starts to modulate. In the present module the charge pump current is set to zero simultaneously with the start of the modulation. In this case the *kstart* stands for both but this can be changed in square 5. *time0* is the start time and *time1* is the finish time. *kanal* is the required channel but can be set in another way in square 1. *storpumpstrom* is the charge pump current when the radio is not modulating and *litenpumpstrom* is the current when the radio is modulating. In the present module the phase locked loop is open during modulation and therefore *litenpumpstrom* is set to zero. *anbit* sets how much data that will be transmited. *delta* is the initial phase error. *delta* is not used in this model either.

3) The values of the capacitors and the resistors are set here. *A* to *D* are the constants, which the Laplace function in the loop filter consists of. The Laplace function that compensates for the corruption of the modulating data in square 7 in Fig. 5.1 consists of the *Af* to *Df* constants. This function also needs *Pf*, which is the value of the set *litenpumpstrom*, *KVCOf* and *N*. The other variables help to simulate differences in the given values.

4) This section controls the channel shifts.

5) The current of the charge pump is controlled here.

6) Random data is generated here. The rand-command can theoretically give a sequence of 2^1492 values before repeating it selves. When the real module modulates data there is almost an equal number of ones and zeros in the modulated slots. This code does not create a sequence of equal number of ones and zeros but just a random sequence. To create more reliable data further studies of the asymmetric data is necessary.

7) Values and initial states of the Simulink model are set. In this case the Simulink model “TEST” is going to be run.

```
k=kstart;
p=0;
for n=2:antbit;
   k=k+1;
   tidm(n+p)=k;
   tidm(n+p+1)=k;
   p=p+1;
end
tidm(1)=kstart;
tidm=tidm'*1e-6;
tidm(end+1)=time1;
konst = 160e-5;
konst = 0;
m_varden= m_varden'*konst;
```

```
%x0=[2*pi*delta;0;0;initialoutput;initialoutput;initialoutput];
%x0=[2*pi*delta;initialoutput;initialoutput;initialoutput;0;0];
x0=[];
simoptions=simset('AbsTol',1e-12,'RelTol',1e-12,'InitialState',x0);
tic
sim('TEST',[time0 time1],simoptions)
toc
```

7

8

```
figure(1)
plot(time,(freq-2.4e9)*1e-6+diffkanal,color)
hold on
axis([0 time(end) kanal-120 kanal+120])
plot([0 time(end)],(kanal-0.16)*[1 1],'r')
plot([0 time(end)],(kanal+0.16)*[1 1],'r')
plot([0 time(end)],(kanal-0.02)*[1 1],'r')
plot([0 time(end)],(kanal+0.02)*[1 1],'r')
plot([0 time(end)],(kanal+0.18)*[1 1],'g')
plot([0 time(end)],(kanal-0.18)*[1 1],'g')
plot([0 time(end)],(kanal)*[1 1],'r')
%grid
zoom on



maxvolt=max(bob.signals.values)
```

Figure 5.6 *The third part of the code which controls the simulator.*

8) The Matlab figure 1 is the frequency plot. Red lines on +/- 160 kHz and +/- 20 kHz from the red channel frequency are going to be plotted. Two green lines on +/- 180 kHz from the channel frequency are going to be plotted as well (fig 6.4). *maxvolt* gives the maximum output voltage from the loop filter. Figure 2 illustrates the same output voltage. Figure 3 is a plot over the phase error. This plot belongs to the other model with the approximated phase detector, which will be described later. Figure 4 illustrates the output from the charge pump.

```
figure(2)
plot(bob.time,bob.signals.values)
axis([time0 2e-4 -4 4])
hold on
zoom on
%grid

figure(3)
plot(time,fas,color)
hold on
zoom on
%grid

%figure(4)
%plot(time,pump1)
%hold on
%zoom on
%grid
%end

%spread
```

Figure 5.7 *The fourth part of the code, which controls the simulator.*

5.3 DESCRIPTION OF THE SIMULATOR WITH THE APPROXIMATED PHASE DETECTOR

I am just going to describe the differences between the simulator in Fig.5.1 and the simulator with the approximated phase detector in Fig. 5.8. Therefore only the squares 1,2,3 and 10 are going to be described.

1) The difference in frequency between the regulated wave and the reference wave is calculated here. *u[1]/u[2]* gives the divided frequency and the other part gives the frequency of the reference wave. If the frequency of the controlled wave is bigger than the reference wave then the output from *VCO* becomes positive and if the reference wave is bigger the output will be negative. Despite the name, this part is not the VCO in the real module. This Simulink model is more a kind of a logical model than the other model in Fig. 5.1. Squares 10,1,2 and 3 are all together a logical approximation of the VCO-tank, divider, phase detector and the charge pump, respectively.

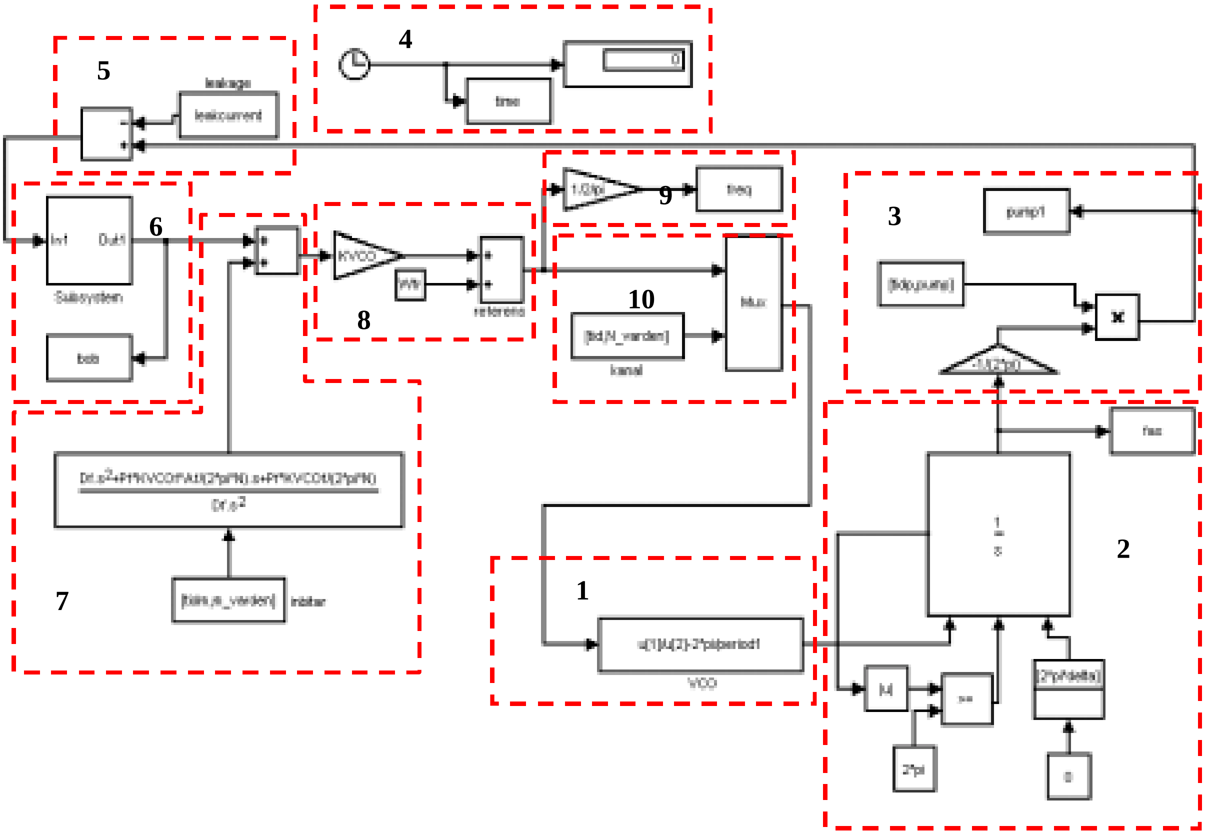


Figure 5.8 *The Simulink model with the approximated phase detector.*

2) The difference in frequency is integrated here. Described in words the input frequency difference becomes a contribution to the phase error, which consists of previous frequency differences. *Delta* is the initial phase error. This input is set to *2*pi*delta* when the time is zero but becomes zero after that. The zero value on this input does not effect the integrator before the input in the middle becomes 1 and that happens when the integrator exceeds or becomes equal to +/- 2π. What we get is the slip that the real phase detector has. Actually this slip only happens when the initial phase error is really big. *fas* stores the phase values to the workspace and can be seen as a plot (Matlab figure 3).

3) The approximation in this model is that the output from the charge pump is continuos. That means that the regulating current into the loop filter is continuos instead of discrete pulses. In the long run no differences between the two models will be seen but short time effects will be seen as spikes in the plot. This effect is a result of the short time dynamics. If the phase is positive this means that the regulated wave's positive slop comes before the reference wave's slop and therefore the charge pump current has to be negative so that the loop filter reduce the frequency. In the opposite case the charge pump current will be positive. Because of the

continuos regulation the output from the integrator has to be divided by 2π.

10) The value of the current frequency gets the first place in the vector that is created by *Mux*. The divider will have the second place where the N-value belonging to the required frequency is placed. The vector is labeld u. Observe square 1.

5.4 SIMULATOR WITH EXACT REALIZATION OF THE LOOP FILTER

Figure 5.9 below illustrates the subsystem of a Simulink model implemented with capacitances and resistances. To create this model access to another program is necessary, which is power system blockset toolbox. With this subsystem there are possibilities to change initial values of the loop filter, i.e. initial frequency. The saturation voltage is measured on the input and therefore a more realistic model is created. There are also possibilities to understand the dynamics in the loop filter. Measurements can be done everywhere in the loop filter.

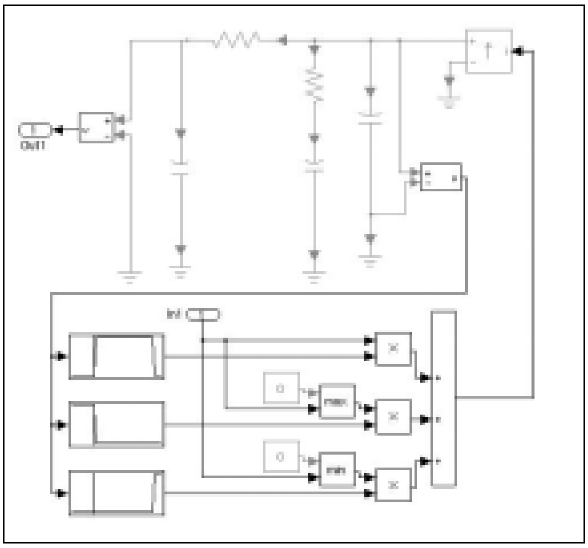


Figure 5.9 *The Simulink model for the loop filter subsystem built with resistors and capacitors.*

5.5 THE LOOP FILTER

The loop filter is of great importance to the frequency regulator. The properties of the filter are sensitive for variations in the capacitances and resistances. The Laplace function of the filter is derived below.

