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Smart Sensor Systems Design for Smartphones, Tablets and IoT: New Advanced Design Approach

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Tutorial, August 23, 2015, Venice, Italy

Outline

1. Introduction: Markets and Definitions
2. Modern Challenges
3. Sensor Systems Design: Introduction
4. Advanced Sensor Systems Design
5. Sensors Systems Examples
6. The Future and Summary

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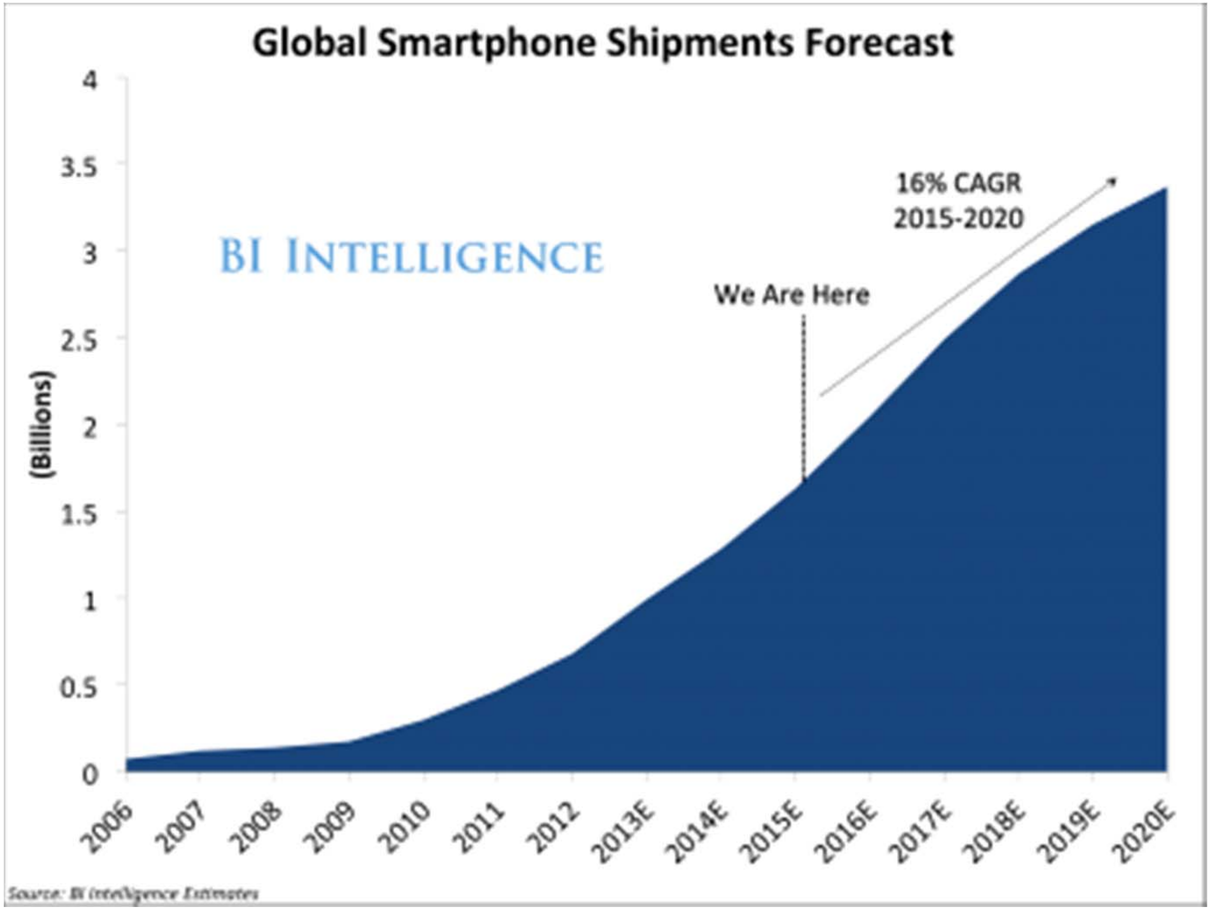
Internet of Things (IoT)

- Devices are focused on sensing and actuating of physical environment
- IoT represents the convergence in advances miniaturization, wireless connectivity, increased data storage capacity and batteries
- IoT wouldn't be possible without sensors
- A common requirement for IoT end nodes is the need for small size

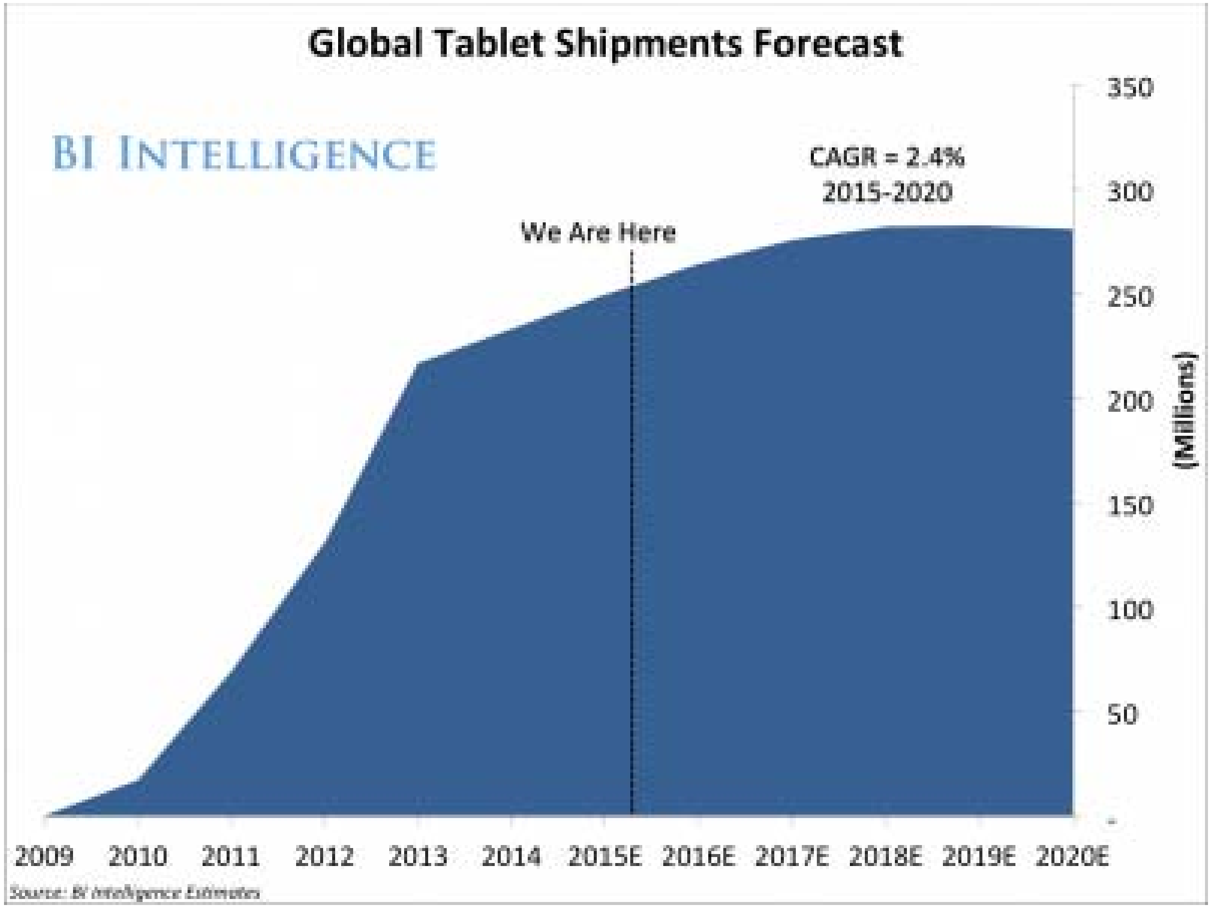
Global Internet of Things (IoT) Market

- Grows at a compound annual growth rate CAGR of **31.72 %** over the period 2014-2019 (*Research and Markets*)
- **50 billion** devices are expected to be connected to the Internet by 2020 (*Cisco's IBSG)*
- By 2020, sensors will link **212 billion** of objects through the Internet of Things (IoT): (*IDC*)
- Internet of Things market is on track to hit **$7.1 trillion** in 2020 (*IT research agency, IDC*)

Global Smartphone Shipments



Global Tablet Shipments



Global Sensor Markets

- **Global Sensor Market** will reach US **$154.4** Billion by 2020 with a five-year compound annual growth rate (CAGR) of 10.1% (*BCC Research*)
- **Global Microsensors Market** (including MEMS, biochips and nanosensors) will reach US **$15.8** Billion by 2018 with CAGR) of 10.0 % (*BCC Research*)
- **Global Smart Sensors Market** to reach US **$6.7** Billion by 2017 (*Global Industry Analysts*, *Inc*.)
- **European Smart Sensors Market** expected to grow up to US **$2,402.15** million till 2018 with a CAGR of 39.90 %.

Application Market Niche

- **Smartphone and Tablets Sensors Market** will rise to US **$6.5 billion** in 2018 (*IHS*)
- **Combo-sensor Market** will growth to **1.5 Billion EUR** by 2016

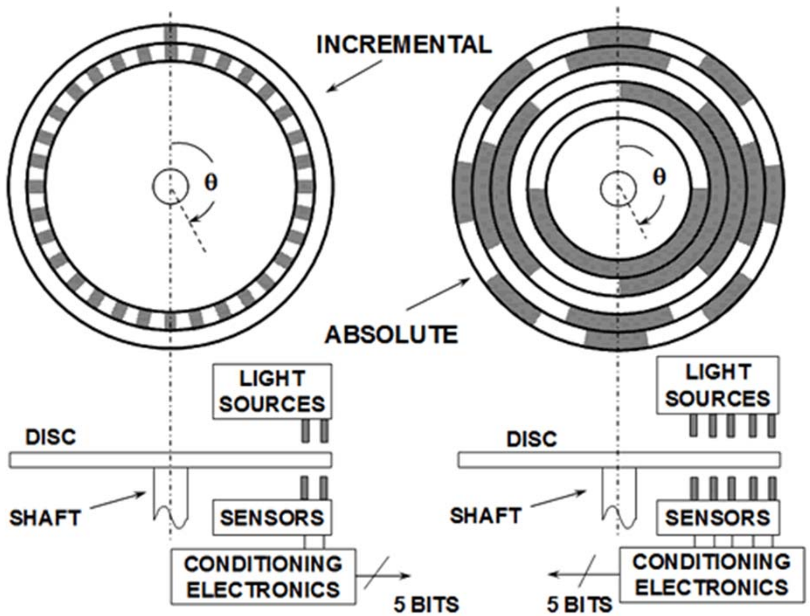
Smartphone Sensors Classification

- Sensors for Smartphones
  - Internal Sensors
  - External Sensors
    - Wire Sensors (USB, dock-connector)
    - Wireless Sensors

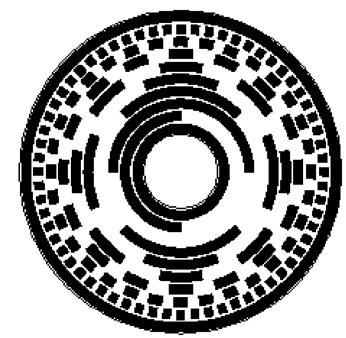
Digital Sensors

- Number of physical phenomenon, on the basis of which direct conversion sensors with digital outputs can be designed, is essentially limited
- Angular-position encoders and cantilever-based accelerometers – examples of digital sensors of direct conversion
- There are not any nature phenomenon with discrete performances changing under pressure, temperature, etc.

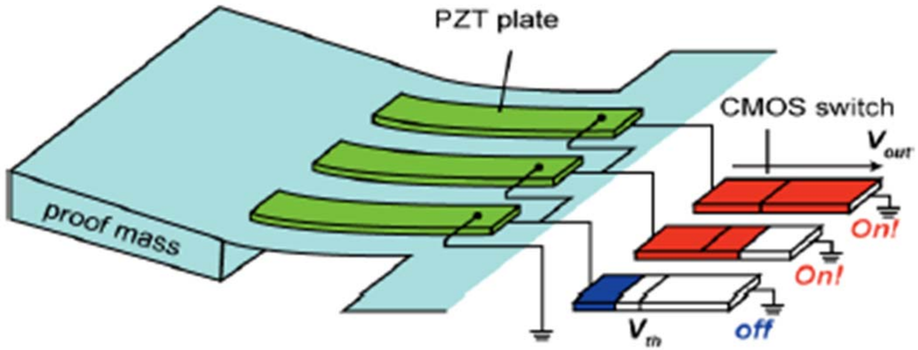
Angular-Position Encoder



decimaal	Gray-code
0	0000
1	0001
2	0011
3	0010
4	0110
5	0111
6	0101
7	0100
8	1100
9	1101
10	1111
11	1110
enz.	enz.

