DCF77 Phase Decoder and Clock

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January 30, 2024

Abstract

I describe my project "Radio control clock using phase modulation DCF77 signal". I write a little about time and then hardware and software of the clock. Phase decoder is based on Steve Marchant[9] project but moved to a Nucleo[11] board.

Contents

Glossary

ADC analog-to-digital converter (ADC, A/D, or A-to-D) is a system that converts an analog signal, into a digital signal. 6

AGC automatic gain control. 6

carrier base frequency of a transmitter. 2, 3, 6

chips bits that extra modulate carierr frequency, called so to avoid confusing them with message bits. 3

coax coaxial cable is a type of electrical cable consisting of an inner conductor surrounded by a concentric conducting shield, with the two separated by a dielectric (insulating material); many coaxial cables also have a protective outer sheath or jacket.. 6

DCF77 it is name of a German longwave time signal and standard-frequency radio station. 1–3, 5

PLL a phase-locked loop or phase lock loop is a control system that generates an output signal whose phase is related to the phase of an input signal. The signal adjusting the oscillator to keep the phases matched. 6

PPS a pulse per second (PPS or 1PPS) is an electrical signal that has a width of less than one second and a sharply rising or abruptly falling edge that accurately repeats once per second. 6

preamp a preamplifier is an electronic amplifier that converts a weak electrical signal into an output signal strong enough to be noise-tolerant and strong enough for further processing, or for sending to a next amplifier. Without this, the final signal would be noisy or distorted. 5, 6

Tx serial transmission of data. 6

Figure 1: The low frequency T-aerial antennas of the continuously operated DCF77 signal in Mainflingen at night.

1 DCF77[1]

Almost all own or have seen advertisement for "atomic" or "radio controlled" clock. They, in our part of Europe, are synchronized by (receive) signal from German radio-station DCF77. The time signal is sent on long waves, on frequency 77.5 kHz from Mainflingen near Frankfurt am Main.

Electronic in these, home clocks, decodes amplitude changes; ideal sketch of such signal shows below (fig 3).

1.1 What information sends

First, before I will try to tell how the time information is sent, I must to tell what is sent: in each second in one minute, DCF77 is sending one bit (zero or one), which correct grouped give values of current minute, hour, day, day of week, month and year.

If we want to send an information via radio waves, we have to change a plain sinus signal (carrier frequency) in step with needed information.

1.2 Aplitude modulation

The DCF77 signal uses amplitude[1]-shift keying to transmit digitally coded time information by reducing the amplitude of the carrier to 15% of normal for 0.1 or 0.2 second at the beginning of each second. A 0.1 second reduction denotes a binary "0"; a 0.2 second reduction denotes a binary "1". As a special case, the last second of every minute is marked with no carrier power reduction.

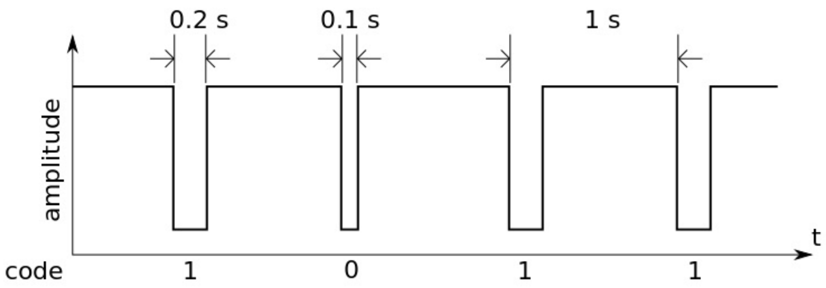

Figure 3: Amplitude modulated signal of DCF77 as a function of time.

This solution is easy to decode, the problem is noise from switched-mode power-supplies, washing machine, MP3 players, computers. There is trade-off between low bandwidth (low noise) and sharpness of the received signal (time precision).