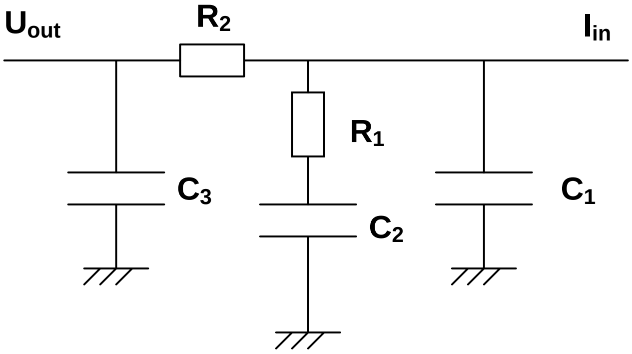


Figure 5.10 *The loop filter.*

This is the loop filter, which consists of three capacitors and two resistors.

$$\frac{1}{Z} = sC_1 + \frac{1}{R_1 + \frac{1}{sC_2}} + \frac{1}{R_2 + \frac{1}{sC_3}}, \qquad (3)$$

where is Z the total impedance of the loop filter.

$$U_{in}(s) = Z(s) I_{in}(s) \qquad (4)$$

$$U_{out}(s) = \frac{\frac{1}{sC_3}}{\frac{1}{sC_3} + R_2} U_{in}(s) \qquad (5)$$

$$H(s) = \frac{U_{out}(s)}{I_{in}(s)} = \frac{1}{1 + sR_2C_3} \cdot \frac{1}{sC_1 + \frac{1}{R_1 + \frac{1}{sC_2}} + \frac{1}{R_2 + \frac{1}{sC_3}}} \qquad (6)$$

$$H(s) = \frac{sR_1C_2 + 1}{s^3 R_1R_2C_1C_2C_3 + s^2\left(R_2C_2C_3 + R_1C_2C_3 + R_1C_1C_2 + R_2C_1C_3\right) + s\left(C_1 + C_2 + C_3\right)} \qquad (7)$$

$$H(s) = \frac{As + 1}{Bs^3 + Cs^2 + Ds} \qquad (8)$$

5.6 THE COMPENSATING LAPLACE FUNCTION

In square 7 in fig. 5.1 and 5.8 you can find the Laplace function, which compensates for the corruption of the transmitting data that will arise when it goes through the regulator. The function is derived below.

If the regulator is active during modulation of the data in form of +/-160 kHz the frequency difference will be observed as a phase error. The regulator wants to eliminate the phase difference and the corrupted data is a fact. This effect will cause oscillations of the centre frequency.

To prevent this effect the modulating signal could be filtered before it is fed into the VCO to compensate for the regulation. This means that the data is modified in an opposite way before it goes through the regulator. The required transfer function, denoted H_f, is derived below.

This Laplace function is only active when the radio is transmitting data and that means that P and N can be observed as constants. The charge pump current does not change during the modulation.

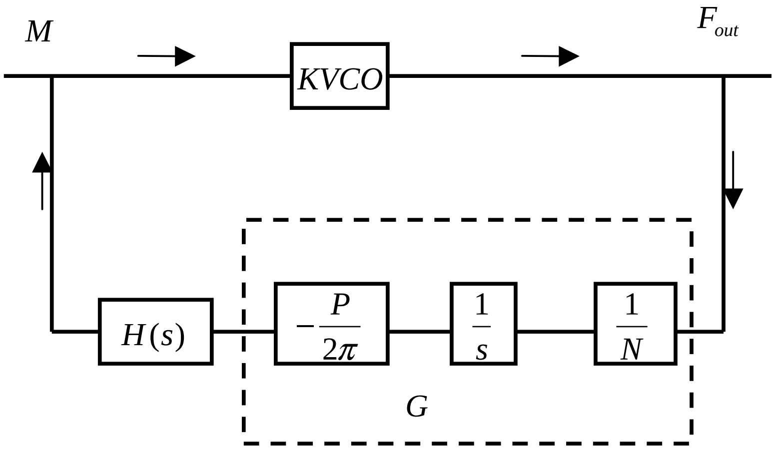


Figure 5.11 *A high level description of the regulator.*

$$G = -\frac{P}{2\pi}\frac{1}{N}\frac{1}{s} \tag{9}$$

$$H = \frac{As+1}{Bs^3+Cs^2+Ds} \tag{10}$$

$$\left(M + F_{out}GH\right)\cdot KVCO = F_{out} \tag{11}$$

$$F_{out} = \frac{KVCO}{1-G\cdot H\cdot KVCO}M \tag{12}$$

$$F_{out}^{ideal} = KVCO \cdot M \tag{13}$$

The relation 12 should be like relation 13 to be free from corruption, therefore we multiply the M signal with H_f which is the compensating Laplace function that the M signal should go through.

$$H_f = 1 - G \cdot H \cdot KVCO \tag{14}$$

$$H_f = \frac{Bs^4 + Cs^3 + Ds^2 + \frac{P \cdot KVCO}{2\pi N}(As+1)}{Bs^4 + Cs^3 + Ds^2} \tag{15}$$

Eq. 15 can be approximated to a second order function

$$H_f = \frac{Ds^2 + \frac{P \cdot KVCO}{2\pi N}(As+1)}{Ds^2} \tag{16}$$

$$H_f = \frac{s^2 + A_{fr}s + B_{fr}}{s^2}. \tag{17}$$

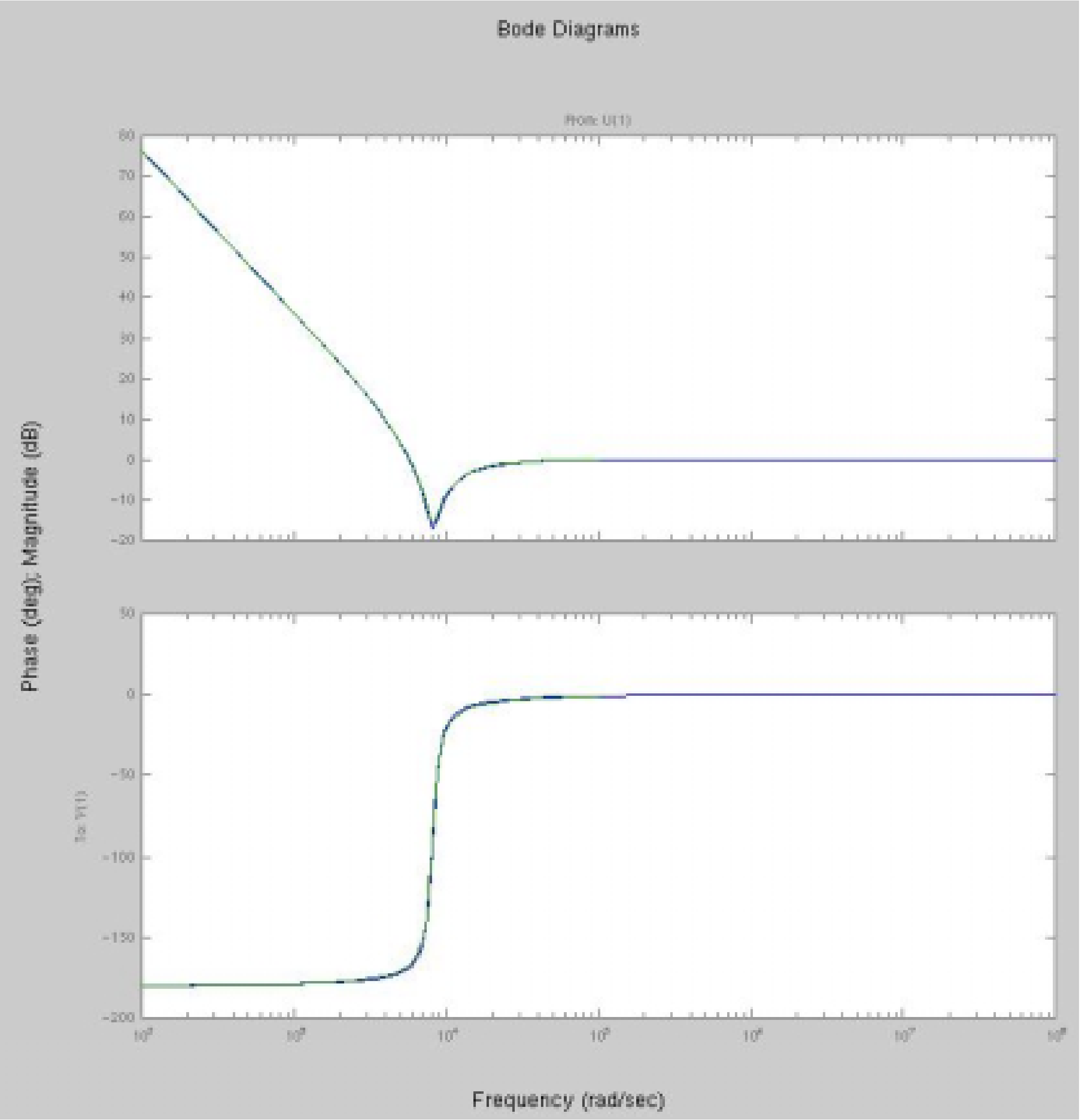


Figure 5.12 *Bode diagram of the original and the approximated Laplace function.*

The Bode diagram illustrates the approximated function (Eq. 16) with a green curve and the original function (Eq. 15) with a blue curve. There is almost no difference at all. That means that a function of second degree is good enough. The contributions of the third and fourth degree are small and effect the dynamics little. The approximated function seems not able to handle frequencies exceeding 10^5 rad/sec. This is not a problem though. The high frequencies over 10^5 rad/sec do not need to be reinforced or to be phase shifted. The original function is in high frequencies close to zero for both phase and magnitude. Besides that it is the slow dynamic that interests us.

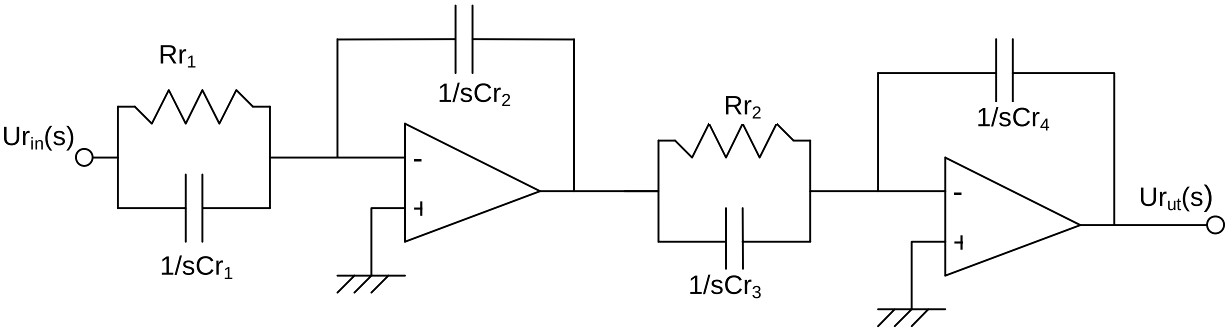


Figure 5.13 *Physical realisation of Eq. 16.*

$$Hfr(s) = \frac{Ur_{out}(s)}{Ur_{in}(s)} = \frac{(sRr_1Cr_1 + 1)(sRr_2Cr_3 + 1)}{s^2 Rr_1Cr_2Rr_2Cr_4} \tag{18}$$

$$Hfr(s) = \frac{s^2\left(\frac{Cr_1Cr_3}{Cr_2Cr_4}\right) + s\frac{(Rr_1Cr_1 + Rr_2Cr_3)}{Rr_1Rr_2Cr_2Cr_4} + \frac{1}{Rr_1Rr_2Cr_2Cr_4}}{s^2} \tag{19}$$

$$Hfr = Hf \tag{20}$$

The values have to be chosen so the relations below are accomplished.

$$Cr_1Cr_3 = Cr_2Cr_4 \neq 0 \tag{21}$$

$$A_{fr} = \frac{P \cdot KVCO}{2\pi \cdot N}\frac{A}{D} = \frac{Rr_1Cr_1 + Rr_2Cr_3}{Rr_1Rr_2Cr_2Cr_4} \tag{22}$$

$$B_{fr} = \frac{P \cdot KVCO}{2\pi \cdot N \cdot D} = \frac{1}{Rr_1Rr_2Cr_2Cr_4}, \tag{23}$$

where N should be set to 4882. This is the middle channel. P is the charge pump current during the modulation. The constants A and D come from Eq. 8 and 9. All values are written in the code.