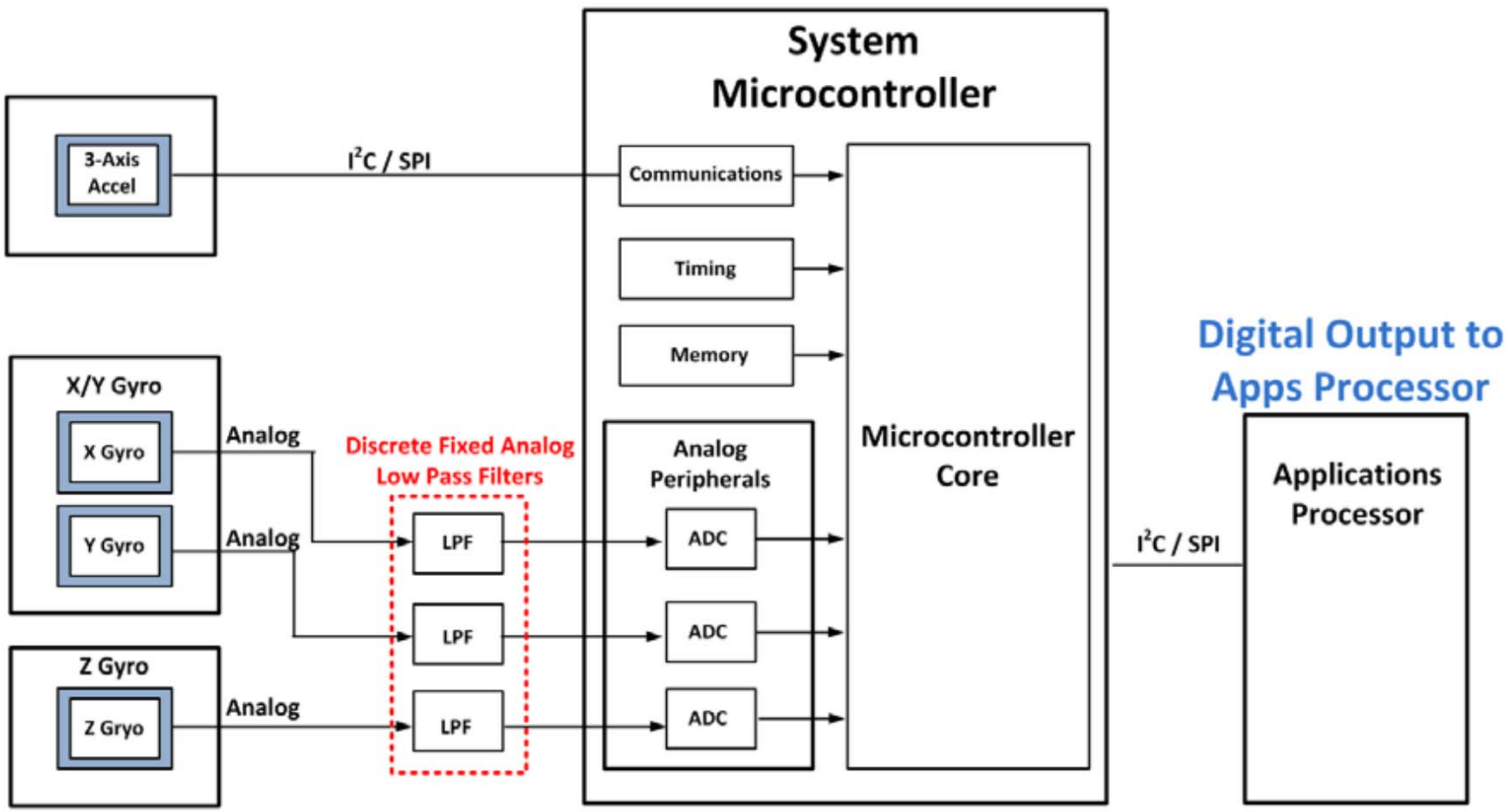


Digital Accelerometer

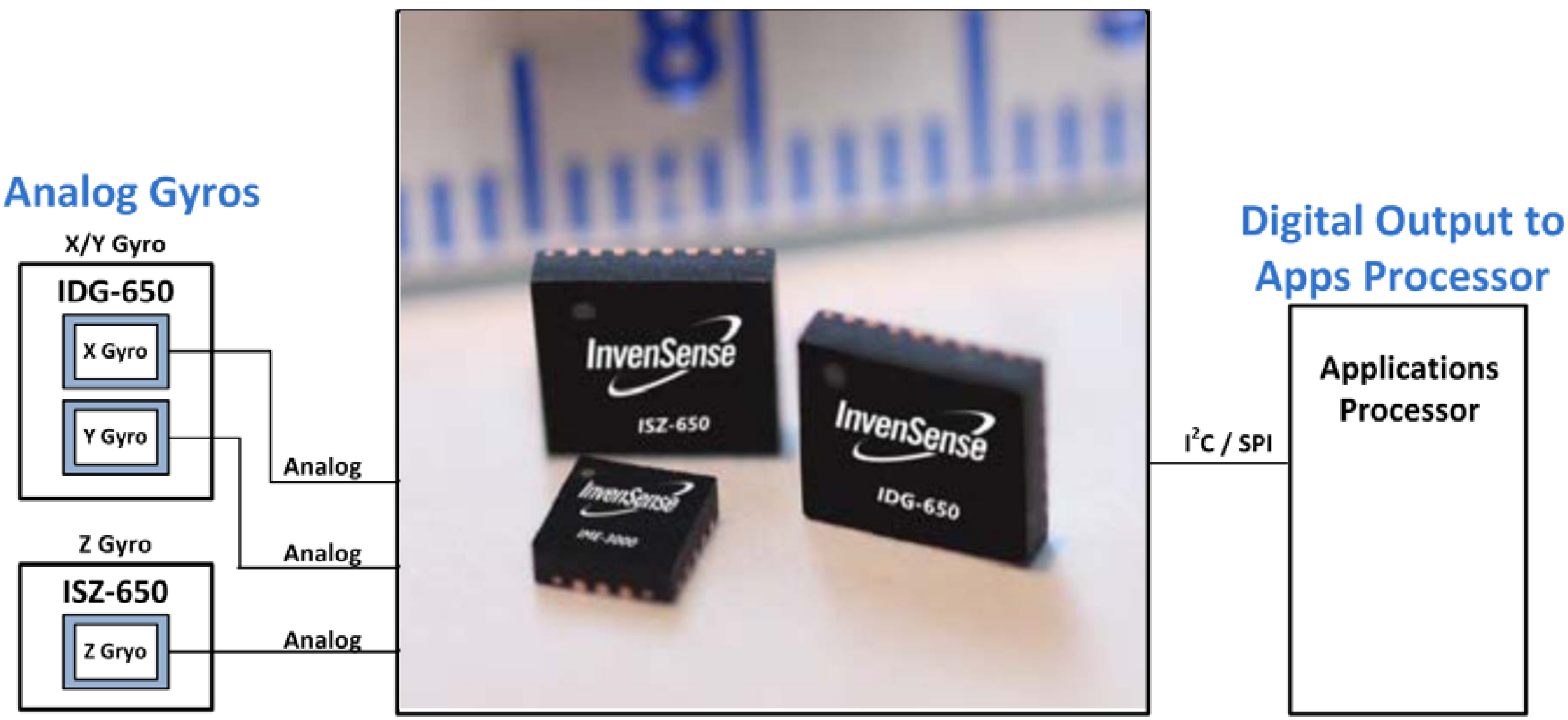


Toshihiro Itoh, Takeshi Kobayashi, Hironao Okada, A Digital Output Piezoelectric Accelerometer for Ultra-low Power Wireless Sensor Node, in *Proceedings of IEEE Sensors 2008*, 26-29 October 2008, Lecce, Italy, pp.542-545.

6-Axis Motion Processing Solution (I)



6-Axis Motion Processing Solution (II)



Modern Challenges

❶ Introduction: Markets and Definitions
❷ Modern Challenges
❸ Sensor Systems Design: Introduction
❹ Advanced Sensor Systems Design
❺ Sensors Systems Examples
❻ The Future and Summary

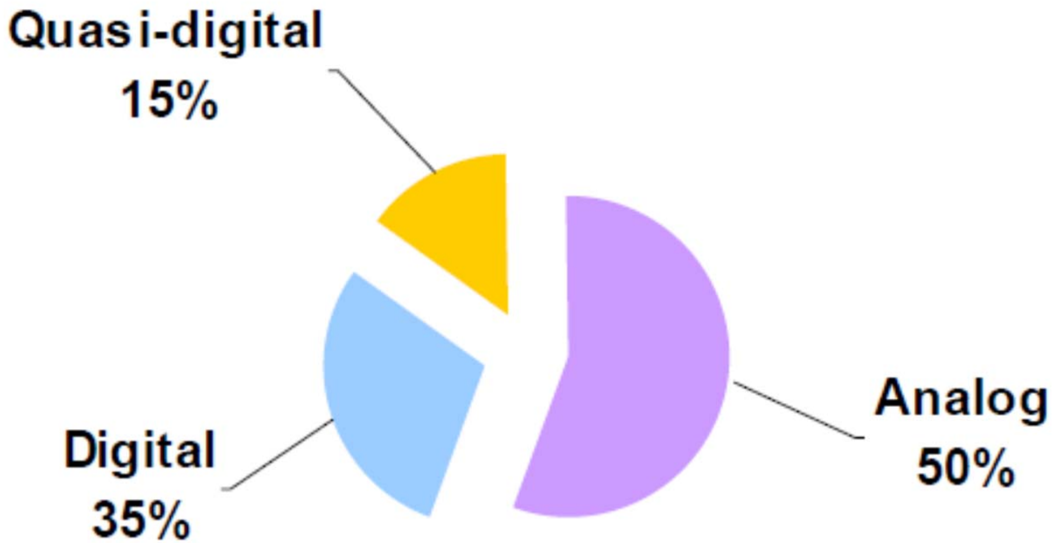
Technological Limitations

- Below the 100 nm technology processes the design of analog and mixed-signal circuits becomes essentially more difficult
- Long development time, risk, cost, low yield rate and the need for very high volumes
- The limitation is not only an increased design effort but also a growing power consumption
- However, digital circuits becomes faster, smaller, and less power hungry

Signal- and Data Processing Limitations

- Sensor Fusion is a complex procedure deals with analog signals
- Only limited number of sensing elements can be integrated into a combosensors

Sensor Types Divided According to Outputs



International Frequency Sensor Association (IFSA), Study, 2014

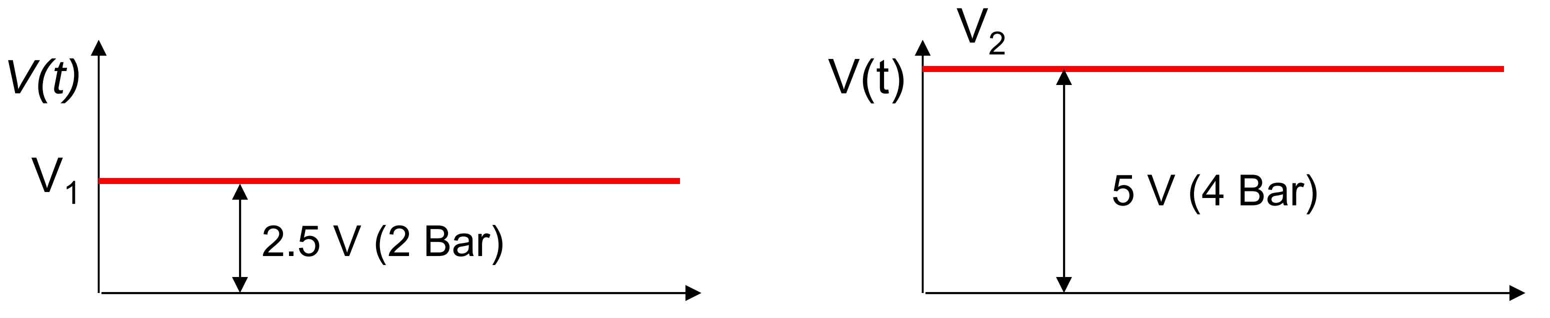
Analog and Quasi-Digital Sensors

Analog sensor *- sensor based on the usage of an amplitude modulation of electromagnetic processes*

Quasi-digital sensors *are discrete frequency-time domain sensors with frequency, period, duty-cycle, time interval, pulse number or phase shift output*

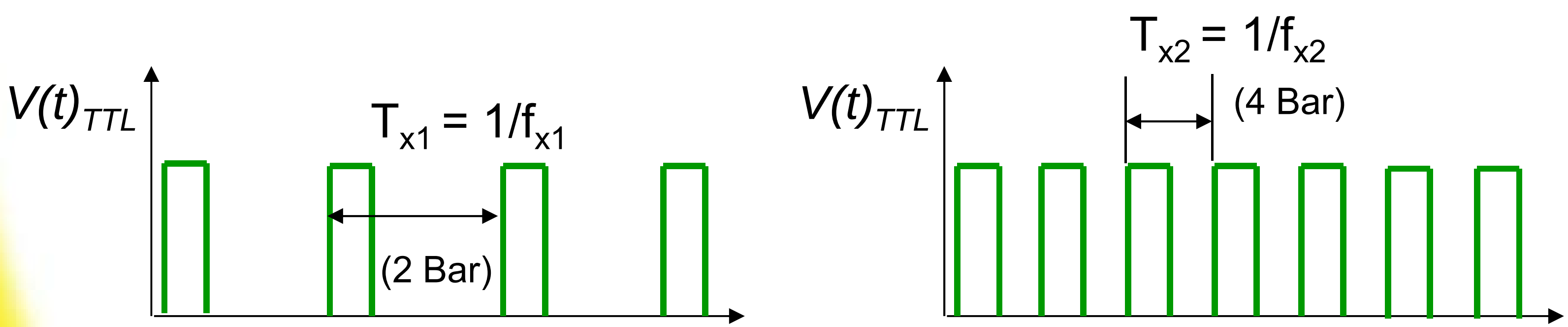
Quasi-digital sensors combine a simplicity and universatility that is inherent to analog devices and accuracy and noise immunity, proper to sensors with digital output

Voltage output vs. Frequency Output



(a) (b)

$V_1 < V_2$

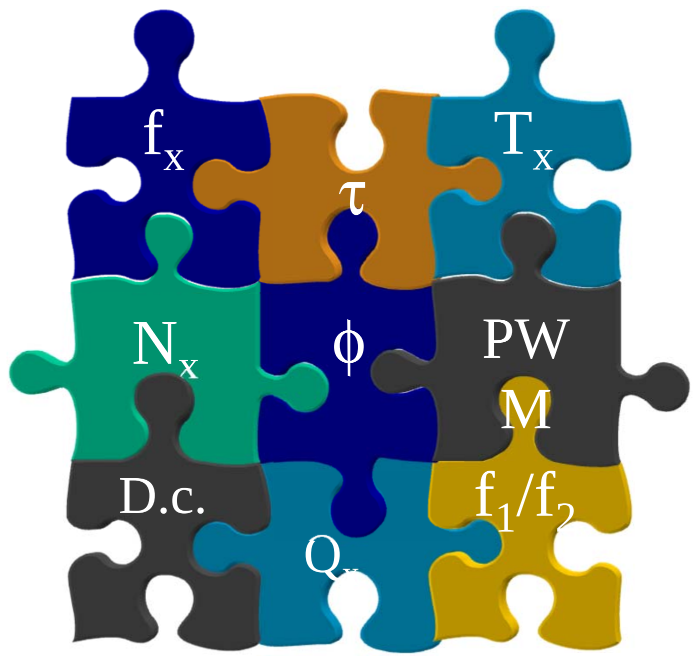


(a) (b)