1.3 Phase modulation, better time resolution, better signal to noise ratio

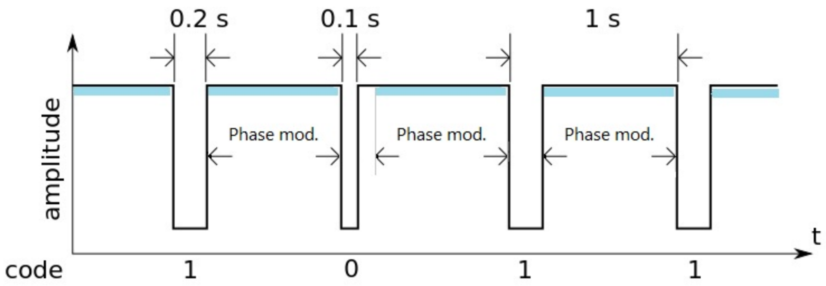

Figure 4: Phase modulation of DCF77.

One uses other, independent kind of modulation, namely *phase modulation.* Interval 0.2 to ca 1.0 second (this interval is not used for amplitude modulering) is phase modulated by 512 long, pseudo-random bit sequence. This sequence is clocked with frequency $77.5\ kHz/120 = 645,8\overline{3}\ Hz$. and is used to modulate the transmitter phase. During 0 chips the carrier is transmitted with a $+13°$ phase advance, while during 1 chips it is transmitted with a $-13°$ phase lag. Detector registers phase changes and try to shift time origin to fit best - expected phase changes with actual (in math language we try to find best correlation).

Our goal is to build receiver-clock that uses this (PM) modulation.

[1]remember that this is amplitude of sinus wave of frequency $77500 Hz$.

2 General about time

Time is a difficult concept to define, Richard Feynman: "Let us consider first what we mean by time. What is time? It would be nice if we could find a good definition of time. Webster defines "a time" as "a period," and the latter as "a time", which doesn't seem to be very useful. Perhaps we should say: "Time is what happens when nothing else happens". Which also doesn't get us very far. Maybe it is just as well if we face the fact that time is one of the things we probably cannot define (in the dictionary sense), and just say that it is what we already know it to be: it is how long we wait!" [2]

Evolution in time measurements – see [3;4].

Is there anything to take care of at all (precise timing), after all most of us need accuracy of the order of a minute (not to be late for a lesson, train or date with a girl/boy friend)? Well, when we look a little further away from the nose or fiancee and we will consider how a GPS [5], common in use system works; let me cite from Wikipedia: "*The GPS concept is based on time and the known position of GPS specialized satellites. The satellites carry very stable atomic clocks that are synchronized with one another and with the ground clocks. Any drift from true time maintained on the ground is corrected daily. In the same manner, the satellite locations are known with great precision. GPS receivers have clocks as well, but they are less stable and less precise.*

GPS satellites continuously transmit data about their current time and position. A GPS receiver monitors multiple satellites and solves equations to determine the precise position of the receiver and its deviation from true time. At a minimum, four satellites must be in view of the receiver for it to compute four unknown quantities (three position coordinates and clock deviation from satellite time)."

Other devices that need accurate time are, for example, radar, television and computers.

There is no such thing as a singular true time derived from natural phenomena, there is no absolutely accurate clock which could be a reference for others clocks. The time reference is the common agreement and actually in use is *Universal Time Coordinated* or, in french, *Temps Universel Coordonné* (UTC). Logically, previous system – GMT was build on astronomic definition of second, UTC – on the definition based on quantum resonance of Cesium atom (approximately one million more accurately).

UTC uses international net of atomic clocks and data from *International Earth Rotation Service* (IERS).

Worlds most accurate optical clock (2014) wouldn't lose or gain one second in the entire age of the Universe [7] (i.e. 13.6 billion years)!