6 SIMULATIONS

6.1 SIMULATOR BEHAVIOUR

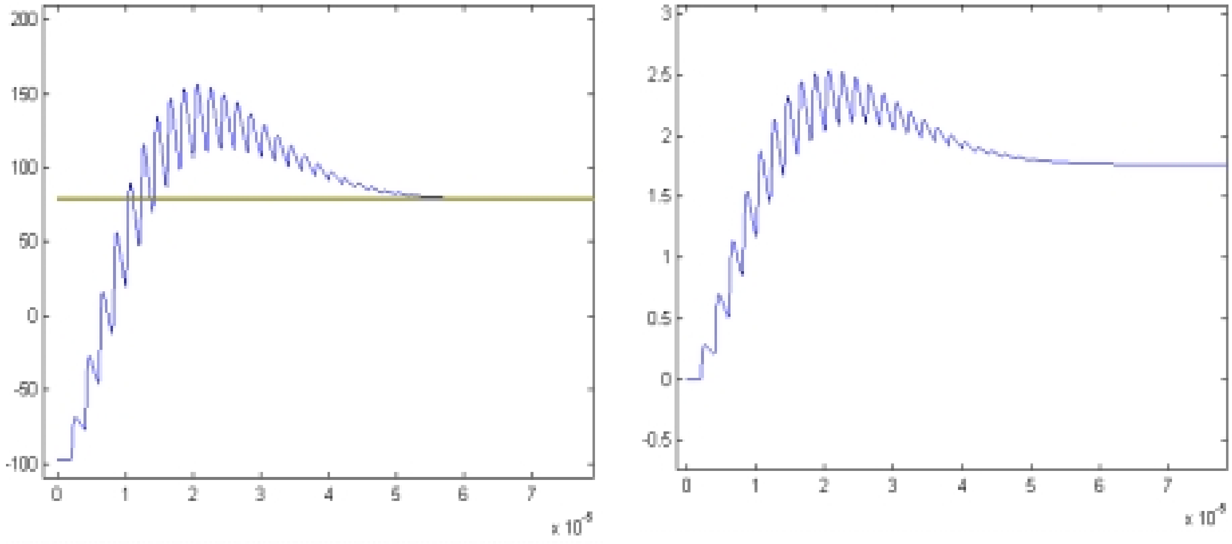


Figure 6.1 *The frequency as a function of time (a) and the output voltage from loop filter (b).*

The pictures above illustrate the frequency and the output voltage from the loop filter as a function of time for the simulator illustrated in Fig. 5.1. The only thing that separates these two plots is a constant, which is KVCO. The output voltage multiplies with KVCO and becomes the frequency. What we see in the plot is the first part of the procedure that the radio has to go through to transmit data. Just before SYNT_ON is set high the registers have been set. The simulator will in this case aim at channel 79. SYNT_ON is set high when time is zero in the plots.

The frequency when the SYNT_ON is set high is 97.5 MHz below 2 GHz (-97.5). That depends on the initial values of the capacitors, which we only are able to set with the subsystem described in Fig. 5.9. The initial output from the loop filter will always be zero volt for the simulators without that subsystem.

$$F_{initial} = channel - KVCO \cdot \frac{uppervolt}{2} \tag{24}$$

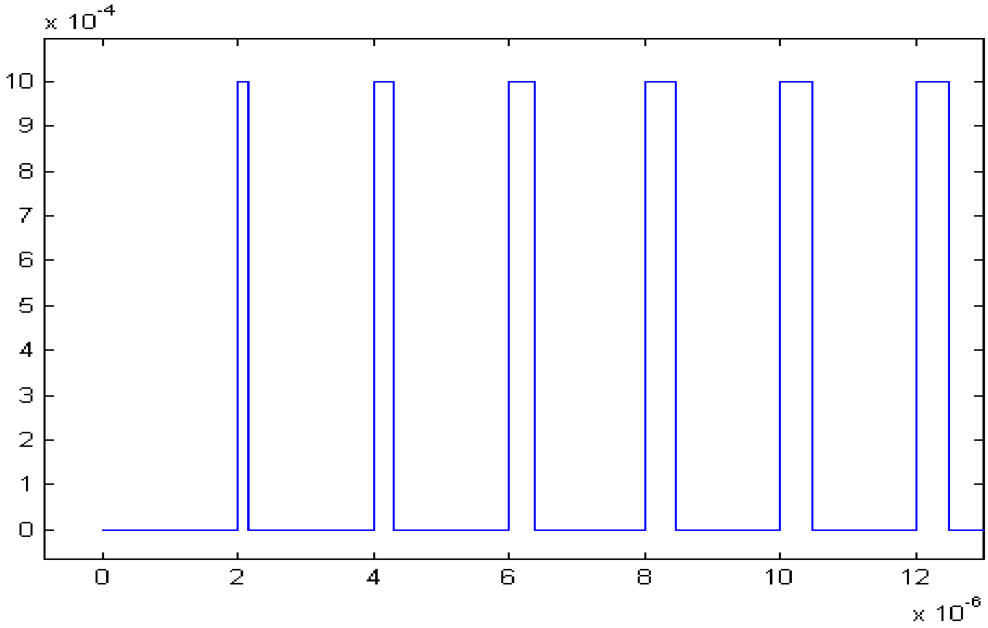


Figure 6.2 *The output from the charge pump*

The spikes in the plots depend on the dynamic effects in the loop filter. When a pulse from the charge pump, shown in Fig. 6.2, reaches the input of the loop filter the loop filter experiences a step with amplitude of 1000 µA. The first capacitor in the loop filter (C_1) is charged and the voltage grows almost linearly with time. During the rest of the 2 µs before the next current pulse comes then stored charge in C1 is to some degree redistributed to C_2 and C_3. How quickly the charges will redistribute is determined by the time constants of the RC-networks. R_2C_3 has a very short time constant compared to R_1C_2 and the output voltage will almost follow the voltage on C_1 during the current pulse. That means that the voltage over C_3 varies with the current pulses. This results in the frequency spikes found in Fig. 4.5 and Fig. 6.1.

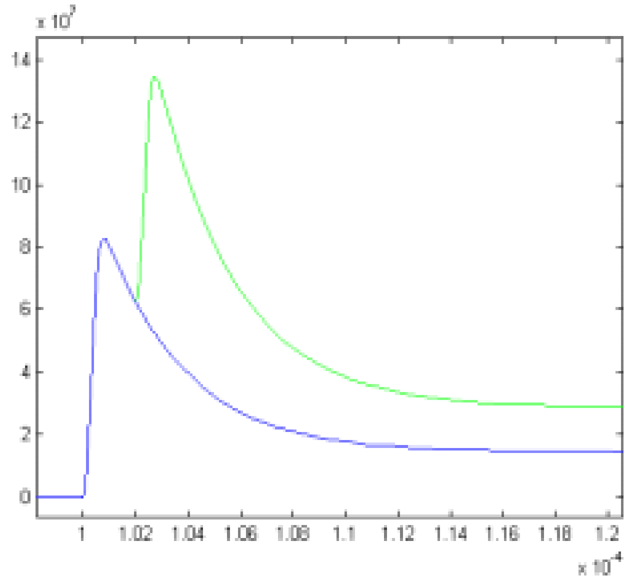


Figure 6.3 *The response of the filter for one and two short current pulses.*

Figure 6.3 illustrates the response of the loop filter for one and two pulses from the charge pump. The blue plot is from one single pulse with an amplitude of 1 mA and a width of 0.45 µs. After 20 µs the transient effect of the pulse is negligible. The output voltage has settled down and the charge in the pulse has been distributed among the capacitors so that they all have got the same voltage. The equilibrium is reached. This time constant is independent on the pulse length. The green plot shows the response of the next pulse with the same width and amplitude as the first. Figure 6.3 shows that the loop filter does not have time to settle down before the next pulse is coming but that the final effect is twice the first. The continuous approximation of the phase detector is then a good approximation.

The short time effects are pretty obvious but the long time dynamics are much more complicated to anticipate. Therefore the phase detector and the charge pump may very well be approximated so that the current pulses out from the charge pump become continuous. The other Simulink model does that and only the long time effect is simulated.

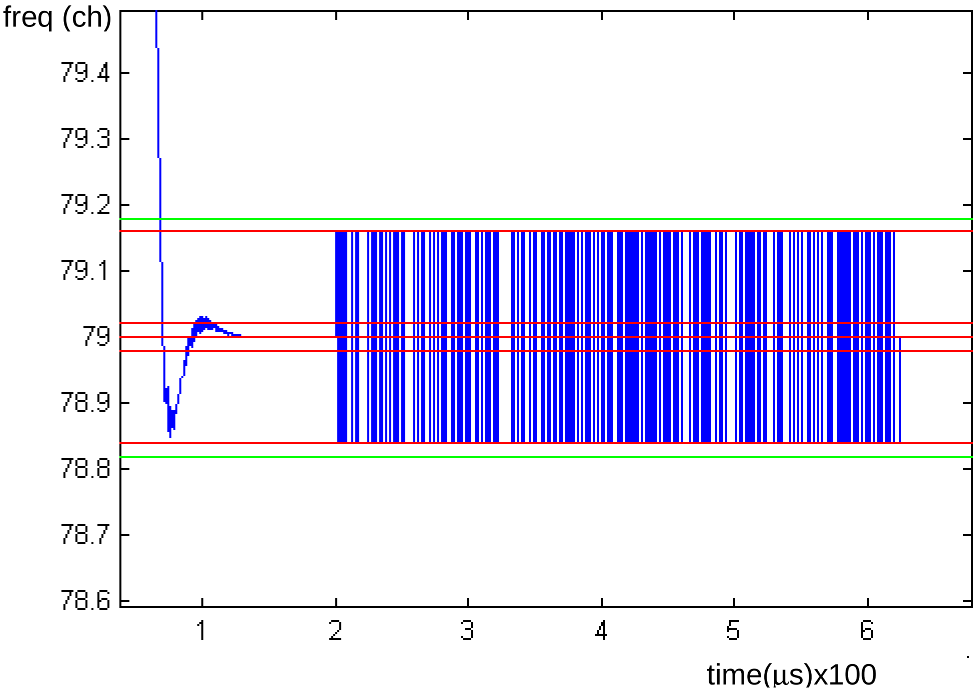


Figure 6.4 *The modulation sequence from the simulator in Fig. 5.1.*

Figure 6.4 illustrates the modulation sequence where the radio starts to transmit data after 200 µs. This simulation is an ideal case of the real module, which never exists. There is no leakage current, no initial phase error and no other disturbing factors. If this always would be the case then there would not be a problem. The modulation is good and there is no drift. But with the disturbing factors in mind the thing is different. Figure 6.4 can be compared to the measurements of Fig. 4.6.