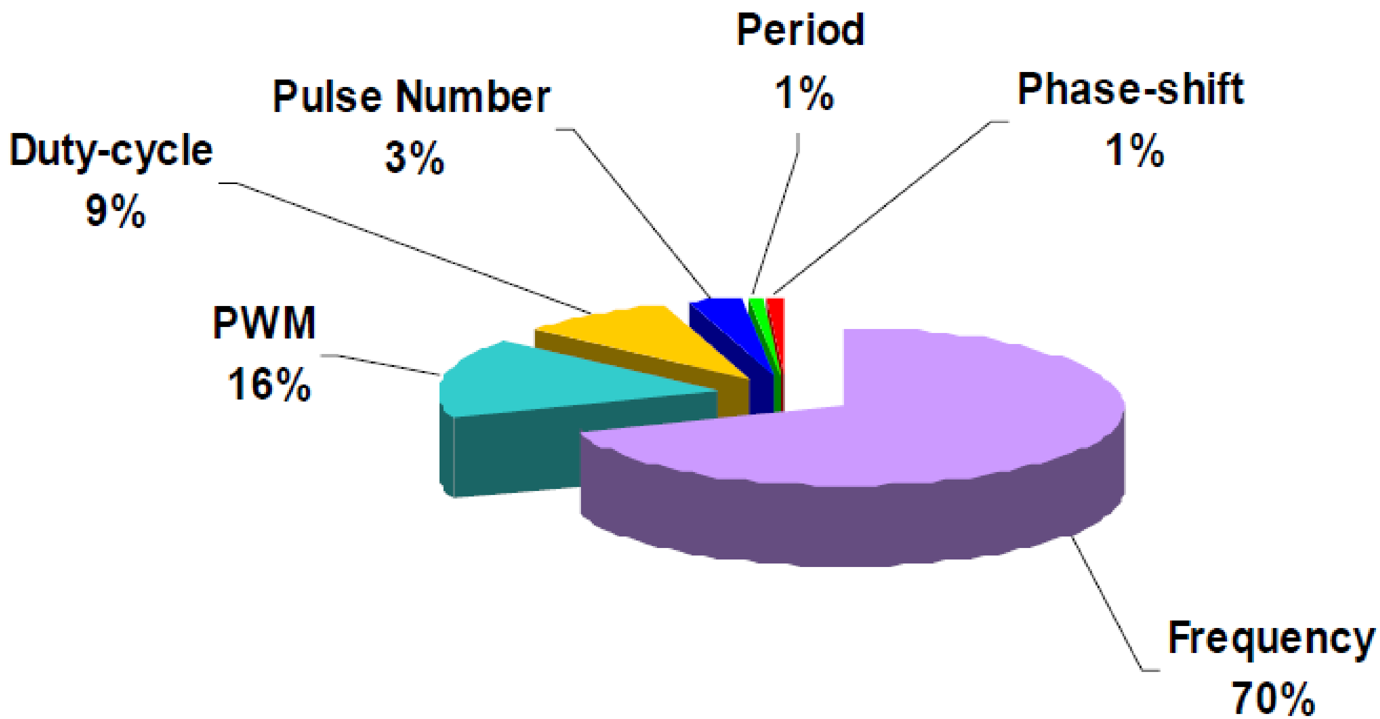
$T_{x1} > T_{x2}\ ,\ f_{x1} < f_{x2}$

Quasi-Digital Sensors

Quasi-digital sensor is a sensor with frequency, period, its ratio or difference, frequency deviation, duty-cycle (or duty-off factor), time interval, pulse width (or space) pulse number, PWM or phase shift output.

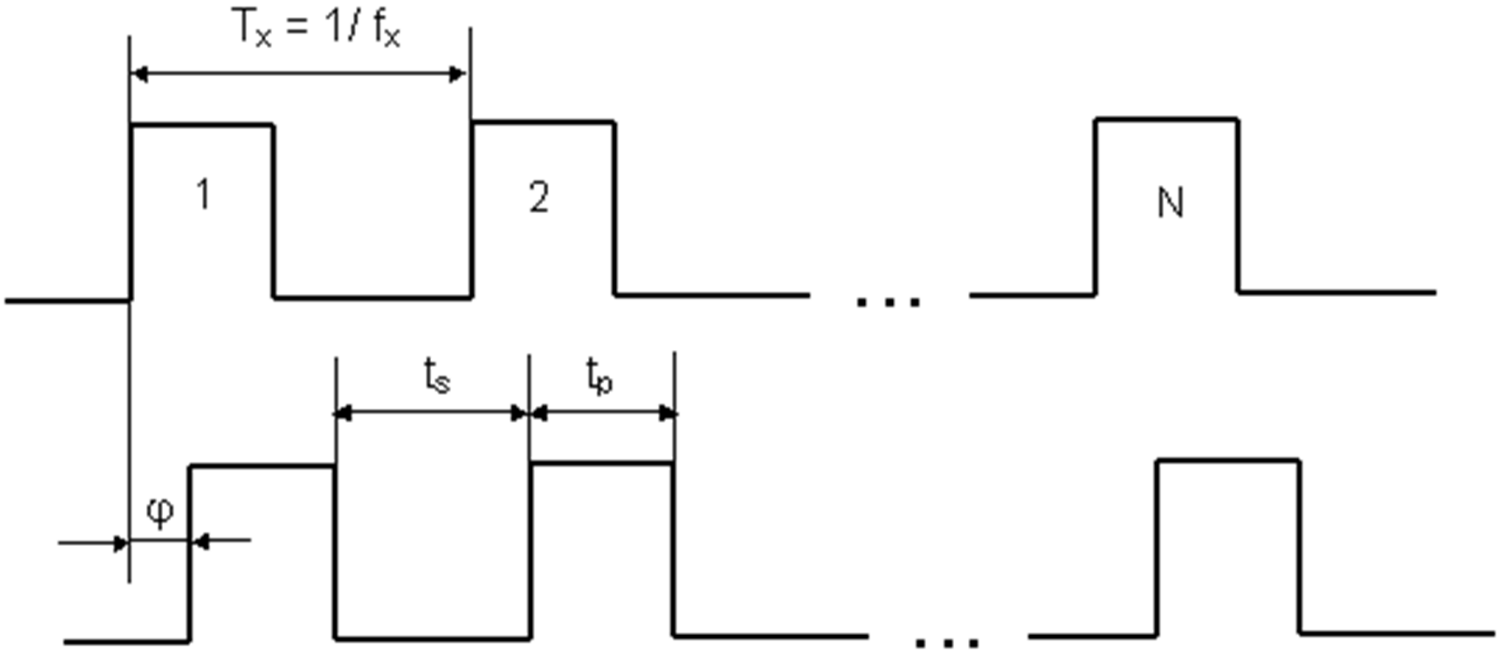


Quasi-Digital Sensors: Types



International Frequency Sensor Association (IFSA), Study 2014

Informative Parameters



- Duty-cycle: D.C.= t_p/T_x
- Duty-off factor: 1/D.C. = T_x/t_p
- PWM signal: t_s/t_p ratio at T_x = constant

Digital Output Sensors

1
0
1
1
0
1
1
1
…
1
0

Binary code

- Serial interfaces RS232/485/422, USB
- Parallel interfaces (8-, 16-, 32-bits)
- Sensor buses: SPI, I2C, CAN, SMBus, LIN, etc.

1 0 1 1 1 0 0 1 0 1 } Binary code

Frequency Advantages

- High Noise Immunity
- High Power Signal
- Wide Dynamic Range
- High Reference Accuracy
- Simple Interfacing
- Simple Integration and Coding
- Multiparametricity

Sensor Systems Design: Introduction

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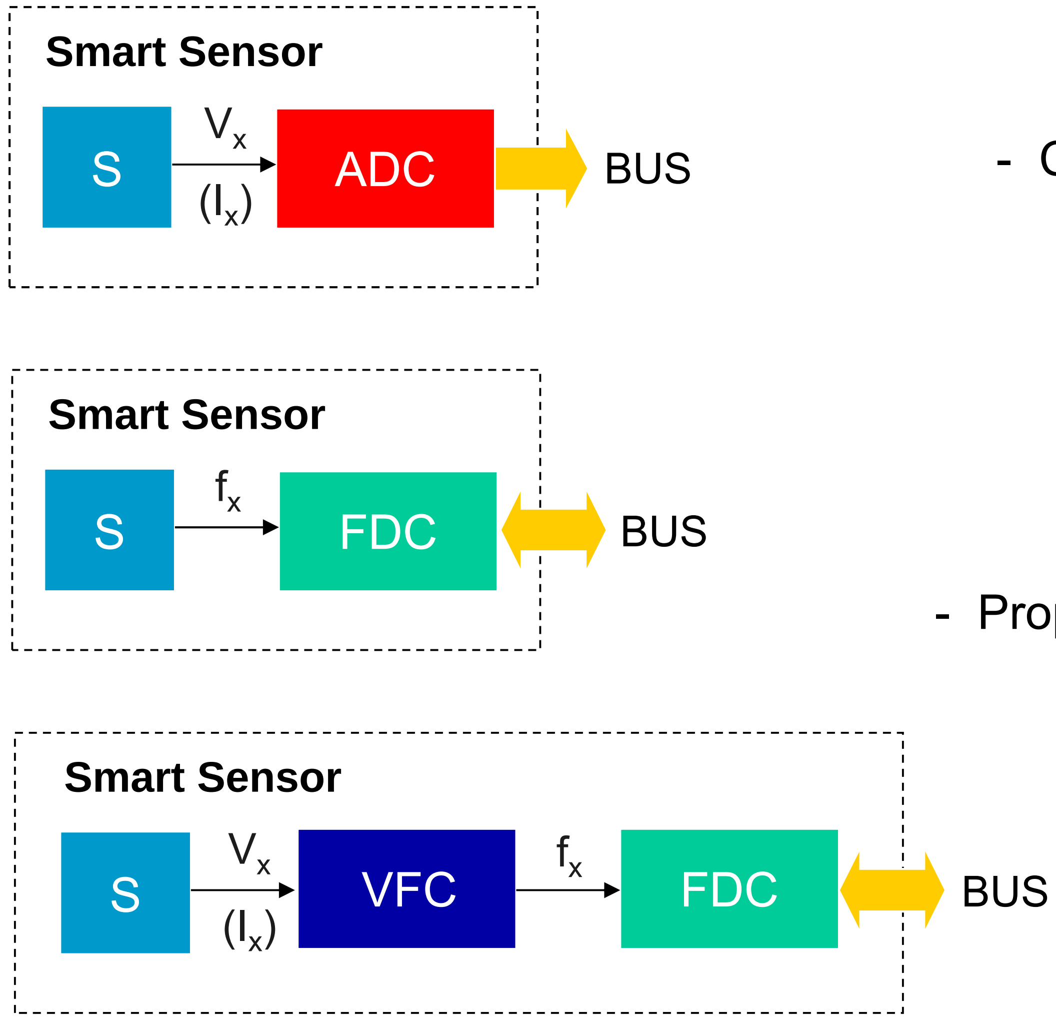
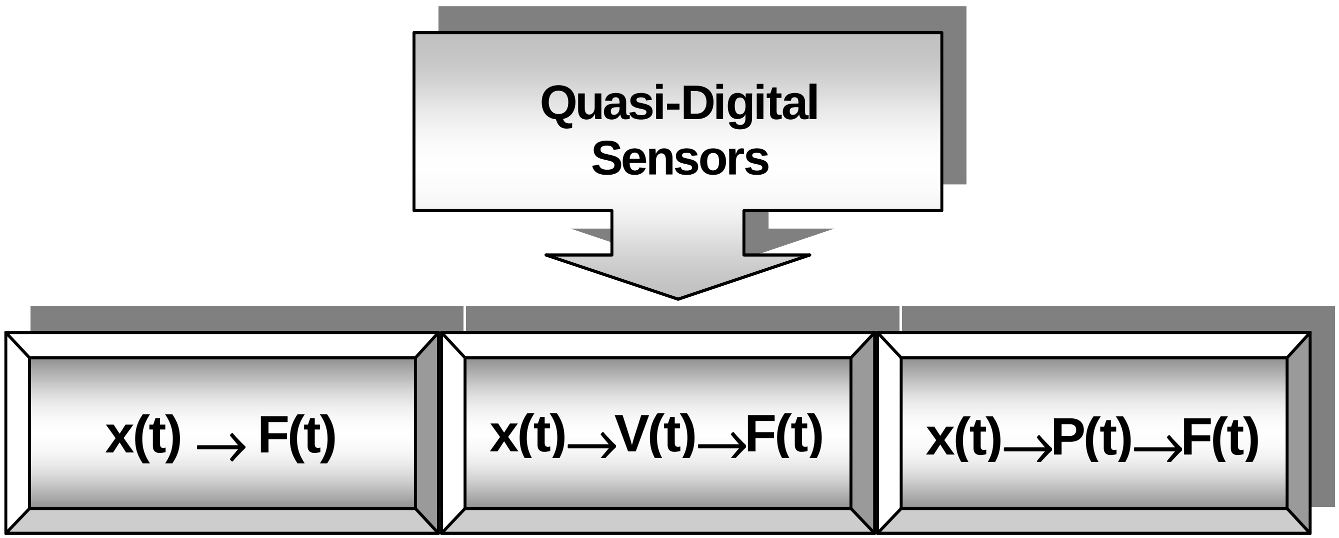
Smart Sensors Design