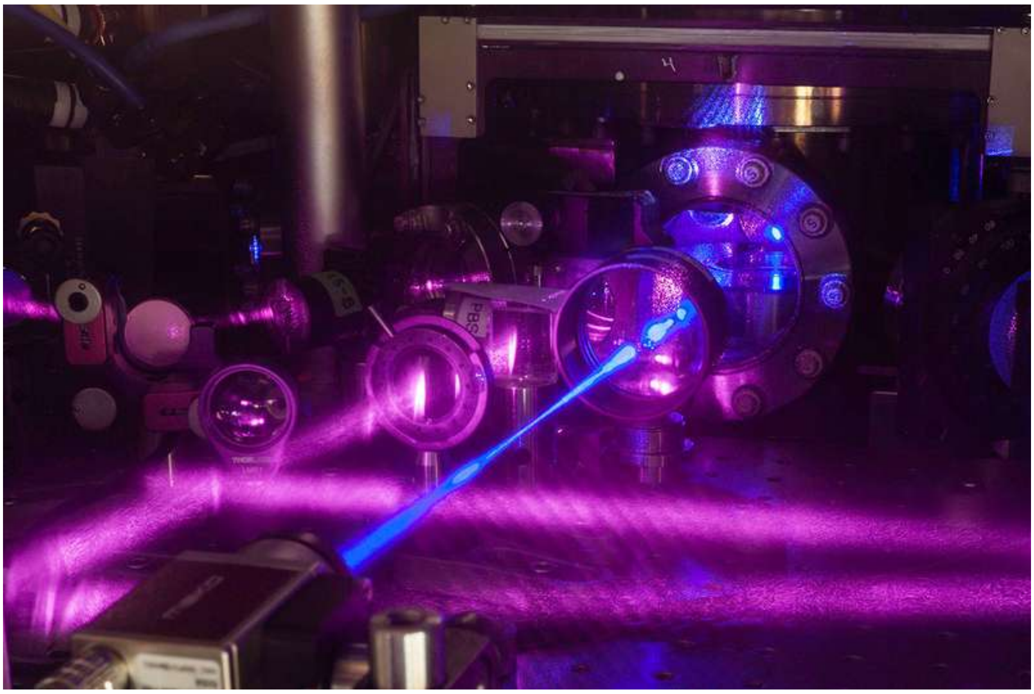

Figure 5: The most precise atomic clock ever made is a cube of quantum gas.

2.1 UTC (Tems Universel Coordonné)[6]

Atomic clock are more accurate than time steamed from astronomical observations, but most of us comes from the Earth and want to have time corresponding to the Earth's rotation around its axis and around the Sun. But the Earth's rotation is irregular, due to the Moon and the oceans. UTC stays within about 1 second of mean solar time at 0° longitude by occasional inserting *leap* second. The number of seconds in a minute is usually 60, but with an occasional leap second, it may be 61 or 59 instead. Thus, in the UTC time scale, the second and all smaller time units (millisecond, microsecond, etc.) are of constant duration, but the minute and all larger time units (hour, day, week, etc.) are of variable duration. Decisions to introduce a leap second are announced at least six months in advance in "Bulletin C" produced by the International Earth Rotation and Reference Systems Service. The leap seconds cannot be predicted far in advance due to the unpredictable rate of rotation of the Earth. Last corrections was in June 2015 and December 2016.

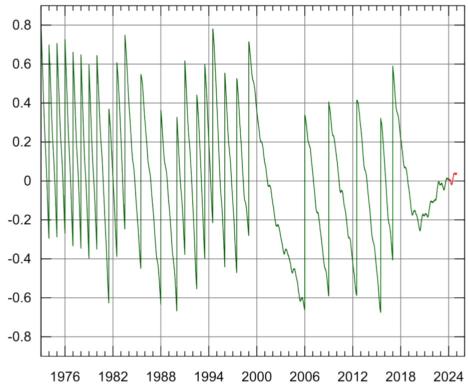

Figure 6: Graph showing the difference DUT1 between UT1 and UTC (in seconds). Vertical segments correspond to leap seconds.