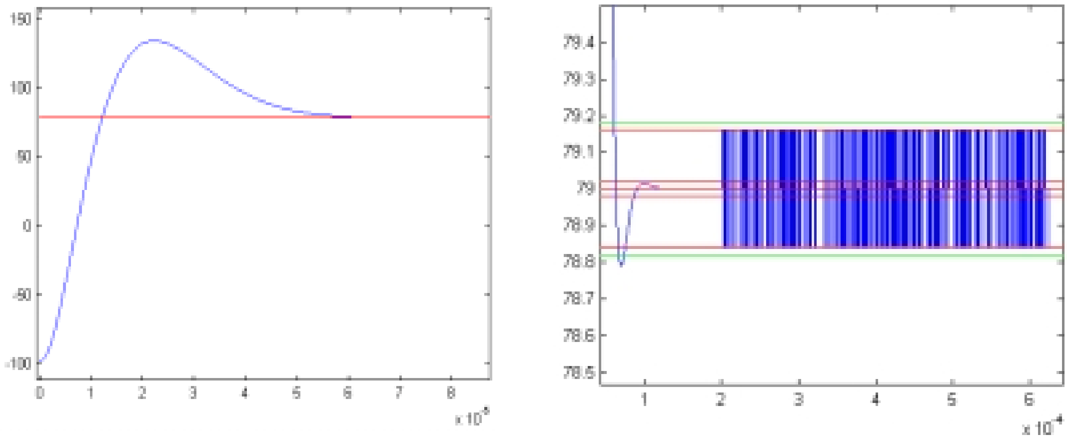


Figure 6.5 *Frequency plots from the simulator in Fig. 5.8. These plots are two different views of the same sequence. (a) illustrates the first 90µs after SYNT_ON has been set high and (b) the modulating part. Observe the continuous dynamic, i.e. there are no spikes. Compare with fig. 6.4.*

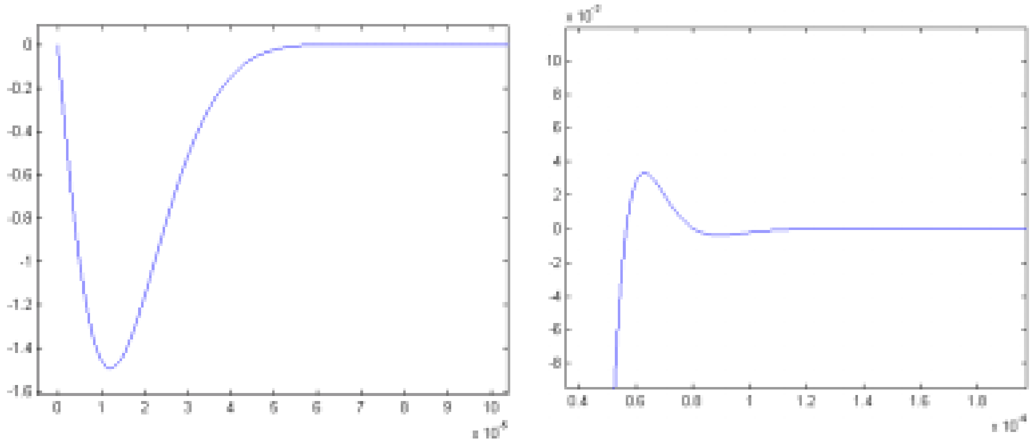


Figure 6.6 *The phase error in the phase detector as a function of time from the simulator in Fig. 5.8. These two plots are two different views as well. (b) illustrates the phase error when the regulator has settled down which hardly can be observed in (a). (a) illustrates the first 50µs well and (b) the remaining part of the sequence.*

A disturbing effect is the turn on of the PA by setting TX_ON high. This effect is not simulated but should be smaller than 500 kHz and occurs about 104 µs before PHD_OFF is set high. The regulator should have settled down.

The initial phase error in Fig. 6.6 is zero. When the phase error increases the charge into the loop filter increases because of the wider pulses. Here the pulses are approximated to continuous regulation.

The maximum and minimum phase error coincides with the times when the derivative of the frequency is zero. When the regulated frequency is below the required channel frequency the phase error will grow negative and the positive pulses from the charge pump will be wider until the frequency tangents the channel frequency. There is no simple way to understand how the phase effects the frequency. The relation between the current frequency and the variation of the phase error is easy to understand but the complicated dynamics in the loop filter makes the relation between phase error and frequency difficult to predict. It is for example not necessary for the phase error to change sign to cause a changed direction of the frequency regulation. That means that the minimum and maximum of the frequency does not need to coincide with the zero places of the phase error.

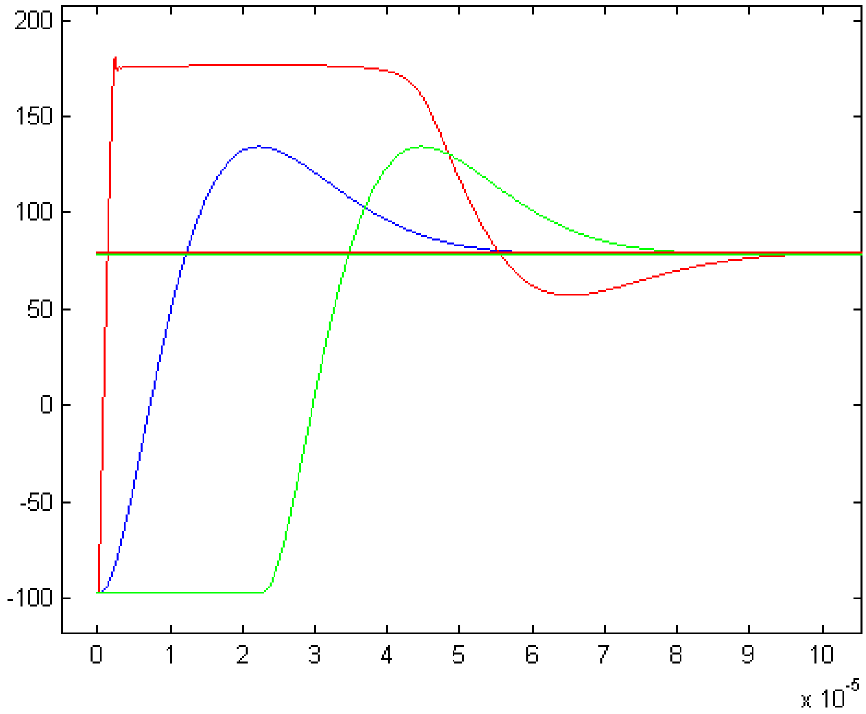


Figure 6.7 *Frequency versus time with initial phase error; delta=0.8 (green line), delta=-0.8 (red line) and the blue line without initial frequency error. delta is the value of the phase error and is represented in the square 2 in Fig. 5.4. delta*2π gives the initial phase error in radians. This is the frequency output from the simulator in Fig. 5.8.*

If the initial phase error is negative the initial output from the charge pump will be positive. That means that the phase detector begins with regulation in the right direction but in this case with an initial phase error of -1.6π (red line) and therefore the initial regulation will be far too big. In a very short time a lot of charge enters the loop filter and this results in that the input voltage of the loop filter exceeds the limit of 2.77 volt. Actually this simulink model measures the voltage on the output but the result will be almost the same as if the voltage is measured on the input. When the input voltage is over 2.77 V the charge pump stops to deliver charge. The frequency is kept at its maximum. This can be seen as saturation in Fig. 6.7. The loop filter settles down and waits for the phase error to change sign and after that, negative pulses caused by positive phase error are generated and the regulation towards the required channel can proceed.

The green line shows the frequency plot when the initial phase error is set to 1.6π. Observe that the initial output from the loop filter is zero volt and stands for the lowest possible frequency. In the beginning, the positive phase error should generate negative charge pulses into the loop filter. But because of the initial zero output from the loop filter the charge pump can not generate charge. The loop filter is saturated and has to wait for the phase to become negative. The straight green line in the beginning illustrates the saturation caused by the low limit. The length of the straight section depends on how long it takes for the frequency difference between the reference wave and the regulated wave to generate the initial phase difference. If the initial channel frequency had been higher the corresponding section had been started with a fast drop in frequency down to the saturation limit. The regulation process is very fast and therefore the big initial phase error leads to heavy over regulation.

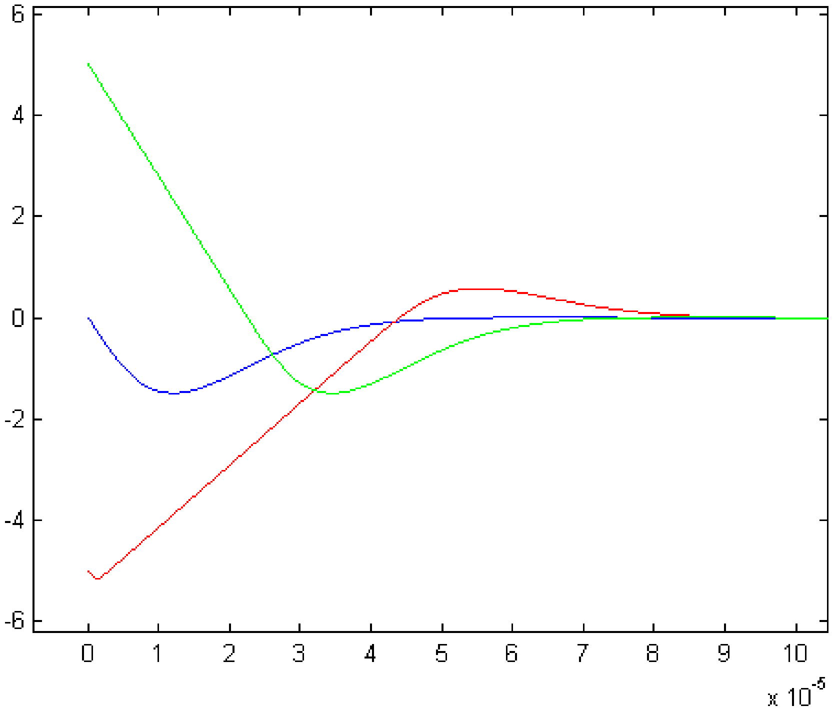


Figure 6.8 *The phase error.*

The little hook in the beginning of the red curve in Fig. 6.8 is a result of the initial negative frequency difference. Before the heavy positive regulation has effected the frequency the already big initial phase difference becomes even bigger. This will always happen if the initial output of the loop filter is below the required frequency channel and if the phase error is negative. The same thing will happen but in opposite direction if the initial output from the loop filter is above the required and the initial phase error is positive. The straight parts in the figure are the wait parts in the frequency plot. The phase error varies with a constant rate, which depends on the magnitude of the frequency difference during that section.