- Classical approach

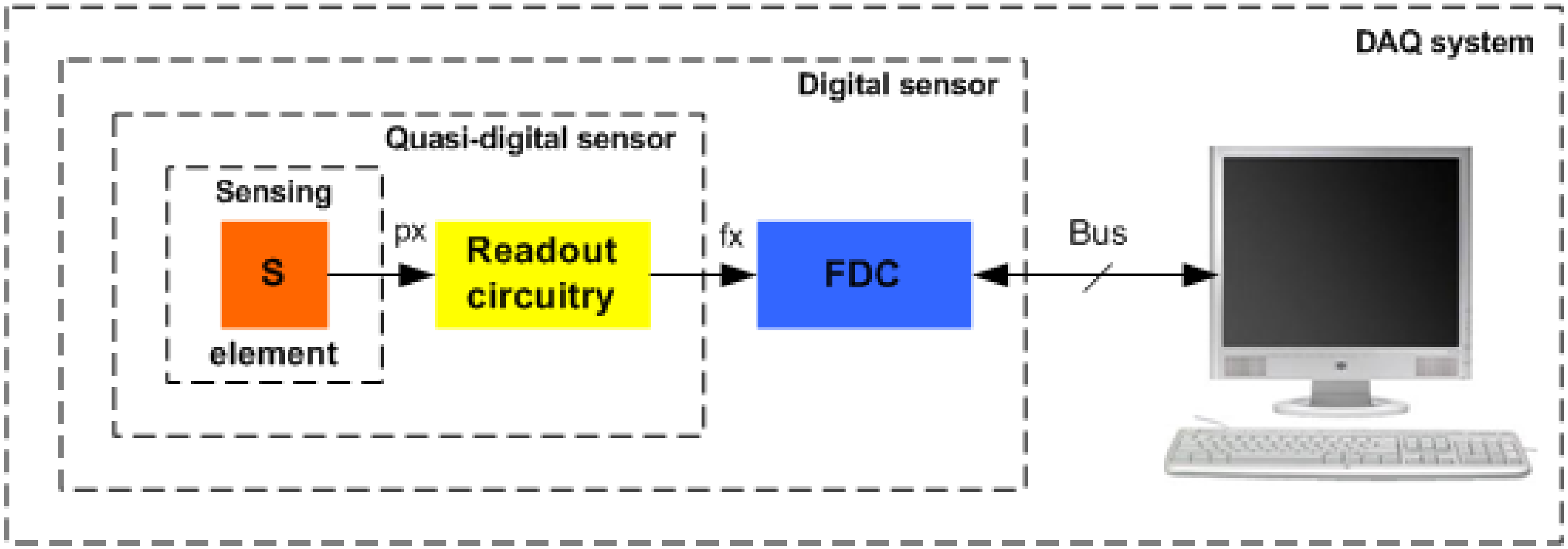
- Proposed approaches

Quasi-Digital Sensor Classification



x(t)–measurand; F(t)–frequency; V(t)–voltage, proportional to the measurand; P(t)–parameter

Quasi-Digital and Digital Sensors in System Hierarchy



IFSA

Quasi-Digital Sensors: Summary

- There are many quasi-digital sensors and transducers for any physical and chemical, electrical and non electrical quantities
- Various frequency-time parameters of signals are used as informative parameters: f_x, T_x, *D.C.*, *PWM*, *T*, φ_x, etc.
- The frequency range is very broad: from some parts of Hz to some MHz
- Relative error up to 0.01% and better

Advanced Sensor Systems Design

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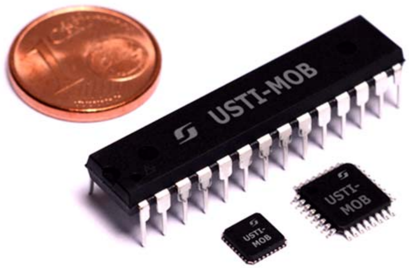
USTI-MOB



- Can measure all frequency-time parameters of signal
- Low relative error up ±0.0009 %
- Wide frequency range: 0.25 Hz to 1.95 (31) MHz
- I2C, SPI and RS232 interfaces
- 2-channel + sensing element
- Supply voltage: 1.8 V
- Active supply current < 0.85 mA
- Packages: 5 x 5 mm MLF package (4 x 4 mm is coming), TQFP, PDIP

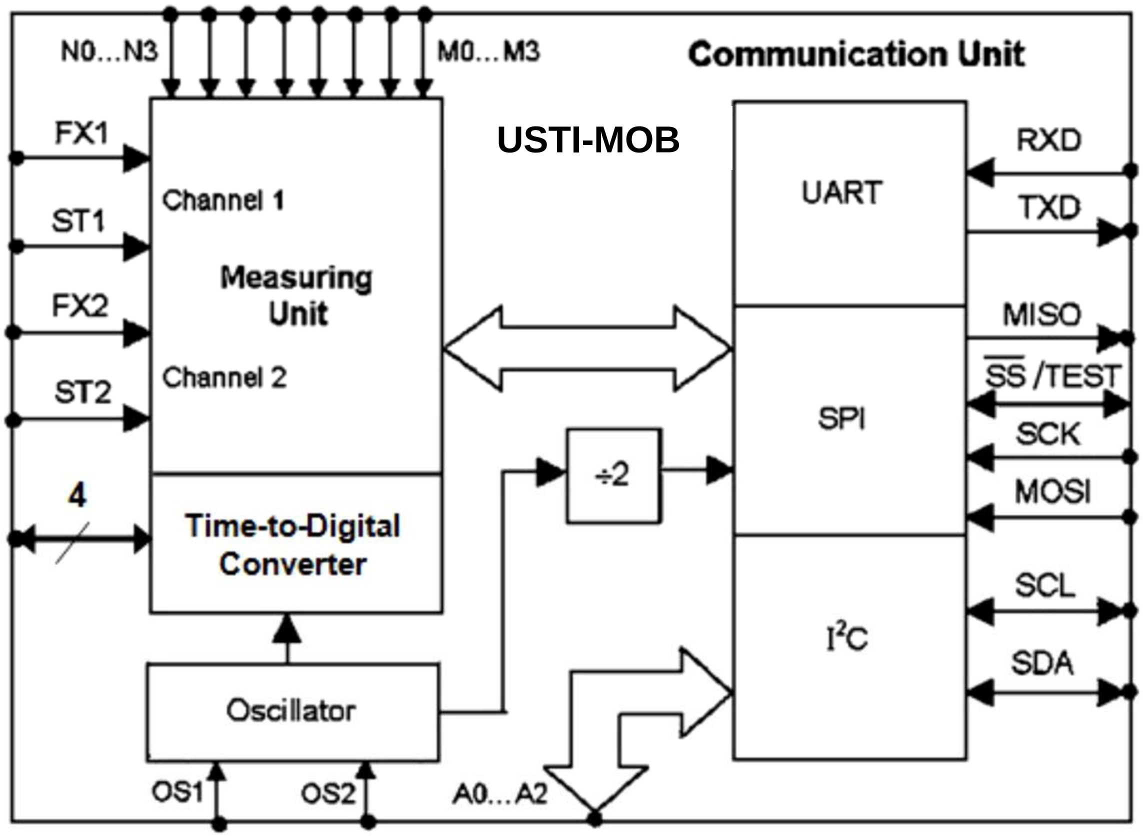
USTI-MOB Features

- Based on four patented methods for frequency, period, duty-cycle and phase shift measurements
- Constant relative error in all frequency range of measurements
- Non redundant conversion time
- Scalable resolution

USTI-MOB's Measuring Modes

- Frequency, $f_{x,}$ [Hz]
- Period, T_X [s]
- Phase shift, φ_X [^{0}]
- Time interval between start – and stop-pulse [s],
- Duty-cycle, D.C. and Duty-off factor, Q
- Frequency $f_{X1} – f_{X2}$ [Hz] and period $T_{X1} – T_{X2}$ [s] difference
- Frequency f_{X1}/f_{X2} and period $T_{X1/}T_{X2}$ ratio
- Rotational speed, n_X [rpm]
- Pulse width, t_p and Space interval, t_s [s]
- Pulse number (events) counting, N_X
- Frequency deviation absolute DA [Hz] and relative DR [%]
- Resistance, R_x [Ω]
- Capacitance, C_x [F]
- Resistive bridges, B_x
- Generating mode *2* MHz

USTI-MOB Block Diagram

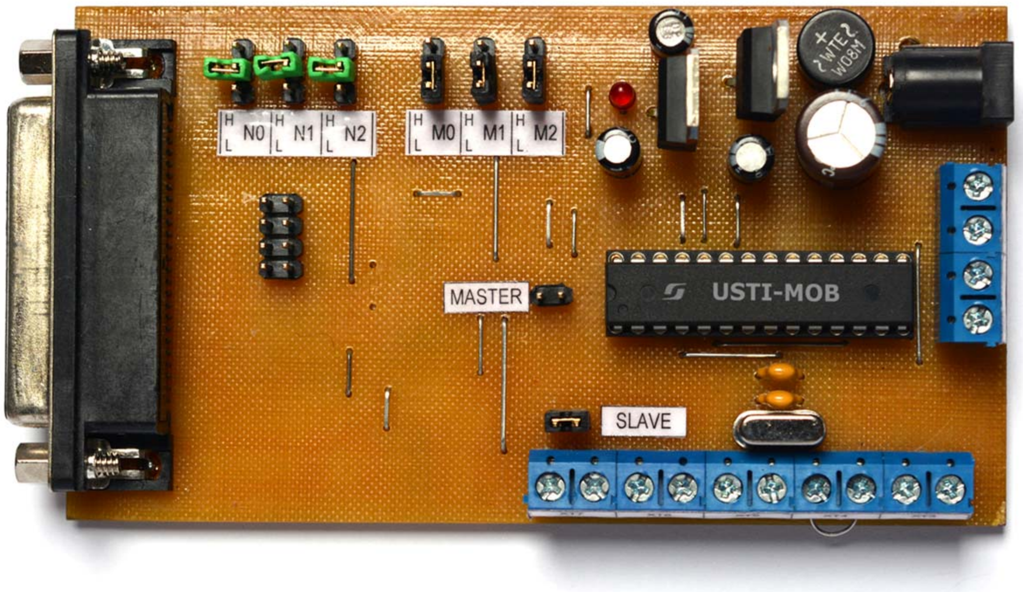


Comparison Performances of USTI-MOB and USTI

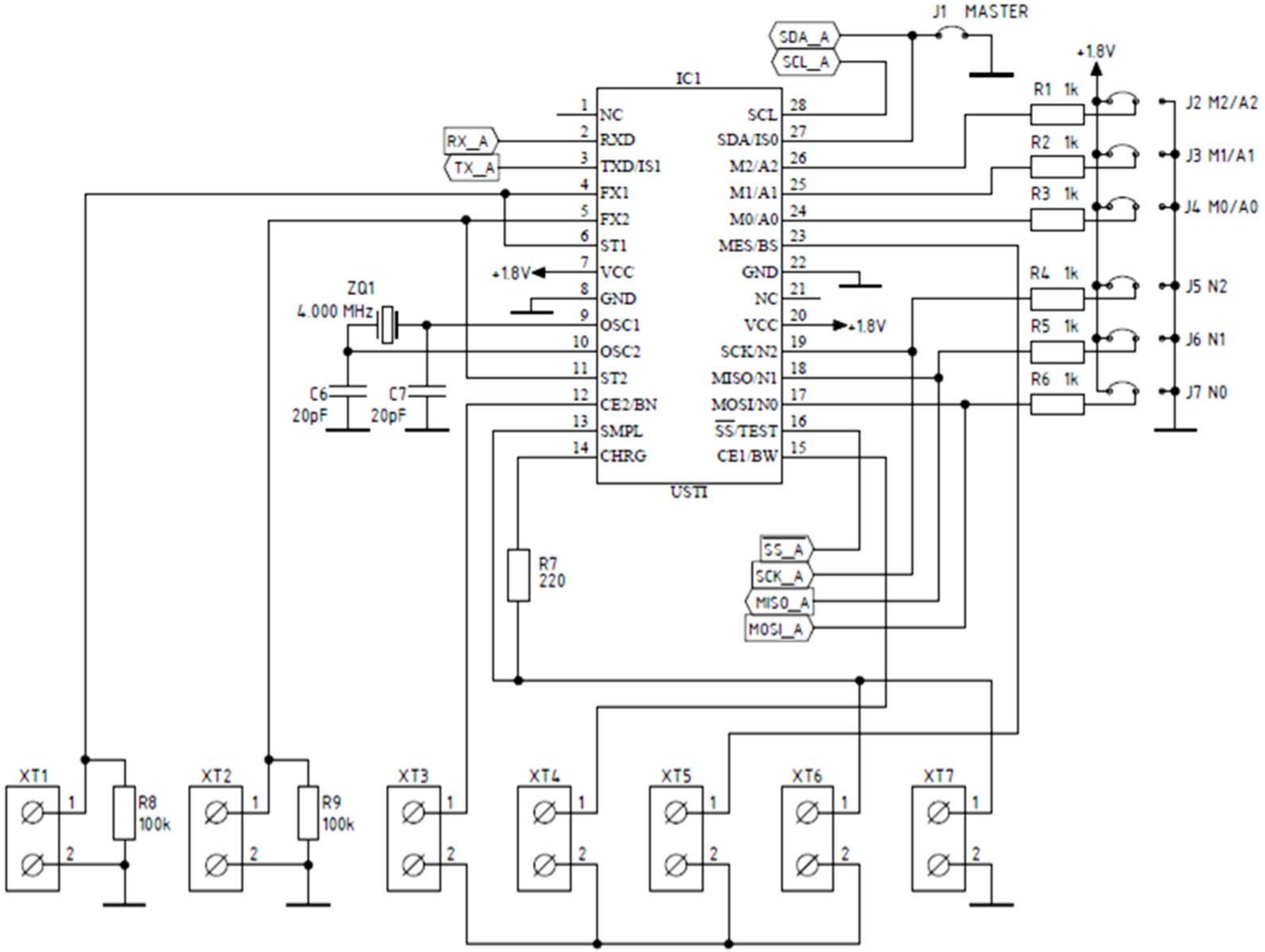
Parameter	USTI-MOB	USTI
Programmable relative error, %	±(1…0. 0009)	±(1…0.0005)
Frequency range of measurement, Hz	$0.25 \ldots 1.95 \times 10^{6}$	$0.05 \ldots 9 \times 10^{6}$
Reference frequency, MHz	4	20
Generating mode, MHz	2	10
Supply voltage, V	1.8	5.0
Current consumption (active mode), mA	0.85	11
Operation temperature range, ^{0}C	-40 ... +85	-40 ... +85