3 Solution

3.1 Constant Delay

The receiver position is (57.64103, 18.316413) and the DCF77 position is (50.01556, 9.01083). The distance (big circle) $\approx 1043\ km$. If radio-waves propagates as ground waves with speed nearly $c = 300000\ km/s$, this gives us **3.5** ms delay and in numbers of DCF77's periods:

$$\frac{length}{c} * 77500 \approx 269$$

(in fact at this distance, ground and atmospheric paths contribute with approximately same strength, se PTB-Mitteilungen 2009, 3[8].

3.2 STM32[10] version of brilliant Steve Marchant PIC[12] solution[9]

After a long search, I have found a brilliant article in magazine *Elektor* from January 2012, p 48: "Ultra-accurate DSP-based DCF77 Timecode Receiver" of Steve Marchant. Even if the magazine is not (at least legally) free available, all information can be found on the author's website[9].

3.2.1 Design

I live in Visby (Gotland, Sweden), more than 1000 km from DCF77, so a radio-signal must be highly amplified. A Steve's preamplifier and active filter work well. Proper siting of the antenna well away from interference sources can greatly improve signal quality.

Original decoder was constructed around micro controller PIC DSPIC33FJ32GP202. One of key thing in the design is to use Voltage-Controlled Crystal Oscillator (VCXO) as master oscillator. Standard frequency of VCXO is 19.2 MHz. My Nucleo F446RE board has 180 MHz max. frequency and with: PLLM = 1/10, N* = 186 and /P = 1/2 one gets 19.2 * 186 /20 = 178.56 MHz (quite near to 180 MHz). The frequency 178.56 MHz is multiple of DCF77 carrier = 77.5 kHz (77.5 kHz * 2304 = 178.56 MHz). This allows to precise tuning the VCXO to lock on the carrier. This clock settings work with boards that have max frequency 180 MHz, I have tried to find correct clock setting (multiple of 77.5 kHz) for my other board Nucleo F767ZI (max f = 216 MHz) and it did not work.

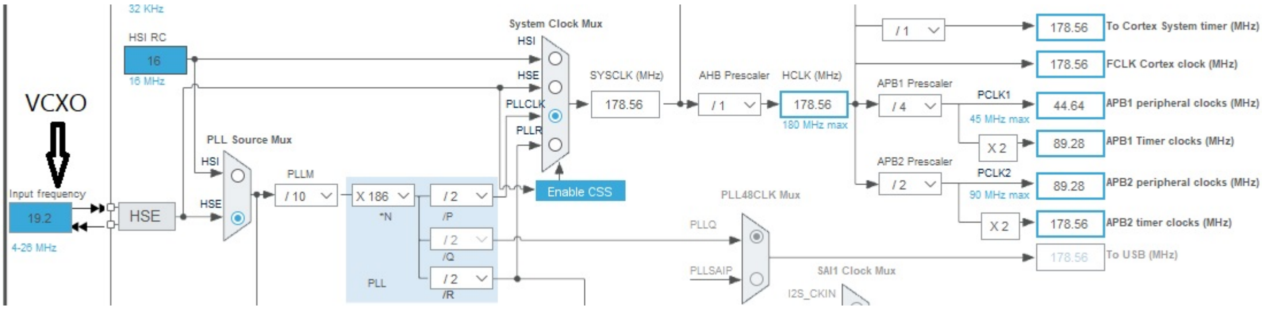

Figure 7: CPU clock setting.

3.2.2 General description

Antenna, preamp Signal from transmitter is received by ferrite antenna and preamplified, then through coax it goes to the amplifier/low-pass active filter.

Active filter, phase decoder ADC is done with sample frequency is $4*77.5\ kHz = 310\ kHz$ so all frequency higher than $155\ kHz$ must be suppressed. For optimal level of analog signal to ADC converter one uses AGC.