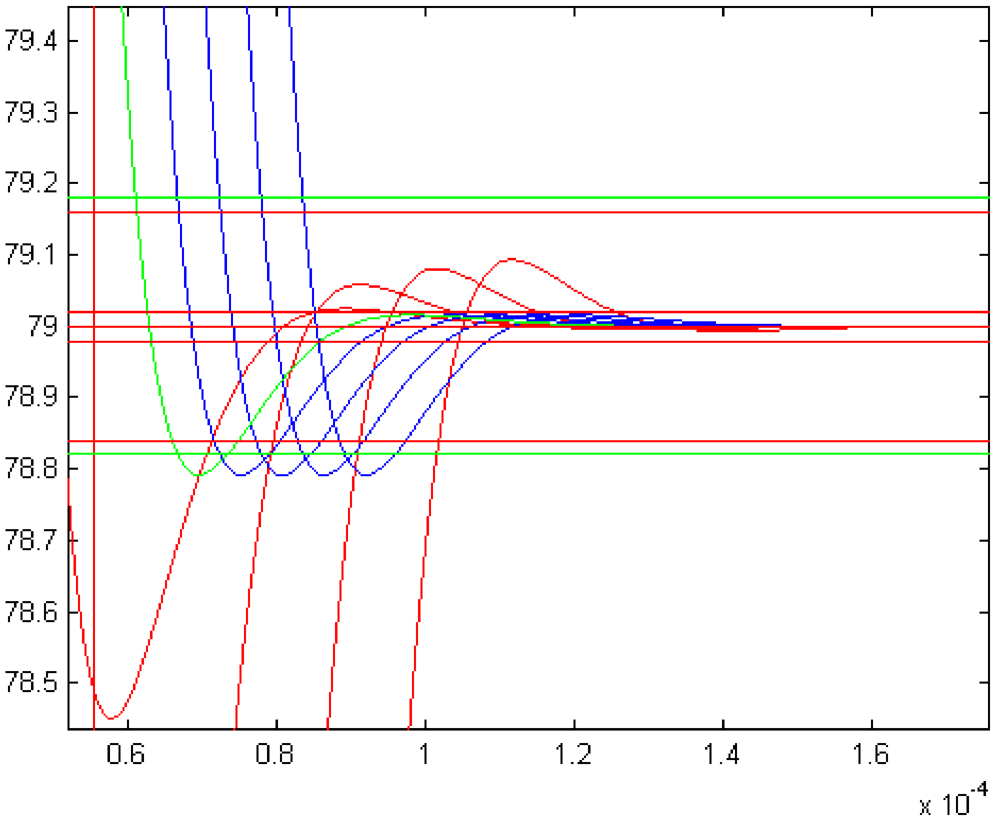


Figure 6.9 *Illustration of the lock in process for signals with different initial phase errors. The red lines in the middle are at a distance of 20 kHz from the 79:th channel. From an application perspective, the frequency can be regarded as locked when the frequency is within +/-25 kHz of the final frequency. In the real module the values of the capacitors vary quite much so the simulation of one collection of values is hardly representative for the properties of the module.*

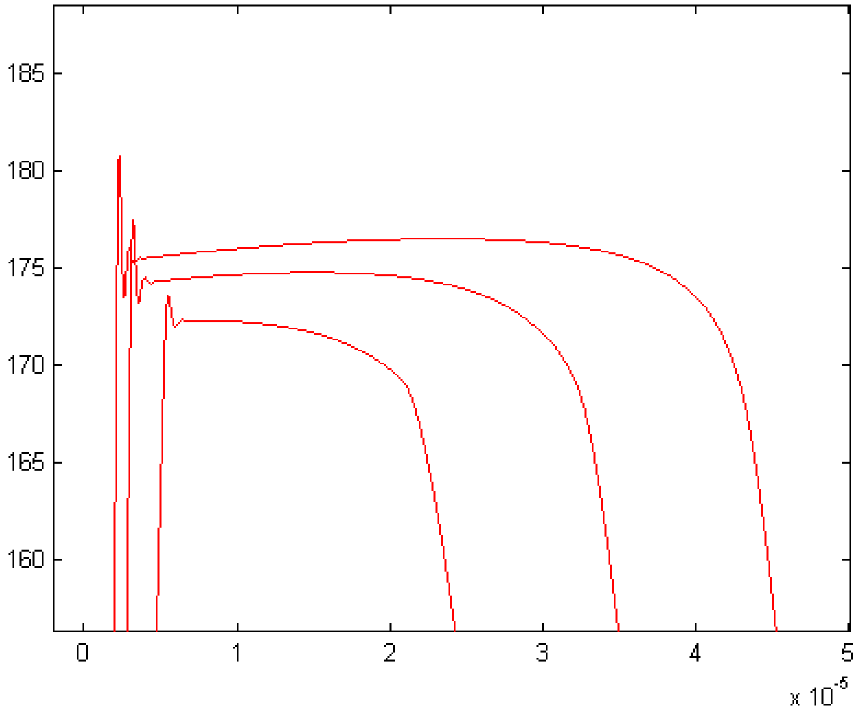


Figure 6.10 *Saturation output voltage of the loop filter for different initial phase errors as a function of time. The plot illustrates the output of the loop filter that is the output from fig. 5.3 when the voltage over the first capacitor exceeds 2.77 volt.*

Figure 6.10 illustrates the saturation section of the signals with a negative initial phase error. Observe that the amplitude is not equivalent despite the fact that the saturation limit is the same. The reason for this is that the representation of the limiting demand in the Simulink model is created so that the charge input into the loop filter decreases constantly from 1 mA to 0 mA during 2.67 to 2.77 V of the loopfilter output. The result of this is that the signal with the biggest charge input in the decreasing part will bring the most charge into the loop filter and cause the highest output voltage when the system settled down. So then the signal with the largest initial phase error and consequently the heaviest regulation obviously has to be the signal with the highest saturation level.

6.2 FREQUENCY DRIFT AND THE NEW POTENTIAL SOLUTION

If the real module had worked just like the simulations, which have been shown, then there would not have been any problems. The carrier would be locked before the modulation starts and the centre frequency would not drift away when the phase locked loop is opened. This is not the case though. In some cases the frequency drift could be too large and be outside the Bluetooth specification. The investigated potential solution to this problem is to keep the charge pump active all through the modulation but with a more gentle regulation. That means that the charge pump will give less charge into the loop filter. The regulation will be slower and because of the no more opened loop, initial conditions like the initial phase and frequency error create new matters of concern. The new properties of the module will put heavier demands on the initial conditions.

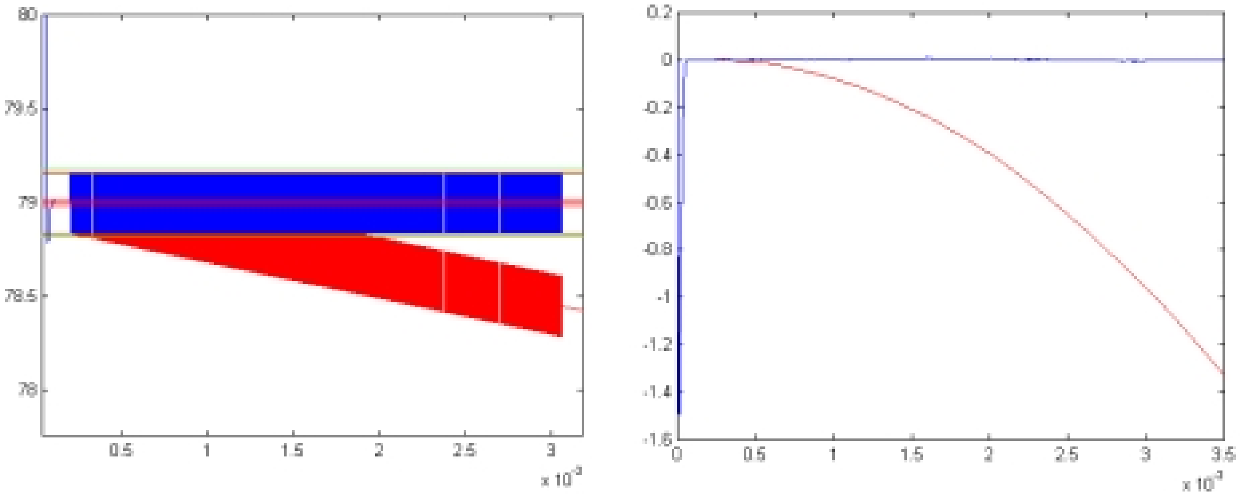


Figure 6.11 *Frequency drift (a) and phase error (b) for both an ideal device and one with drift caused by a constant current leakage.*

The plots in Fig. 6.11 above illustrate a simulated frequency drift compared to the ideal case. It is a very bad case when the drift is about 600 kHz during 3 ms. The drift is simulated as a constant leakage current. Another, more common and therefore also more serious effect in the real module is the memory effect in the loop filter. The memory effect causes a large initial drift rate that then decays with time. The total drift due to the memory effect in a 5-slot packet is less than 150 kHz even for the worst samples, see Fig. 4.7. The magnitude and the exact behaviour of these effects vary from device to device. The constant leakage current of 600 kHz is a good and likely somewhat pessimistic approximation. If the regulation is able to handle this then it is probably strong enough to manage other drift behaviours as well.

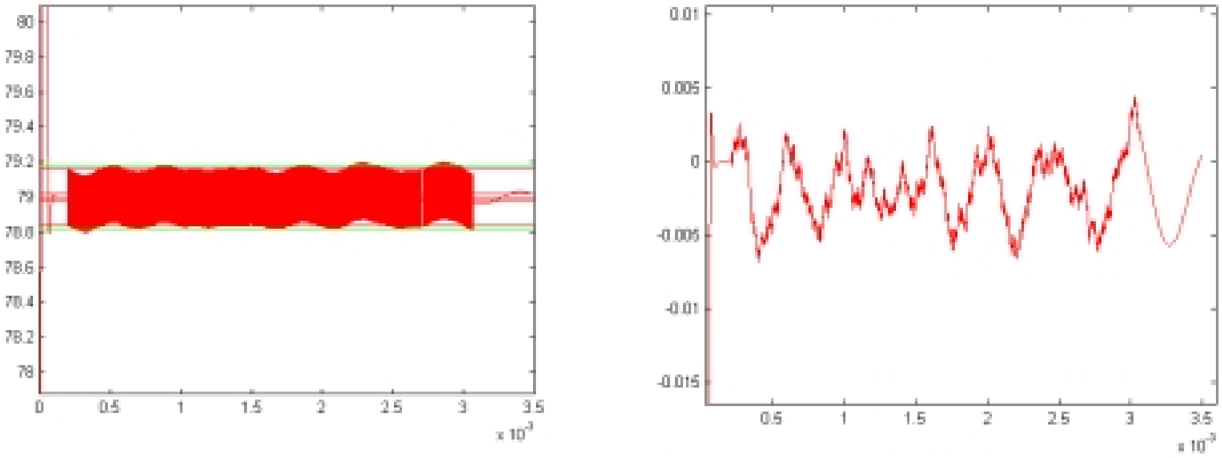


Figure 6.12 *Frequency (a) and phase error (b) with active charge pump. The two plots illustrate the frequency oscillation that occurs when the charge pump is active during the modulation.*

Figure 6.12 above illustrates the modulation part when the charge pump is kept active. No compensating function is used. In the first place the result seems to be a lot worse compared to the case with the open loop. It is obvious that this result never can be accepted, but the advantage of this solution is that if we get rid of the oscillations the regulation will correct all kinds of long time disturbances during the modulation. The present module will always be vulnerable to imperfections. Maybe the leakage current in the loop filter changes magnitude and behaviour when the radio has been used for a while. The technology in the present module is not able to handle these kinds of differences but the new one can be.