*For custom design IC

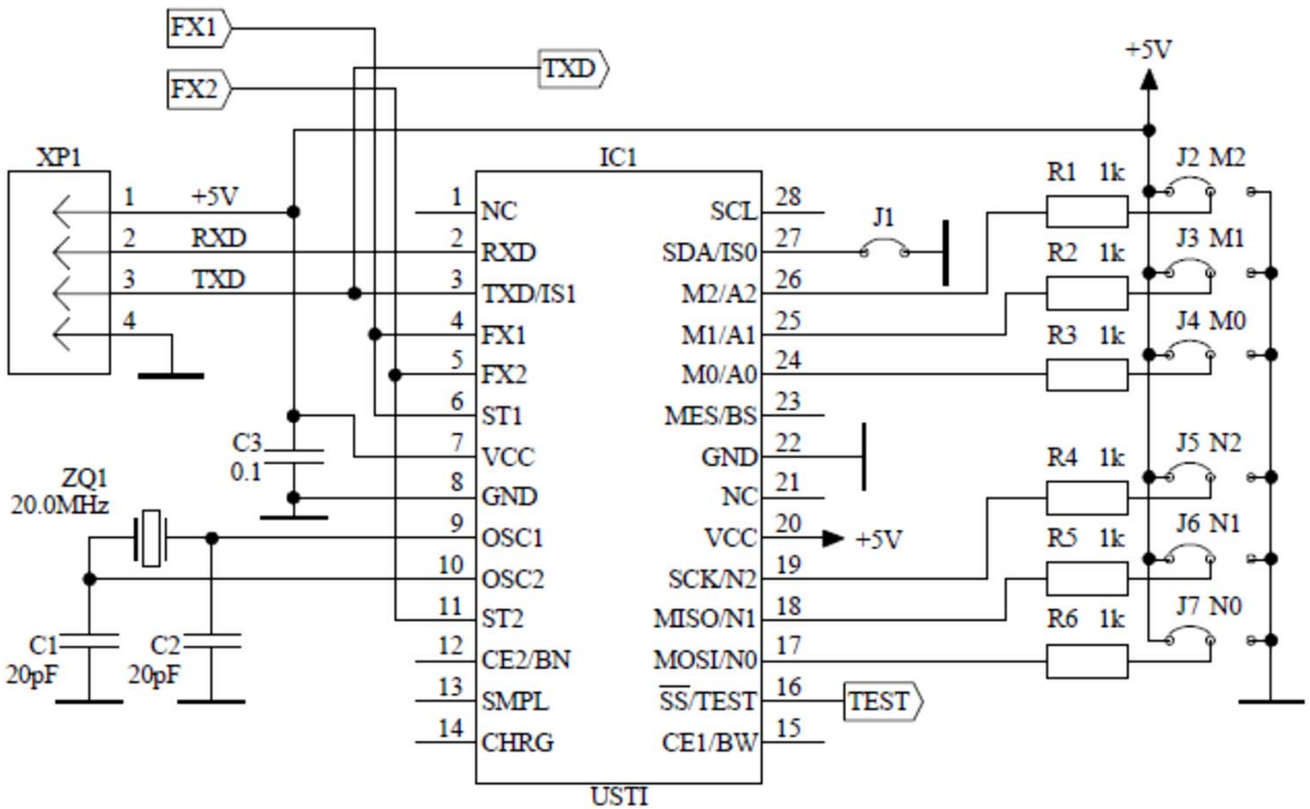
USTI-MOB Evaluation Board Prototype



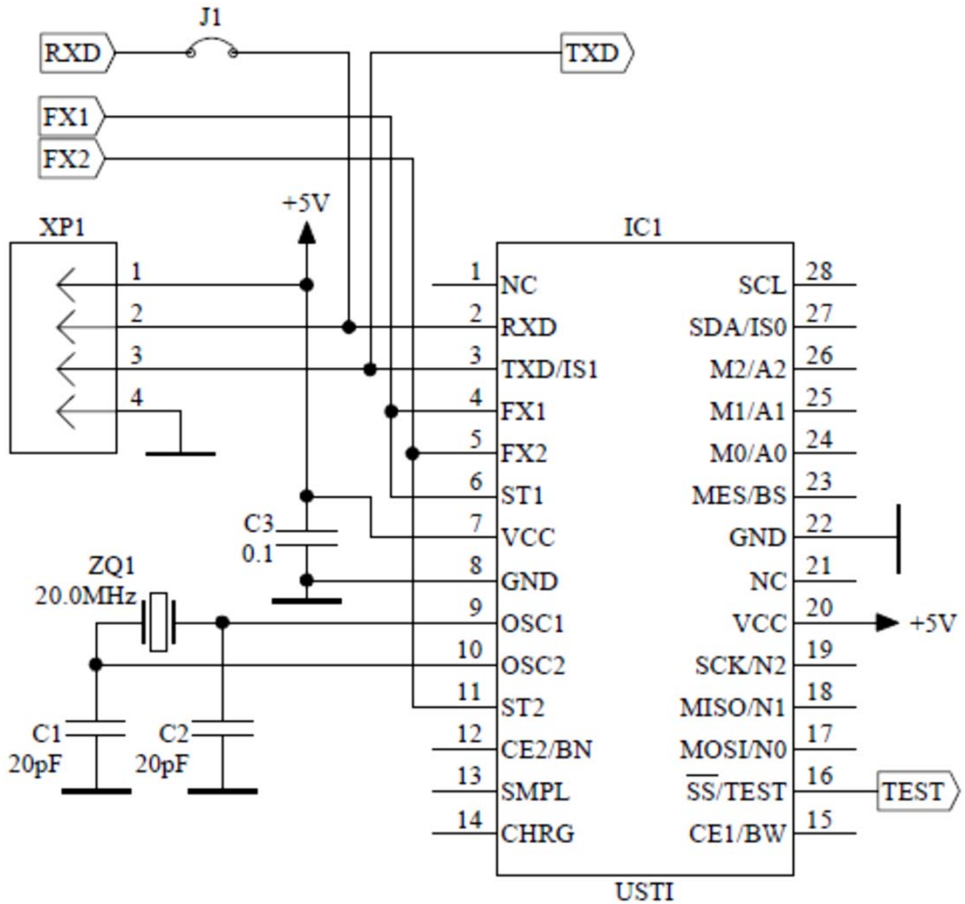
Evaluation Board's Circuit Diagram



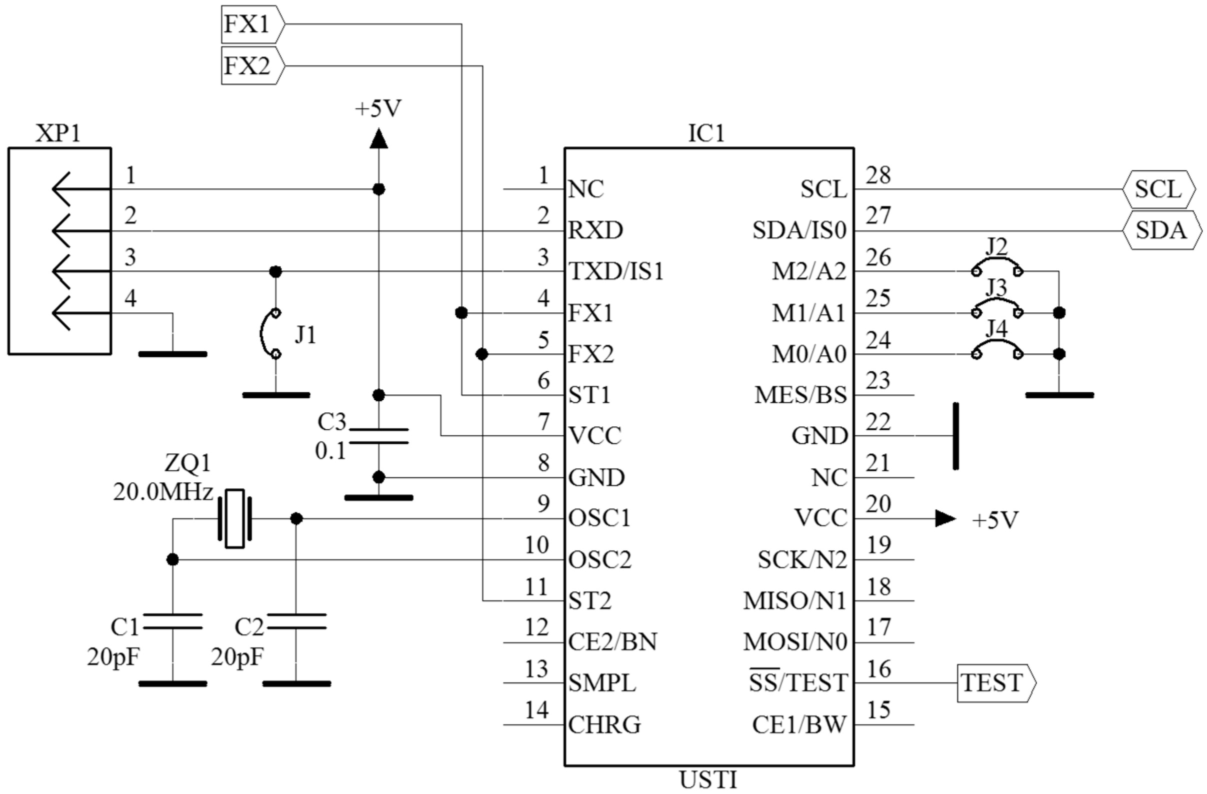
USTI RS232 Interface (Master)



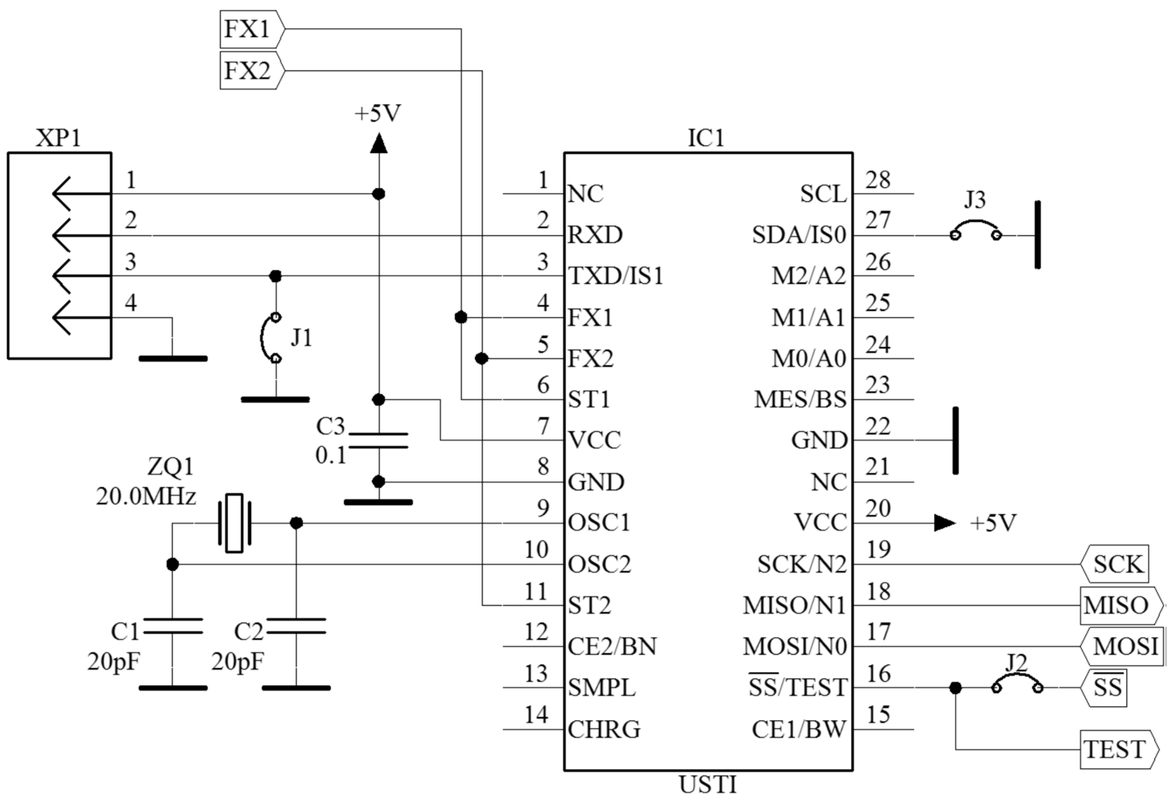
USTI RS232 Interface (Slave)