The pseudo-random sequence which modulate carrier has as many zeros as ones, so average phase and frequency are constant. Detector produces voltage to VCXO in order to stay exactly with carrier $77.5\ kHz$ (PLL).

When the detector can extract data, it produces PPS and sends a message via serial port (Tx) - most important is data bit, but it delivers some diagnostic data as well.

Bit decoder, clock Now, when we have bits, which are send in all second, a detector must find start of minute sequence, i.e. '111111111100000' (0, 1, . . . , to 14 second), during rest of the minute all date information is collected and date can be set. Now, the seconds are added by the timer, which pace is disciplined by PPS signals.

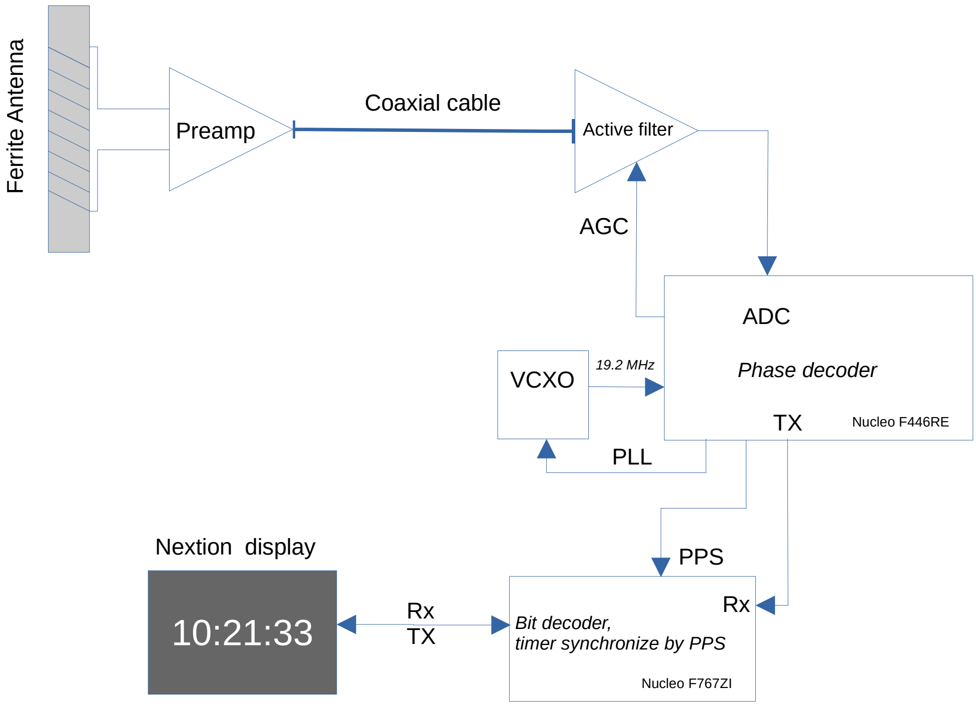

Figure 8: Block schema of my clock.

References

[1] DCF77, (Wikipedia)

[2] The Feynman Lectures on Physics, Vol. I, Ch. 5-2 (online)

[3] A walk through Time, *A NIST Physics Laboratory Presentation*

[4] The Science of Timekeeping, *Hewlett Packard™* (pdf)

[5] Global Positioning System (Wikipedia)

[6] Coordinated Universal Time (Wikipedia)

[7] The most precise atomic clock ever made, *New Scientist*, 2017

[8] `https://www.ptb.de/cms/fileadmin/internet/publikationen/ptb_mitteilungen/mitt2009/Heft3/PTB-Mitteilungen_2009_Heft_3_en.pdf`

[9] http://www.marvellconsultants.co.uk/DCF/index.html

[10] https://en.wikipedia.org/wiki/STM32

[11] https://www.st.com/en/evaluation-tools/stm32-nucleo-boards.html

[12] https://en.wikipedia.org/wiki/PIC_microcontrollers