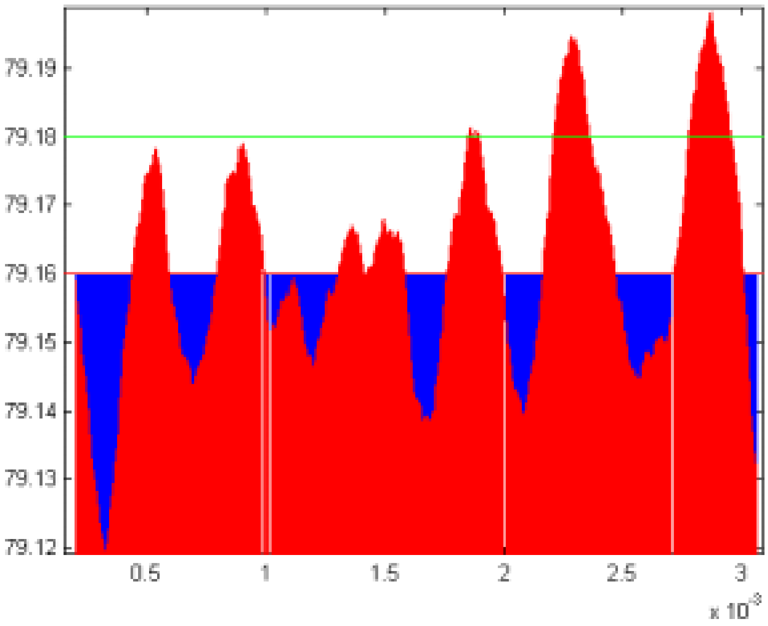


Figure 6.13 *Detailed view of the modulation with active charge pump. The red curve is the same modulating sequence as 6.12 and the blue is an ideal sequence.*

The charge pump current is 20µA during the data modulation. Changes of the charge pump current will result in faster regulation with higher current and slower regulation with lower current. With higher charge pump current the magnitude of the oscillation also will be smaller. The disadvantage of a too heavy regulation caused by a too high charge pump current is that the regulator will respond too fast and too much to the short time differences in the frequency, which are the modulated data. A too heavy regulation will therefore result in big disturbing effects of the transmitting data. Even if the Laplace function 16 compensates for the data the disturbing effects will occur. This is because the function is an approximation of the Laplace function 15 but also because the function 15 is calculated with the continuous approximation of the phase detector. The pulses from the charge pump will result in frequency spikes despite of the compensating function. The magnitude of the spikes grows with the charge pump current. It is the positive long time effects, which an active charge pump will bring that interest us. The magnitude of the charge pump is therefore a matter of priority. The regulator should be fast enough to prevent the oscillation without disturbing the modulated data. In the simulations I found 20µA to be a good value to satisfy the demands of the radio.

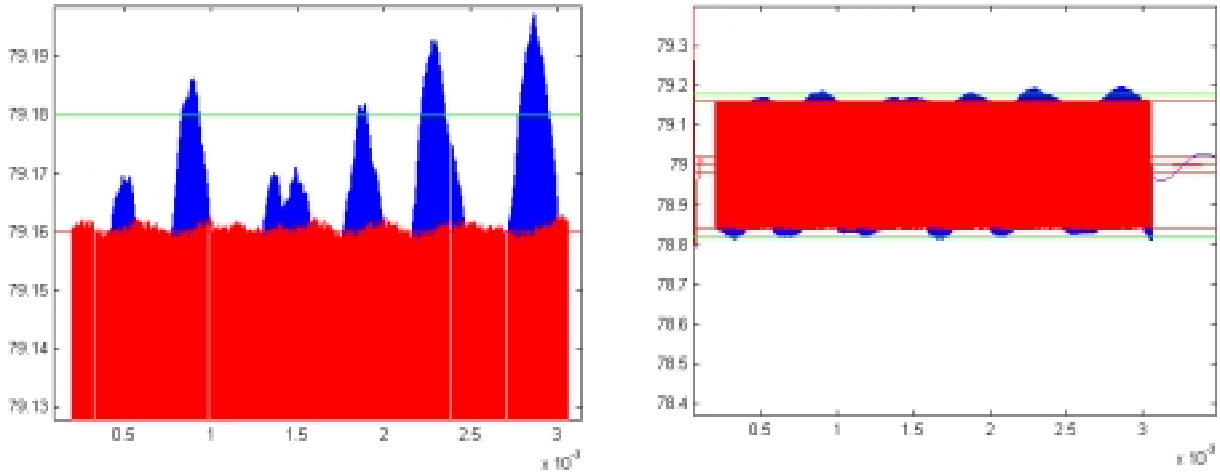


Figure 6.14 *The effect of Laplace function 16. The red plot is the modulation sequence with the Laplace function and the blue plot is the one without.*

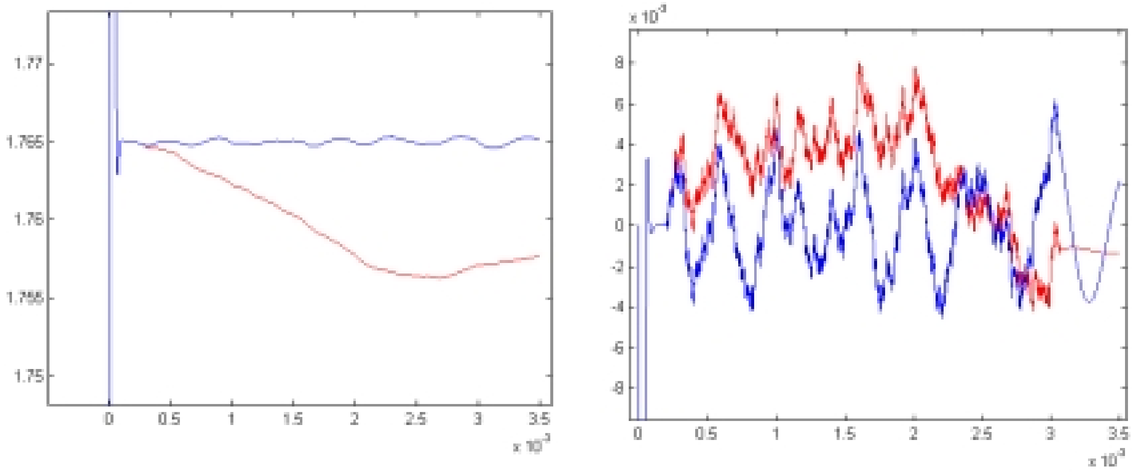


Figure 6.15 *Output voltage from the loop filter (a) and phase error (b).*

The oscillation can be thought of as consisting of two main parts. One part caused by the initial phase error when the current of the charge pump momentarily changes from 1000 µA to 20 µA and another part caused by the asymmetric data. The initial frequency error is not a problem as long as it is small. The frequency does not effect the regulation in any fast way. The frequency error effects the regulation more in an indirect way through the phase error. The problem with the asymmetric data is solved with the Laplace function 16, but the problem with the initial phase error has not yet been solved.

Figures 6.14 and 6.15 above illustrate the difference between the outputs from the regulator using the Laplace function 16 (red line) and the present module without (blue line). The simulation is done with no leakage current to show the effect clearly. Therefore these plots do not include the oscillating part caused by the initial phase error. The function compensates almost completely, which means that the problem with asymmetric data is solved.

At the end of the frequency plot 6.14 after the modulating sequence the final frequency oscillation caused by the asymmetric data is showed. At the end of the plot in figure 6.15 (b) the same thing is illustrated but in form of the phase error. Figure 6.15 (a) and (b) show both how the Laplace-function helps the regulator to compensate for the modulation. The red line in Fig. 6.15 (a) seems to be strange but observe that this output will be mixed with the output from the Laplace function. The result will be the same as for the frequency plot but with a constant difference.

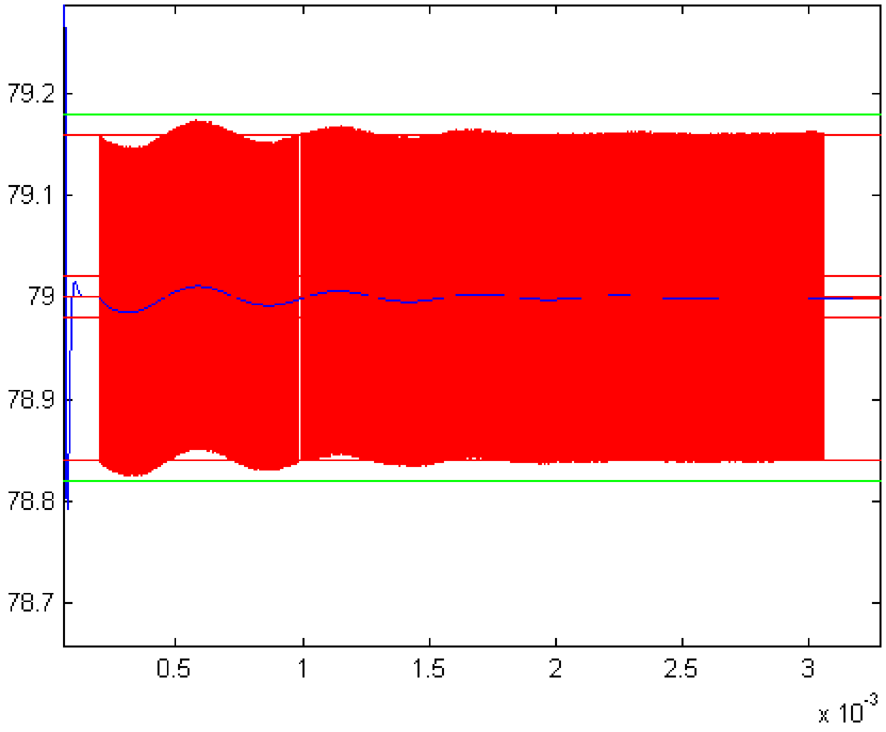


Figure 6.16 *Frequency plot with leakage current without the contribution from the asymmetric data.*

In Fig. 6.16 the red plot is the frequency output from a simulation where data is modulated. The blue line is the same simulation but without modulation. Both simulations have a large leakage current that causes the oscillation. If there had been a difference besides the modulation it would be a contribution from the asymmetric data. That is not the case though, which means that the Laplace function 16 works well. This plot then isolates the contribution from the initial phase error as well.