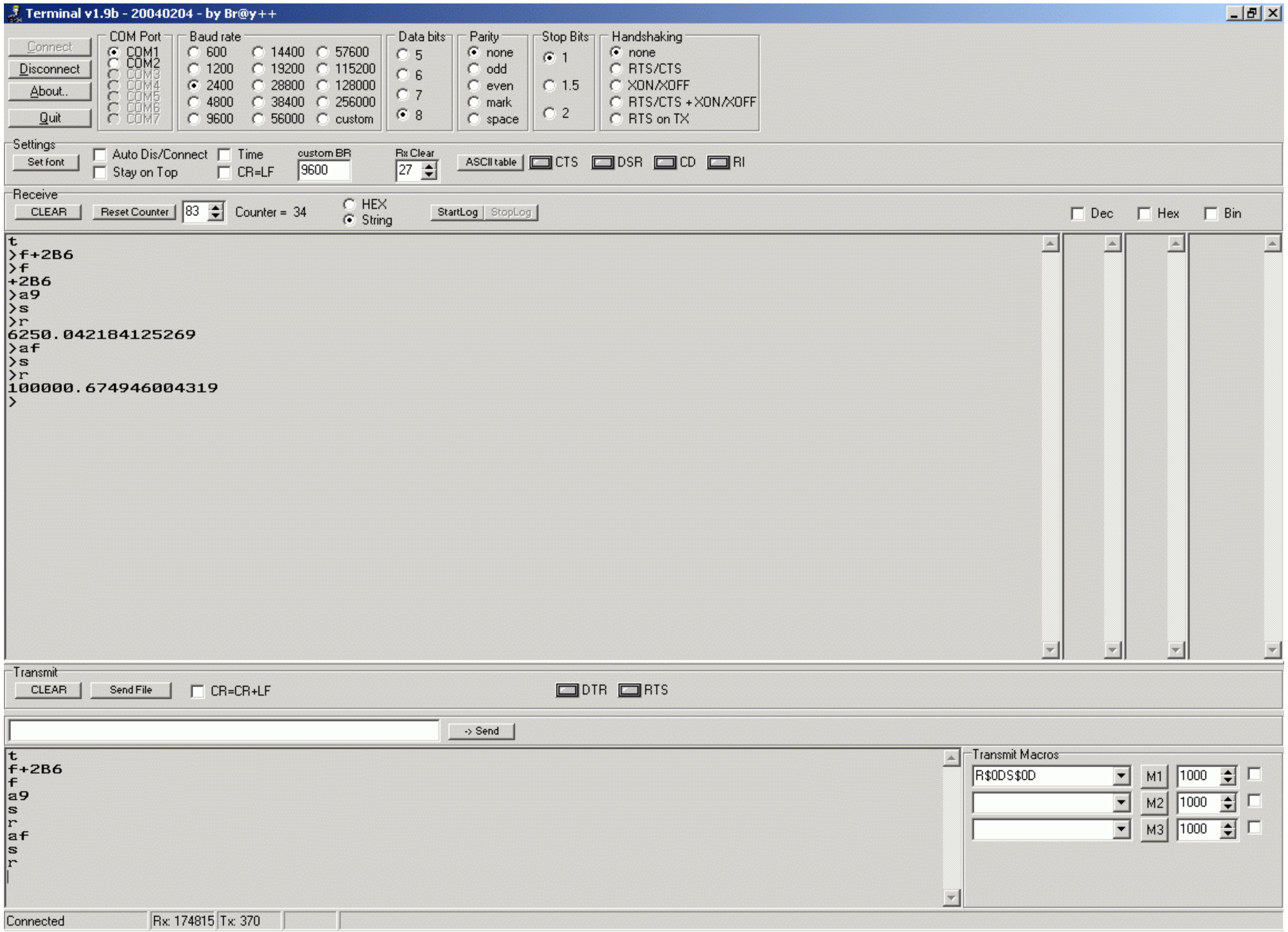
USTI I^2C Interface



USTI SPI Interface

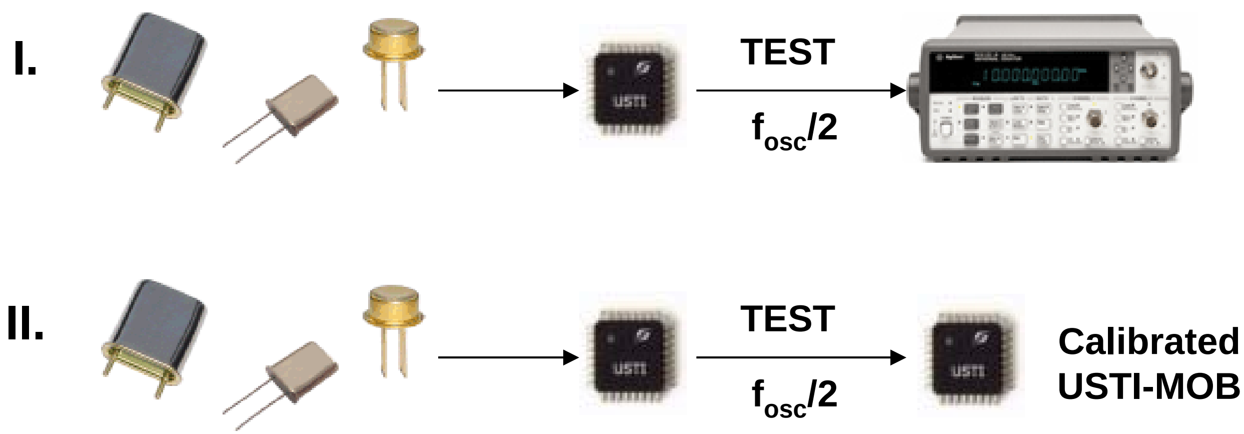


Software (Terminal V1.9b)



USTI-MOB Calibration Procedure

>T	; set the IC into the calibration mode
>F200010.82	; correction command
>F	; check the correction value in the IC
200010.82	; returned correction factor



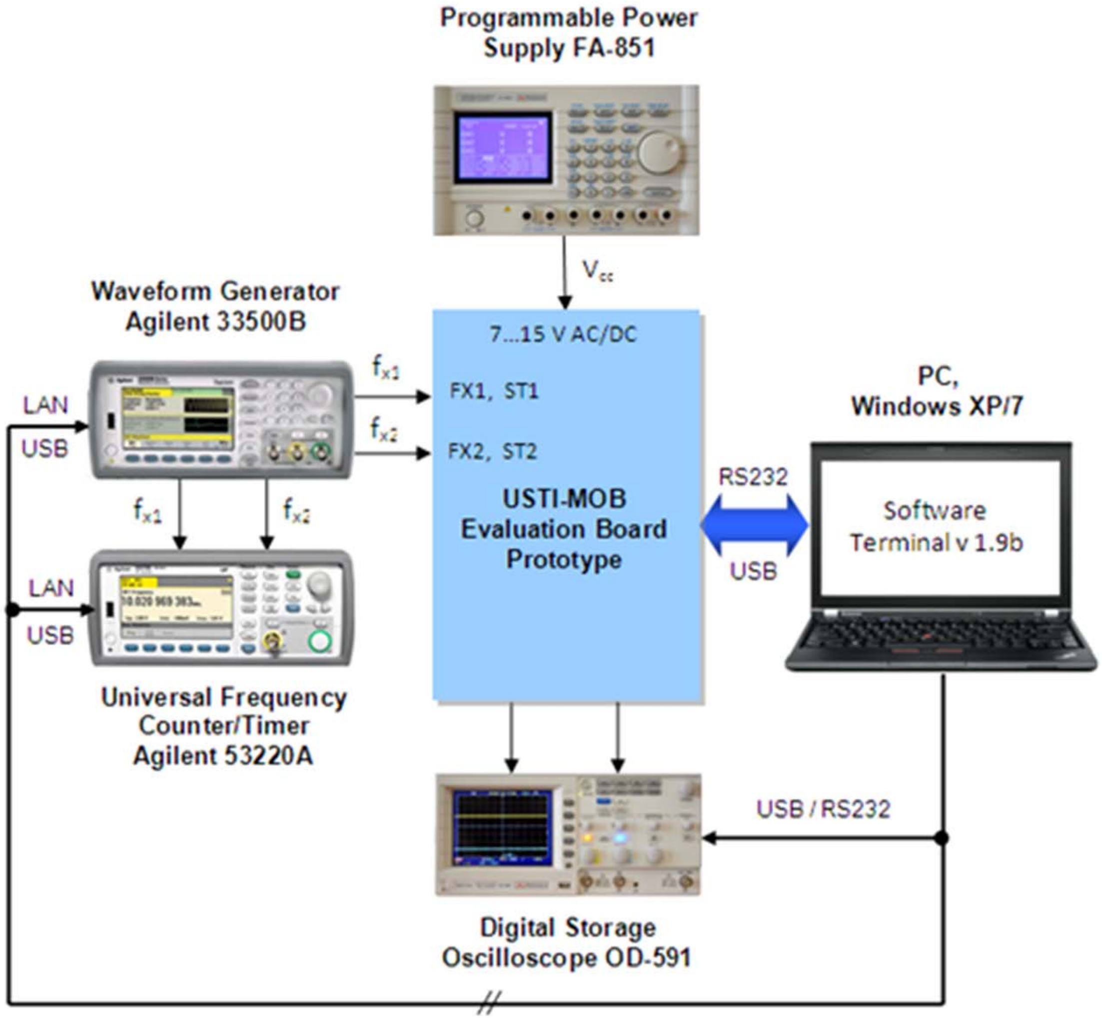
Temperature Drift Calibration

- The USTI-MOB is working in the industrial temperature range: – 40^{o} C...+ 85^{o} C
- Temperature drift error can be eliminated by the calibration in an appropriate working temperature ranges

No Calibrate If:

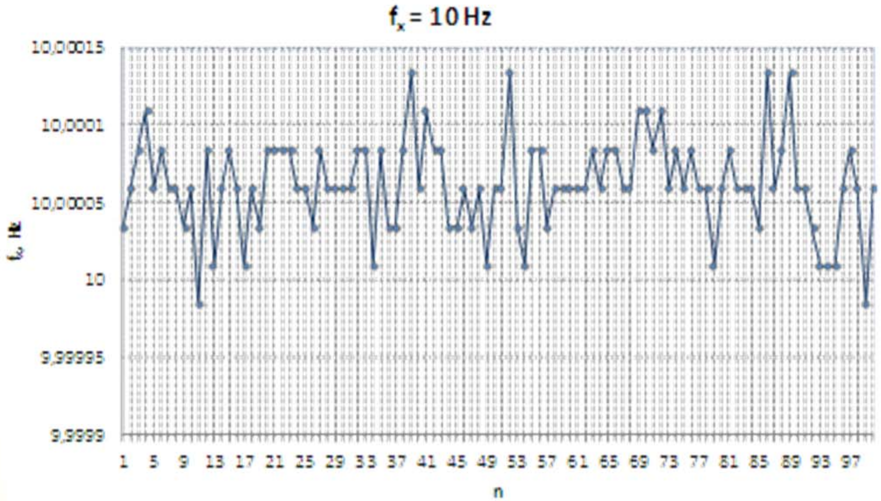
- Relative error of measurement > ±0.026 %
- Use a precision temperature-compensated integrated generator with ±1 ppm frequency stability over the -40°C to +85°C
- In this case a custom designed USTI-MOB should be ordered

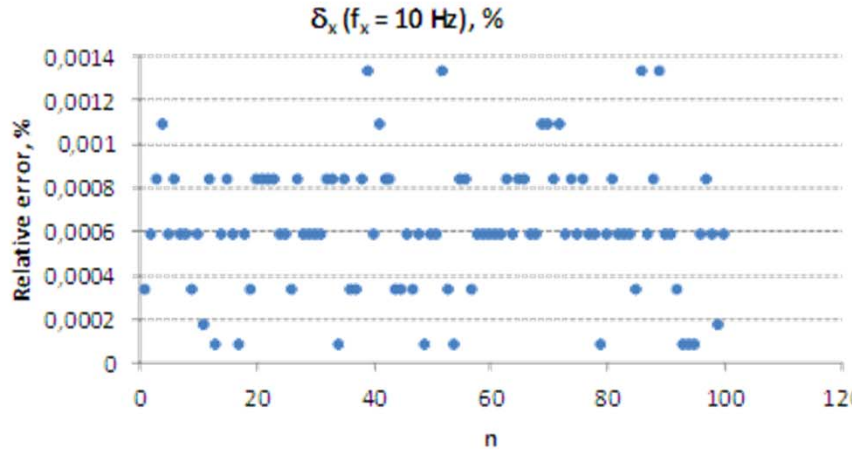
Experimental Set-up: f_x, T_x, t_x, its Ratio and Difference

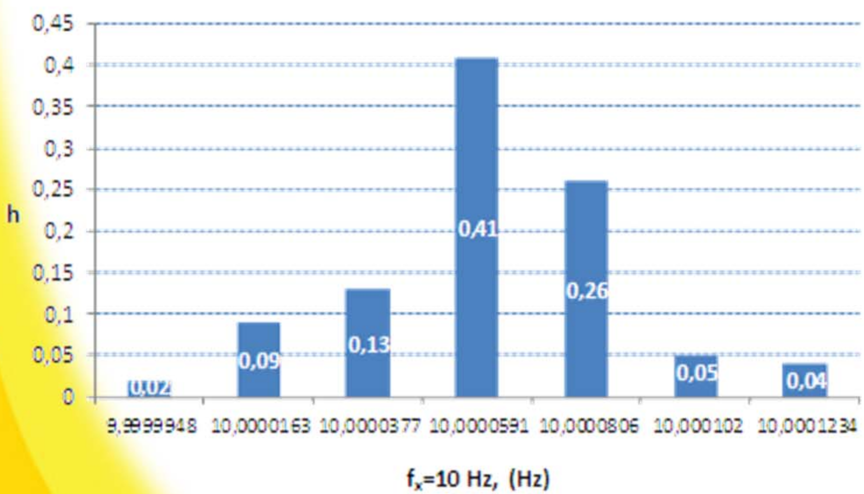


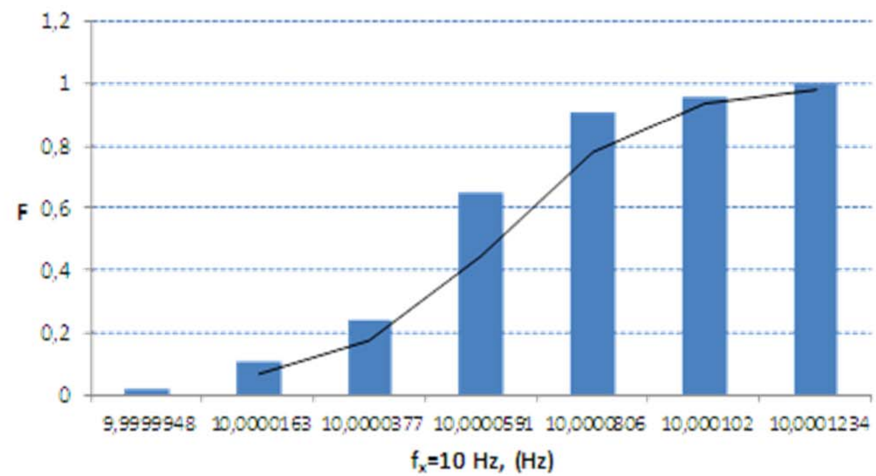
Measuring Equipment

Results of 10 Hz Measurements

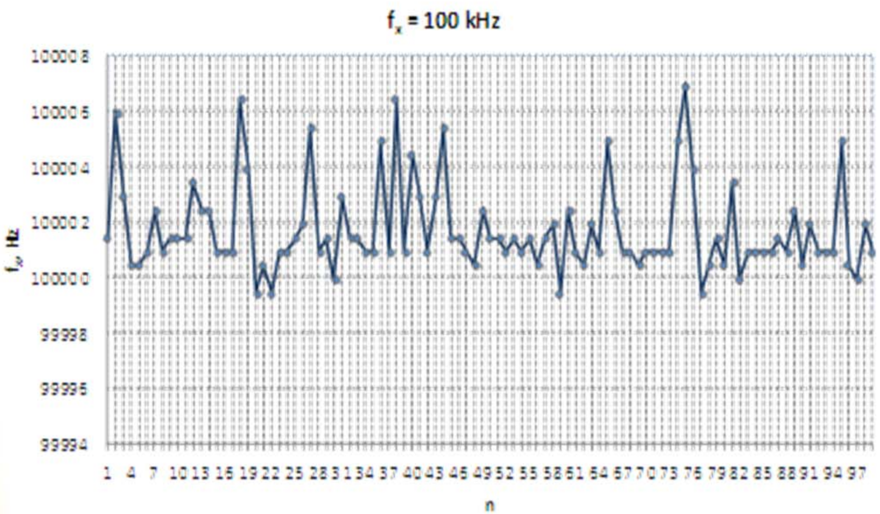


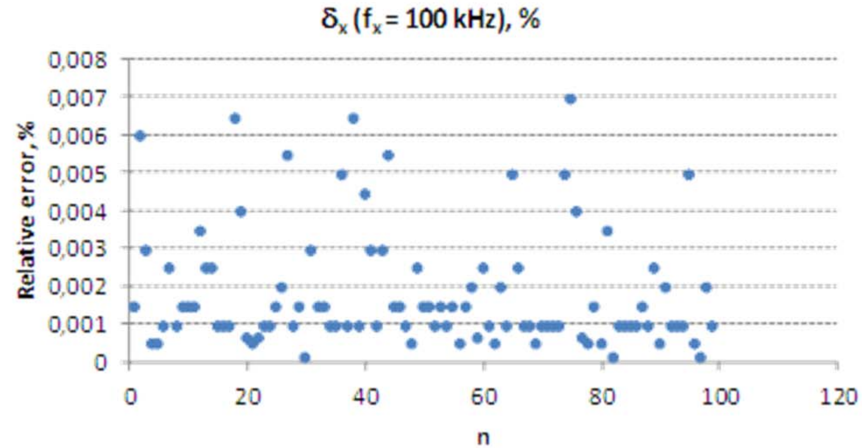


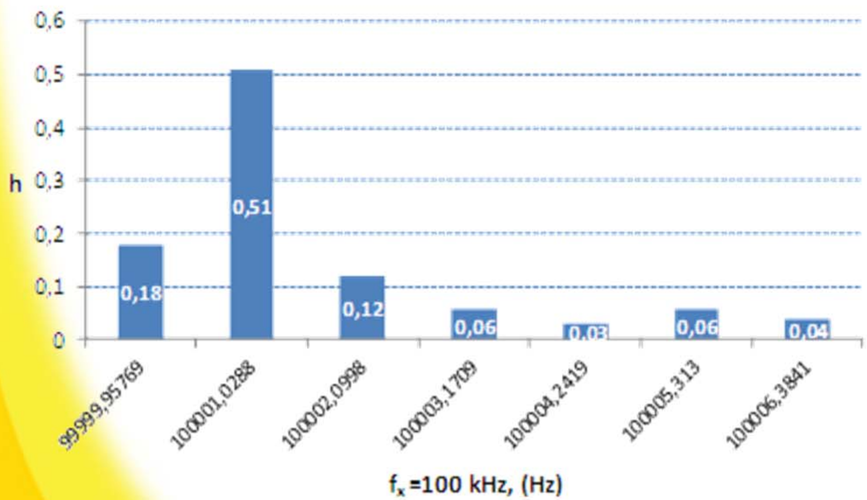


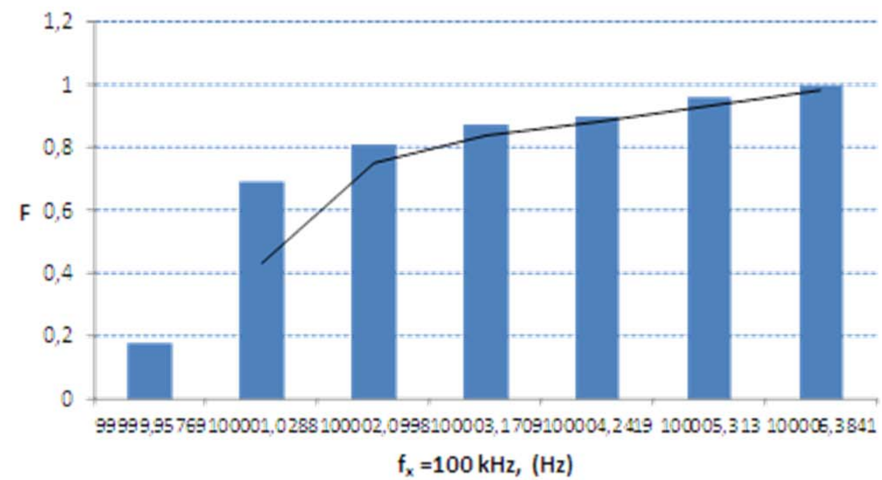


Results of 100 Hz Measurements

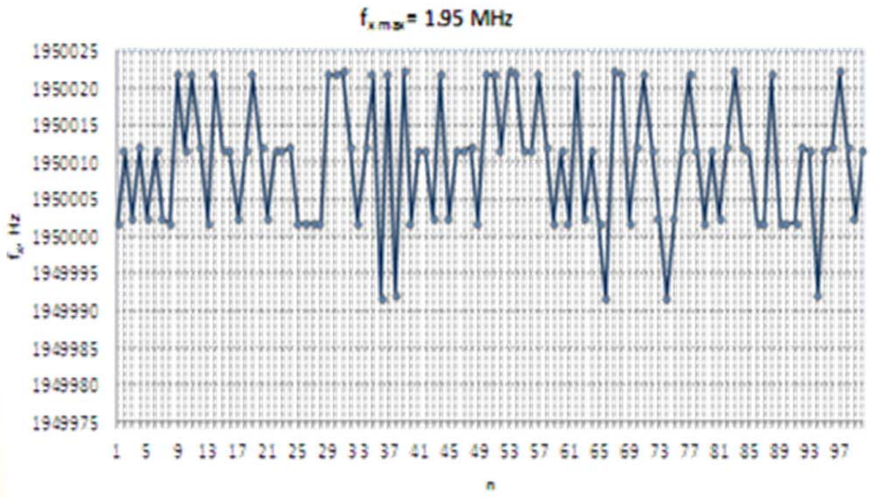


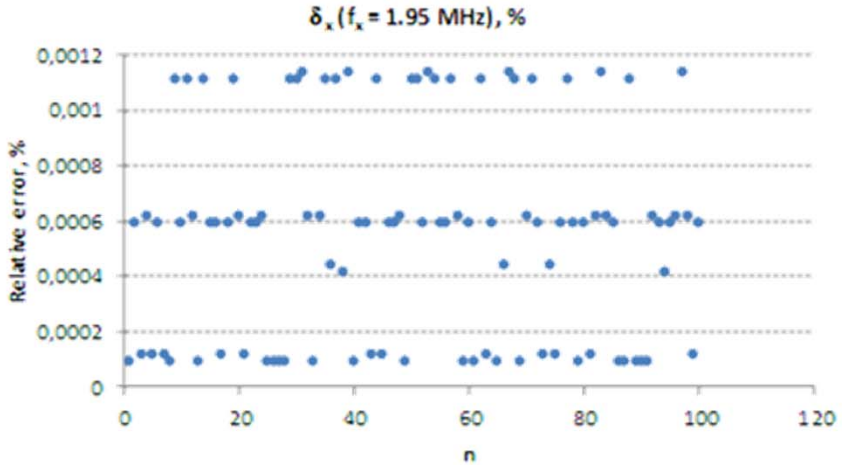


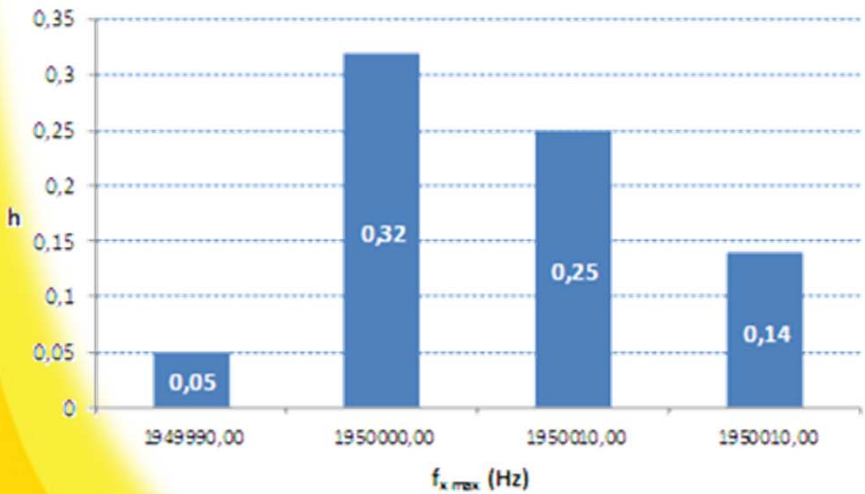