Accordingly the problem left is the problem with the initial phase error. This problem occurs when the phase error is not zero when the charge pump current is changed. This can be caused by leakage currents or memory effects in the loop filter. The major idea of an active charge pump is to compensate for imperfections so if there is no phase error this new idea would not be of interest to us in the first place. So then the oscillating effect due to the initial phase error has to be within the frequency drift limits.

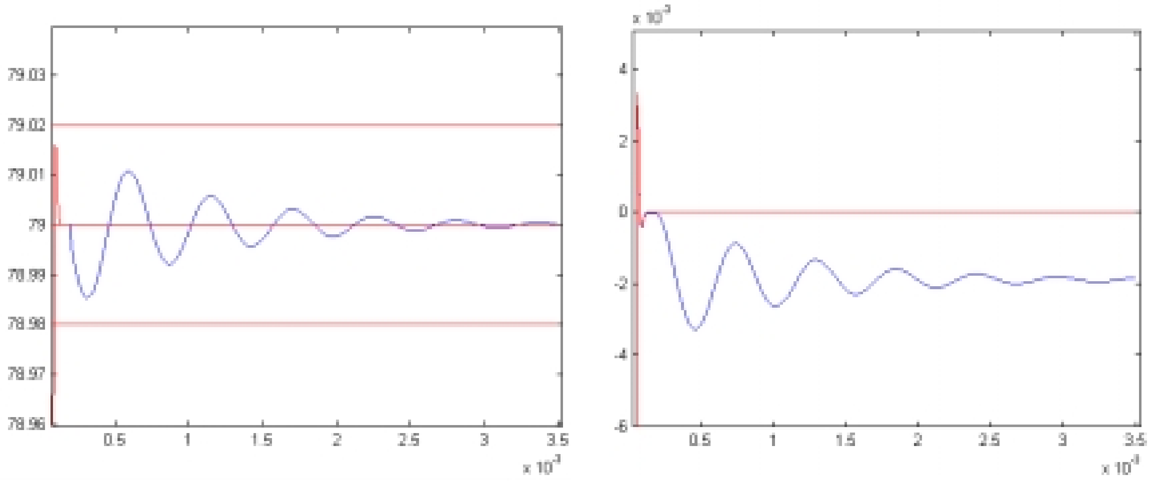


Figure 6.17 *Frequency oscillations (a) and phase error oscillations (b) caused by initial phase error.*

Figure 6.17 (a) illustrates the frequency oscillation caused by an initial phase error, which occurs when charge is leaking. The effect is pretty great but is settling down because of the still regulating charge pump. The charge pump is despite of that far too weak to correct the oscillation. Higher charge pump current would give this problem a decreased effect but has to be compared to the disadvantage of the disturbing effect on the transmitting data that is a result of a faster regulation. Figure 6.17 (b) shows the same phenomena but in form of the phase error.

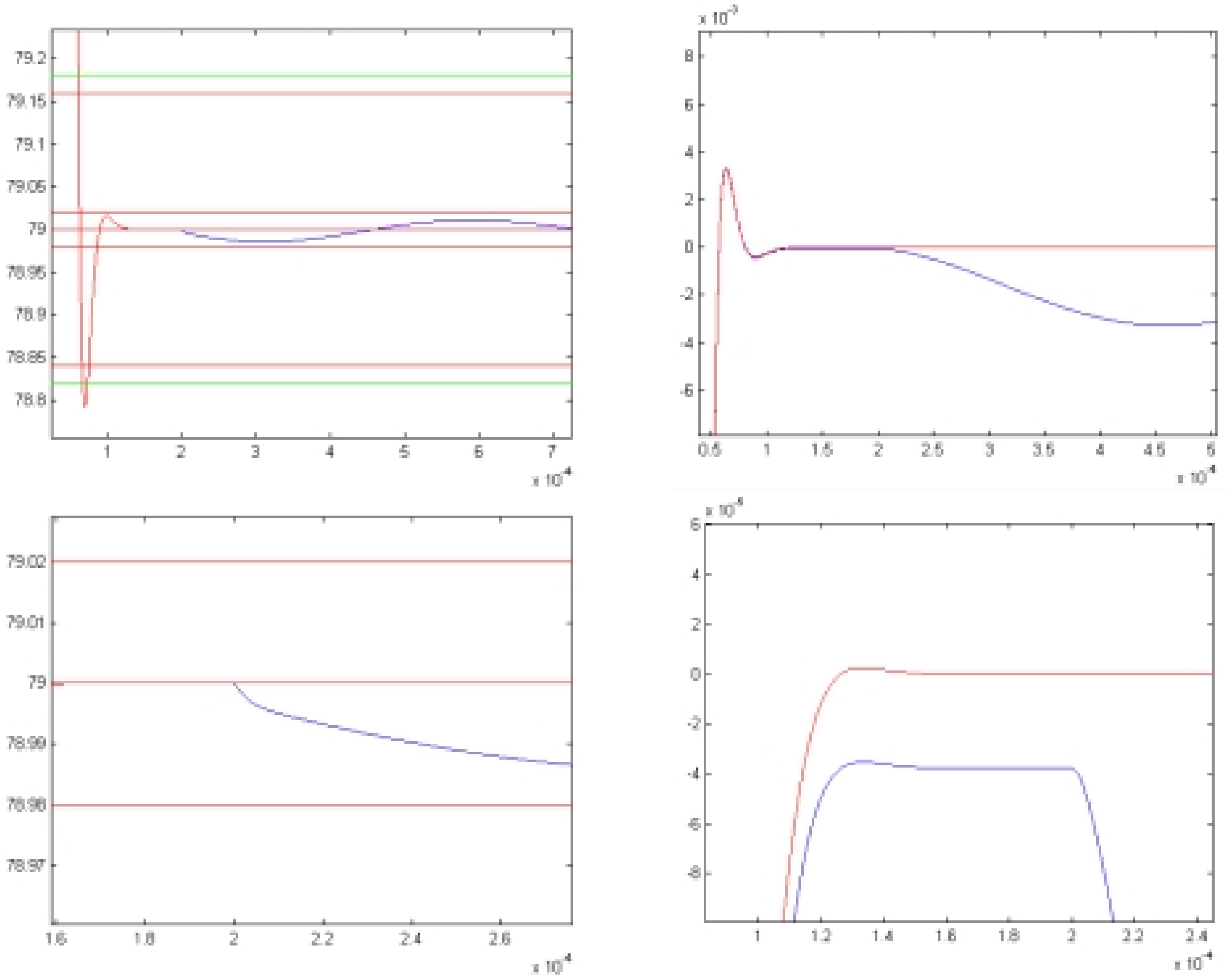


Figure 6.18 *A plot of the frequency oscillation (a) caused by initial phase error without modulation. Plot (b) shows the phase error. A detailed view of the frequency drop is found in (c). The difference in phase error with (blue curve) and without (red curve) leakage currents is shown in (d).*

Figure 6.18 (a) illustrates the effect of the leakage currents. Figure 6.18 (d) shows the difference in magnitude of the initial phase error. Observe that the difference is quite small. The conclusion of that is that a small phase error causes a large reaction.

To compensate for the leakage currents the charge pump always has to generate charge into the loop filter. Otherwise the frequency would drift away from the required channel just like in the present module. This means that if the leakage is constant a constant phase error occurs, which can be seen in Fig. 6.17 and 6.18. This constant charge injection into the loop filter suddenly decreases when the charge pump current goes from 1000 µA to, in this case, 20 µA. This sudden decrease in regulation generates a negative step answer from the loop filter if the initial regulation is positive, and a positive step answer if the initial regulation is negative. After that a new equilibrium has to take place.

A thought could be to make this change over more continuous but simulations show that the change in current has to be very slow and that means that the change consumes more time than what is available. Oscillations caused by small leaks can be prevented with this idea but not the ones of this order.

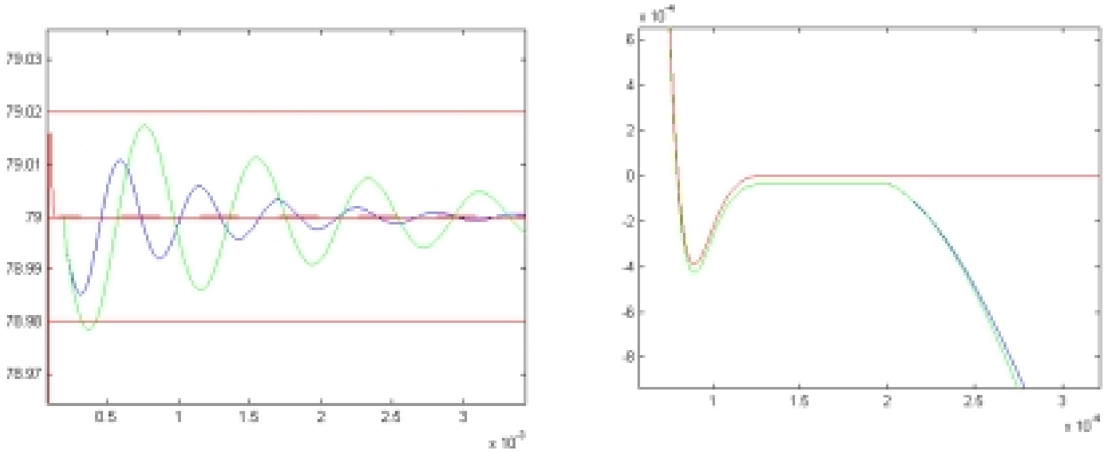


Figure 6.19 *Frequency oscillation with different charge pump currents (a) and the phase error (b).*

Figure 6.19 above illustrates the oscillation when the charge pump is 10 µA (green curve) and 20 µA (blue curve) during the modulation. The 20 µA regulation has better properties in this point of view but both are within the limits of +/-25 kHz. The red lines are +/-20 kHz from the 79:th channel. The red curve is without initial phase error.

All together the simulations says that the whole problem is solved if the Laplace-function 16 is implemented but to be sure further studies of the real module have to be done. We know about the problem of the initial phase error but we do not have a solution of it. Perhaps there are additional factors that make the oscillation exceed the limits. Frequency noise a few multiples lower than the required frequency can be a problem.

7 MEASUREMENTS ON THE NEW TYPE OF MODULE

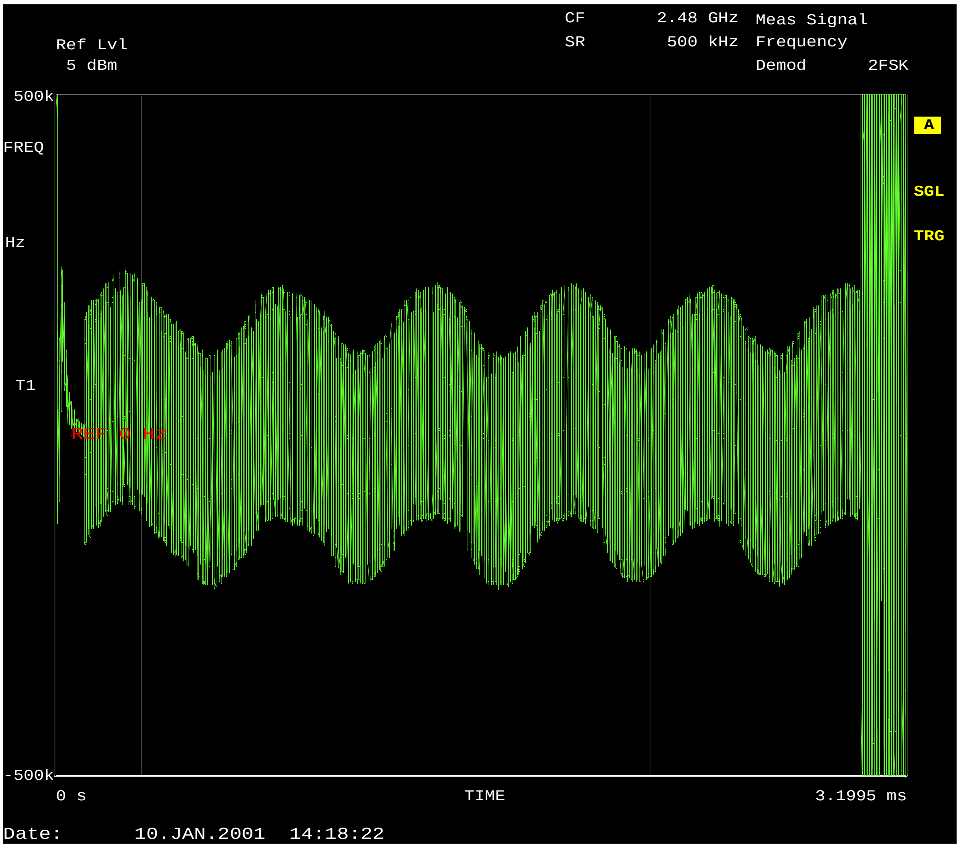


Figure 7.1 *Oscillations in the new type of module without implementation of the Laplace function. The transmitted data is a PN9 sequence. The oscillation is caused by the locally asymmetrical data. These results should be compared to Fig. 6.12 (a).*

Figure 7.1 illustrates the oscillations that occurs in the new kind of module when the charge pump is 20 µA during the modulation. This module lacks the realisation of the Laplace function 16. The function would compensate for the contribution of the asymmetric data of the transmitted pseudo random bit sequence (PN9). That means that the highest number of ones or zeros in a row is nine. The amplitude of the frequency oscillation is around 50 kHz.

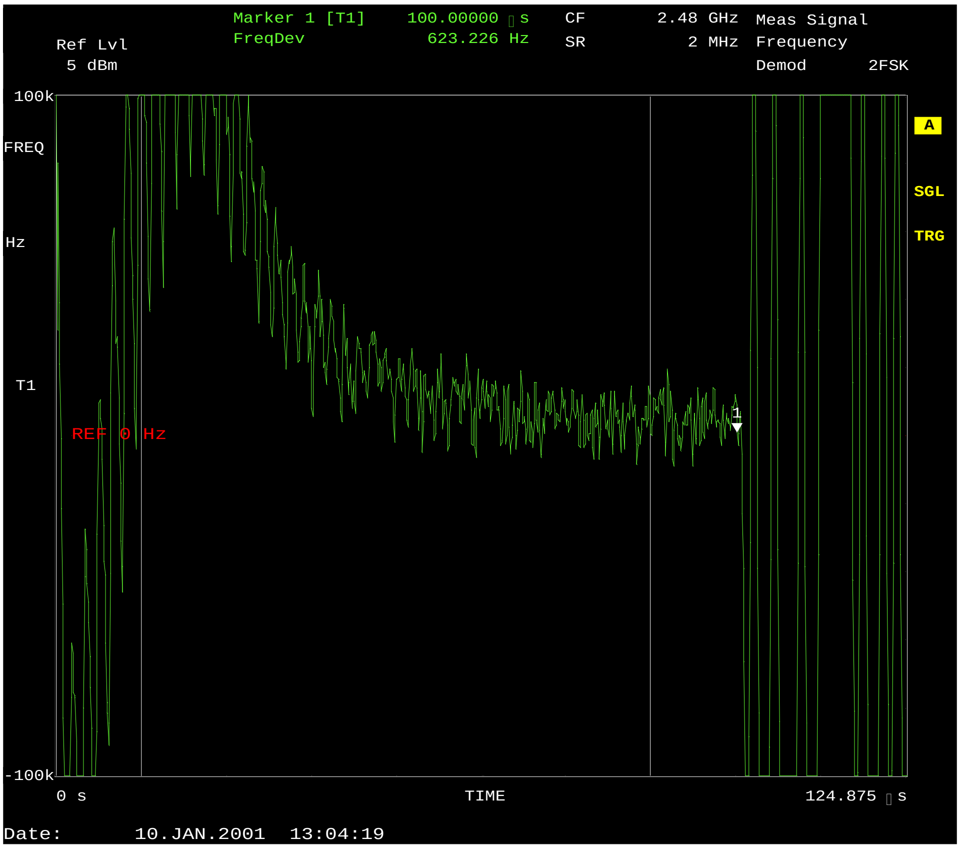


Figure 7.2 *The lock in process.*

Figure 7.2 above illustrates the lock-in process of the carrier. It seems that the frequency has not settled down and reached the required channel completely. It is now obvious that the phase error is the thing that really interests us. But it is hard to say much about the phase error when just the frequency is available.

This signal also contains high frequency noise, which probably not effects the phase error. The only noise that effects the phase error is noise at frequencies a few multiples lower than the frequency of the modulating data. This noise has a wavelength, which is long enough to effect the phase error. To be sure about this, simulations with different kinds of noise should be performed.

Oscillation in the new type of model that exceeds the frequency limits must additionally to the contribution of leaking currents be caused by either frequency noise or that the phase error not completely has settled down. If the phase error not has had time to settle down the phase error could be reduced by beginning the modulation later. However, the timing does not allow for other than marginal adjustments. The same effect could be achieved by increasing the reference frequency. It could be changed from 500 kHz to 1 MHz without compromising anything else. Simulations show that a higher reference frequency will have positive effects on saturation times as well. Accordingly, a changed reference frequency seems to be an improvement.

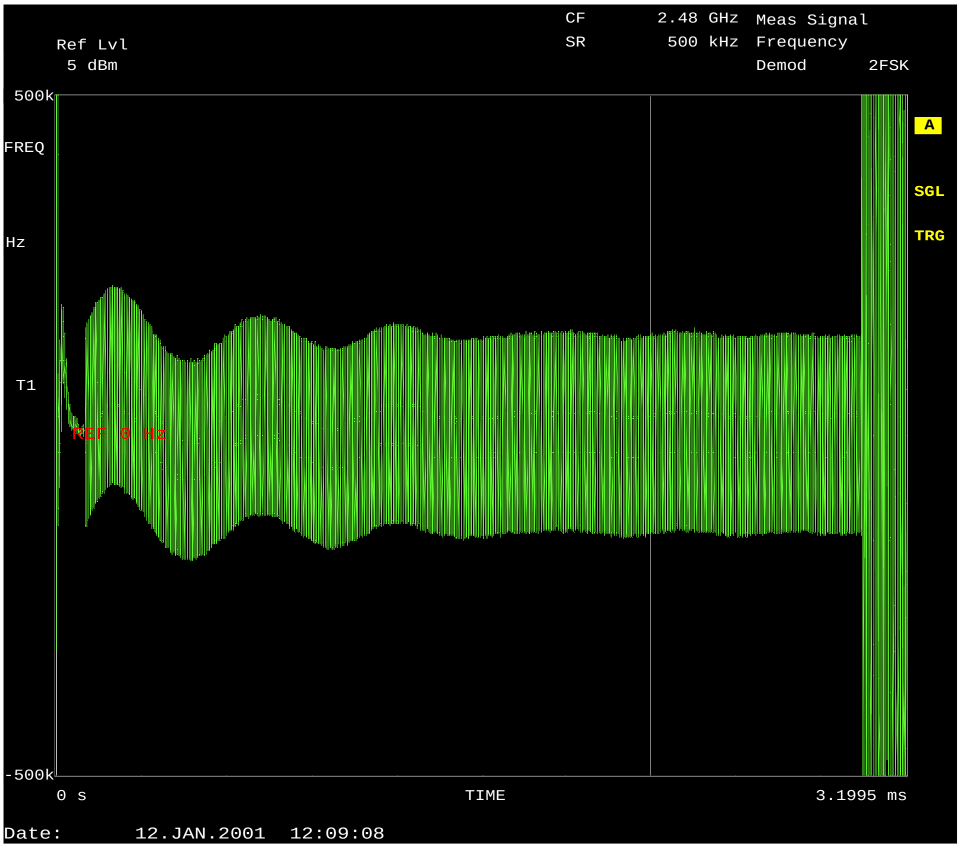


Figure 7.3 *Oscillations in the new type of module without implementation of the Laplace function. The transmitted data is a 1010 sequence. Hence, these oscillations are caused by the initial phase error.*

In Fig. 7.3 the modulated sequence consists of 1010 and therefore the modulation can be observed as a test with an active Laplace function (Eq. 16). The oscillation shown is then an effect of the initial phase error only, just like the simulation of Fig. 7.16.

It is something interesting with these measurements though. First of all the magnitude of the oscillations are pretty big compared to what simulations show. That could likely be explained by incorrect values in the simulator. It is harder to explain that the oscillations start in positive direction. If the memory effect has a negative slope or the leakage currents are negative the slope of the oscillation should start negative. The knowledge about the memory effect says that it is negative in this case when the channel hops from 2 to 80. The leakage currents can be of any sign depending on their origin, but they can be neglected for the measurements in Fig 7.3. Assuming that it is the initial phase error that causes the oscillation, it has to be a result of either noise or that the phase error not completely has settled down. If the reason for this oscillation had been noise the slope had been randomly positive and negative. That is not the case. The conclusion of all is that the main reason for this oscillation has to be insufficient settling time. The oscillation will be dramatically reduced if the regulator gets the required time to settle down. With sufficient time to settle the problem could be solved and the new idea become a solution of the frequency drift problem. To be completely sure tests where the modulating part starts later have to be done.

8 FURTHER STUDIES

These Simulink models can be improved in many ways. The values in the Simulink model maybe not completely accord to the real ones in the module. To get the real values further studies and more measurements have to be done. That kind of work will improve the model but I am not sure it will be worth it. Actually, the present models are good enough to give opportunities to draw the important conclusions.

More important would be to investigate if the oscillation that occurs in Fig. 6.3 depends on insufficient settling time. The test system has to be designed so that the modulating sequence can be able to start later. Then the issue could be definitely settled. I think that these measures will result in good news for the new idea of a frequency regulator.

After that new decisions about what to do can be made. The frequency drift problem was the main reason for this new idea of frequency regulation. If the frequency drift can be reduced with a differently designed loop filter both the original problem with frequency drift and the present problem with oscillation will be smaller. To do this, a good model of the memory effects in the loop filter has to be derived and more simulations have to be done. The oscillations will then probably stay within the limits.

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