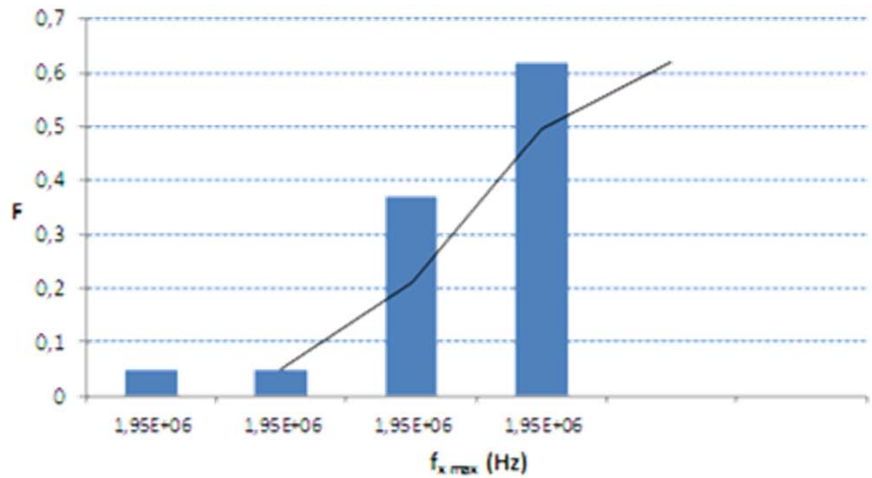


Results of 1.95 MHz Measurements

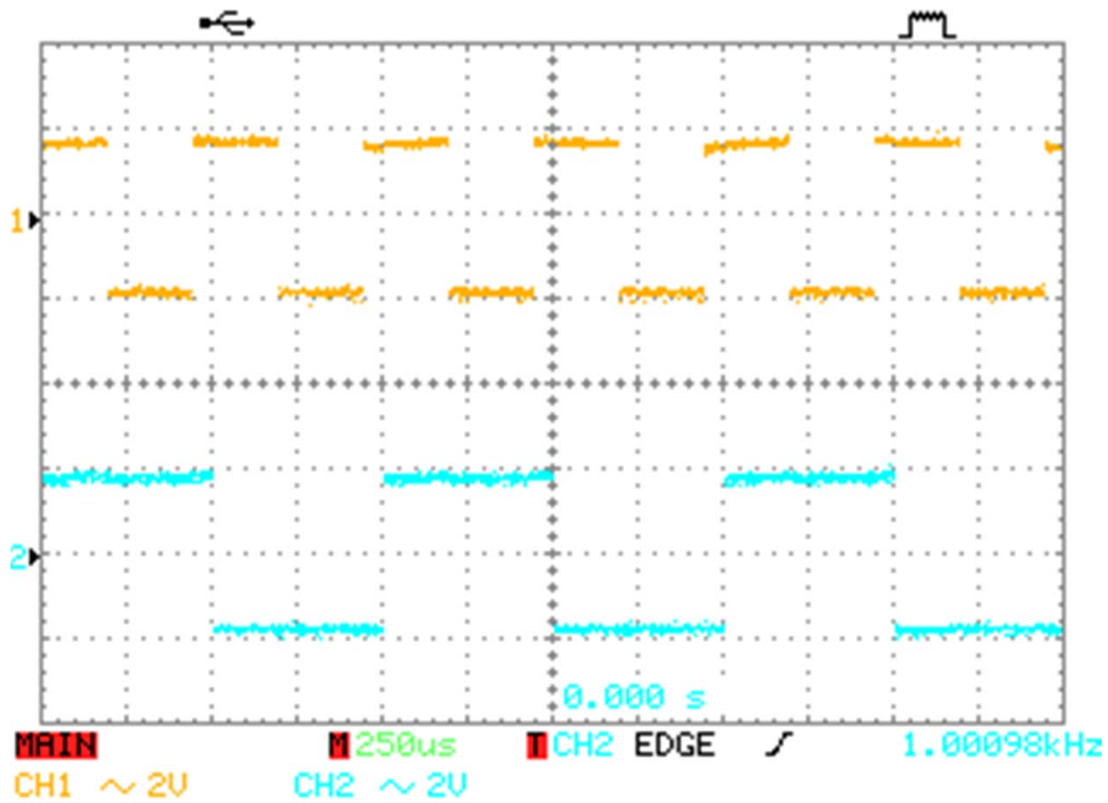




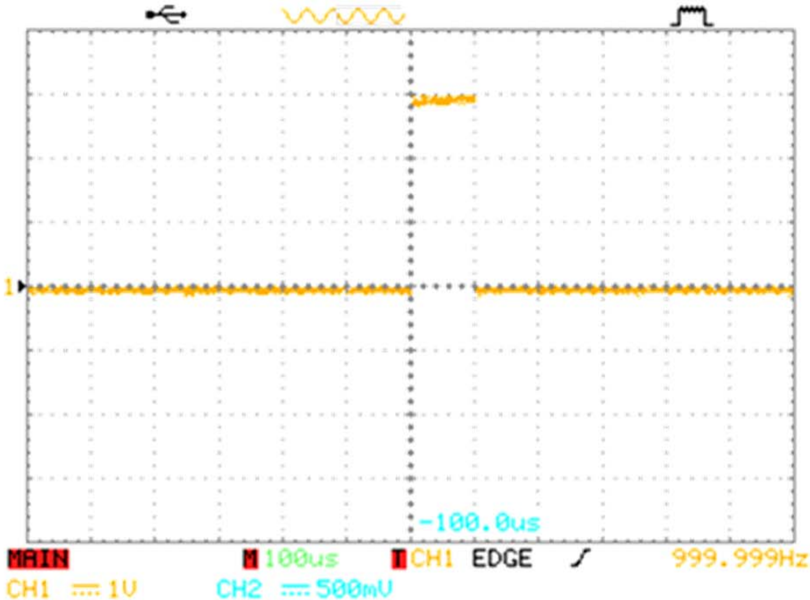


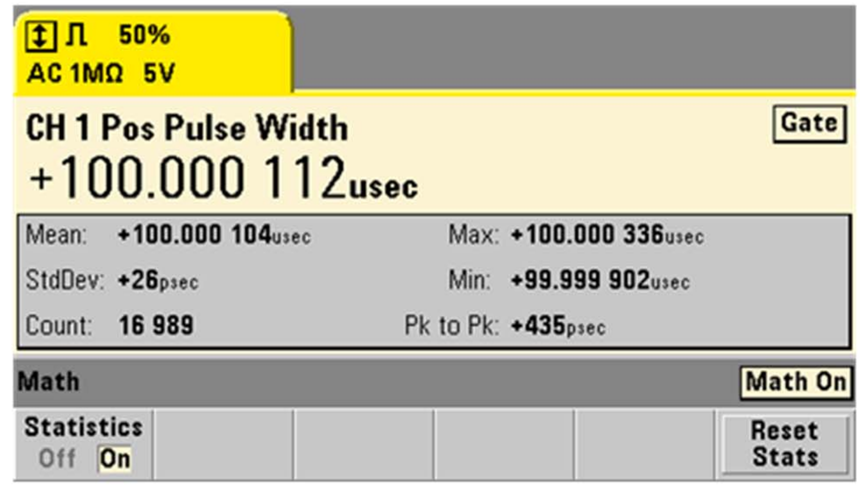


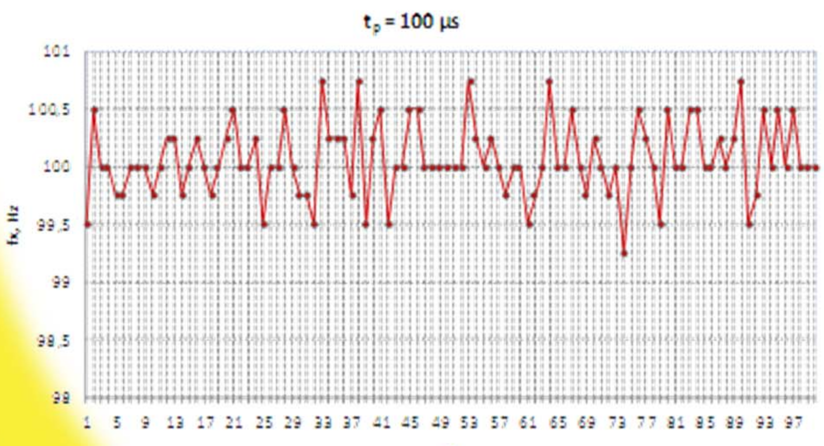
Frequency (Period) Ratio Measurement: f_{x1}/f_{x2} (T_{x1}/T_{x2})

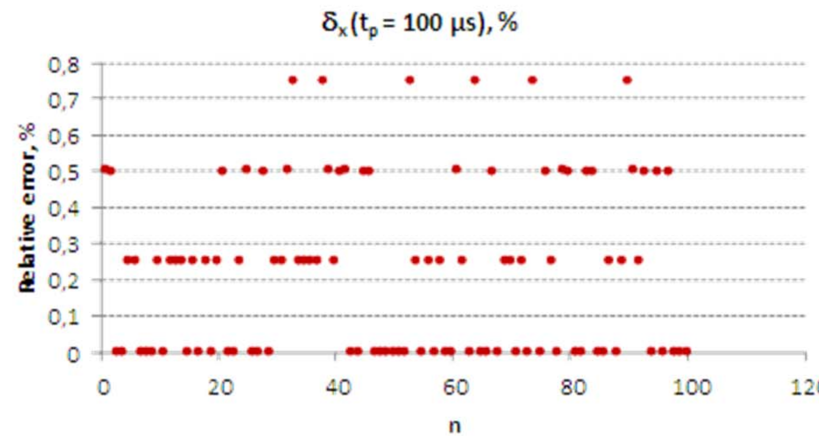


Pulse Width Measurement, t_x

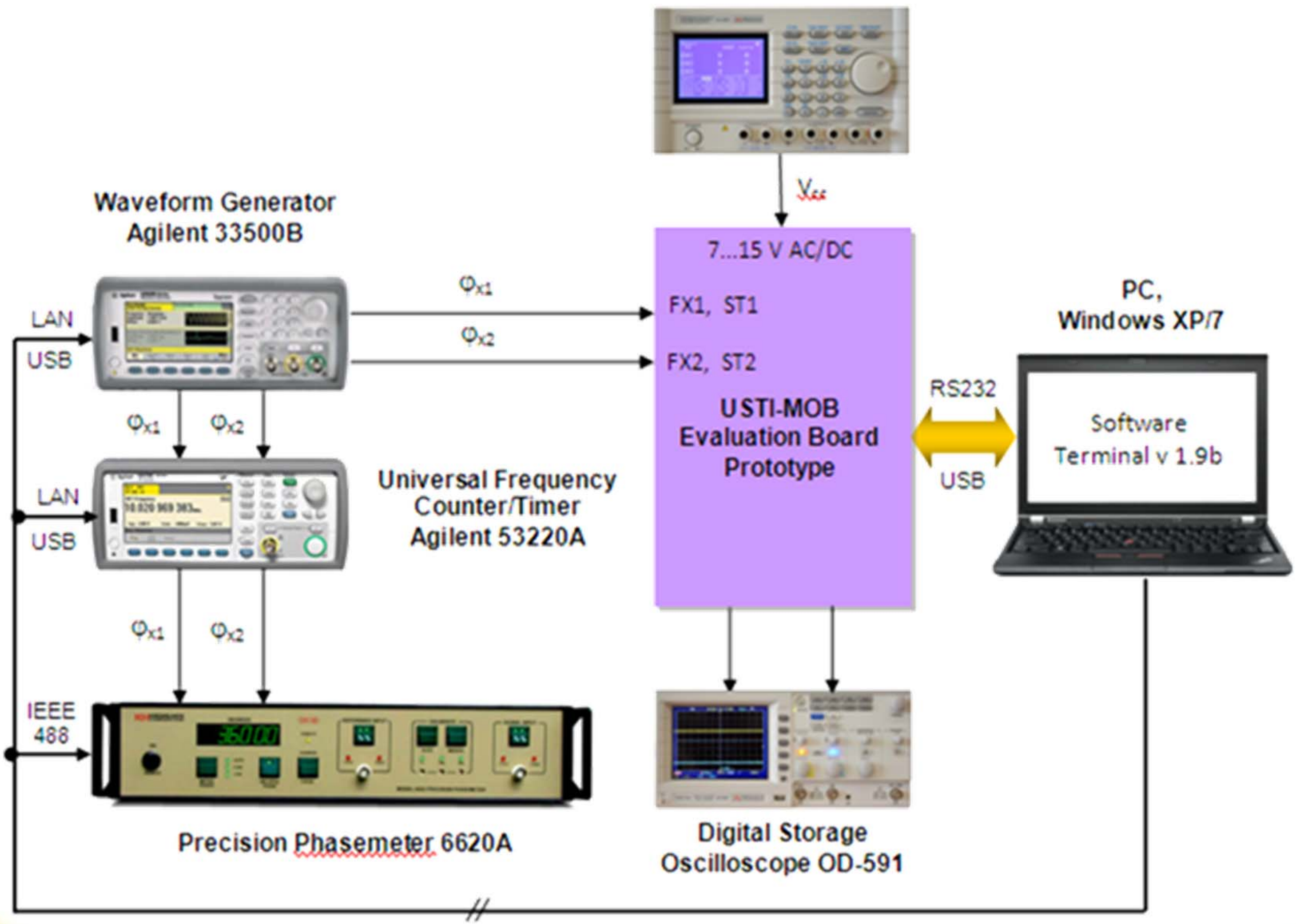




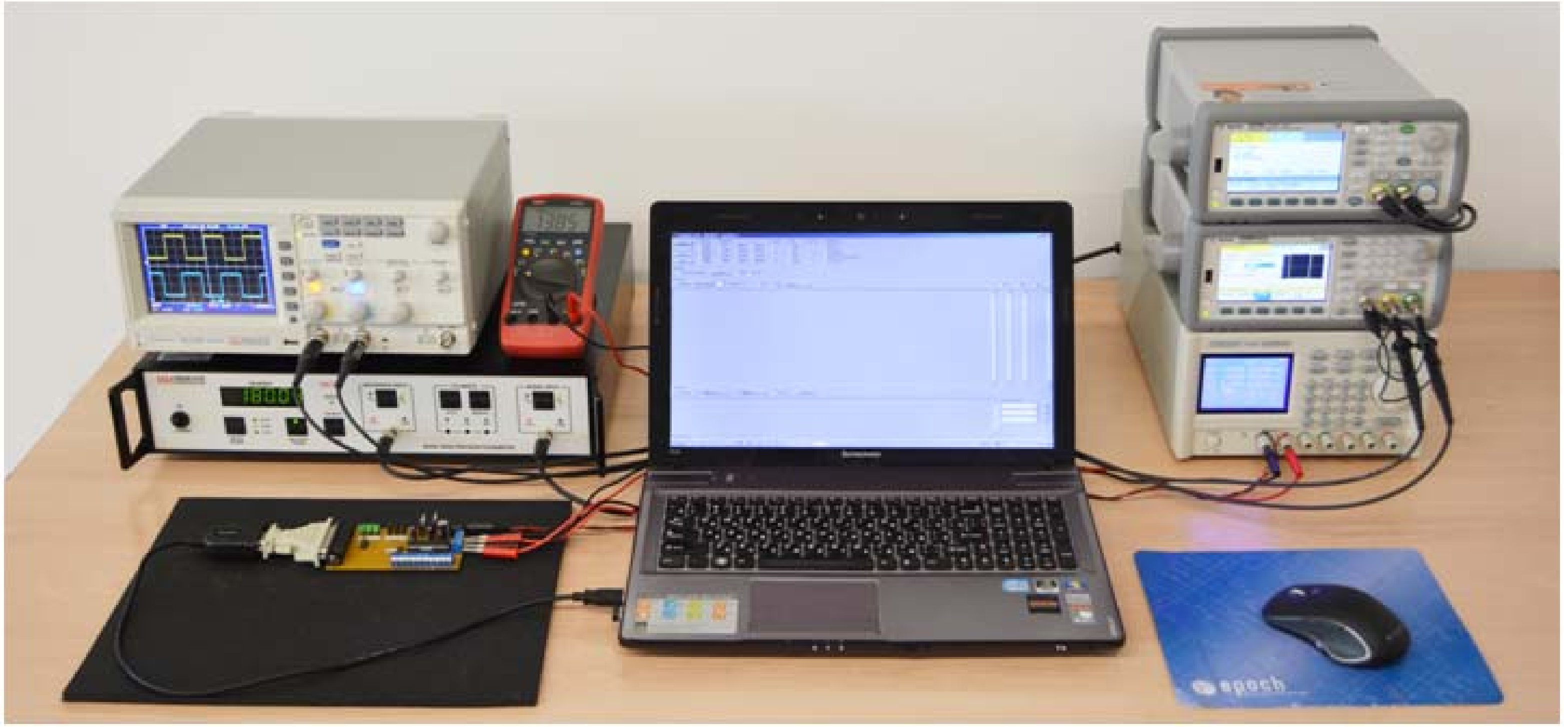




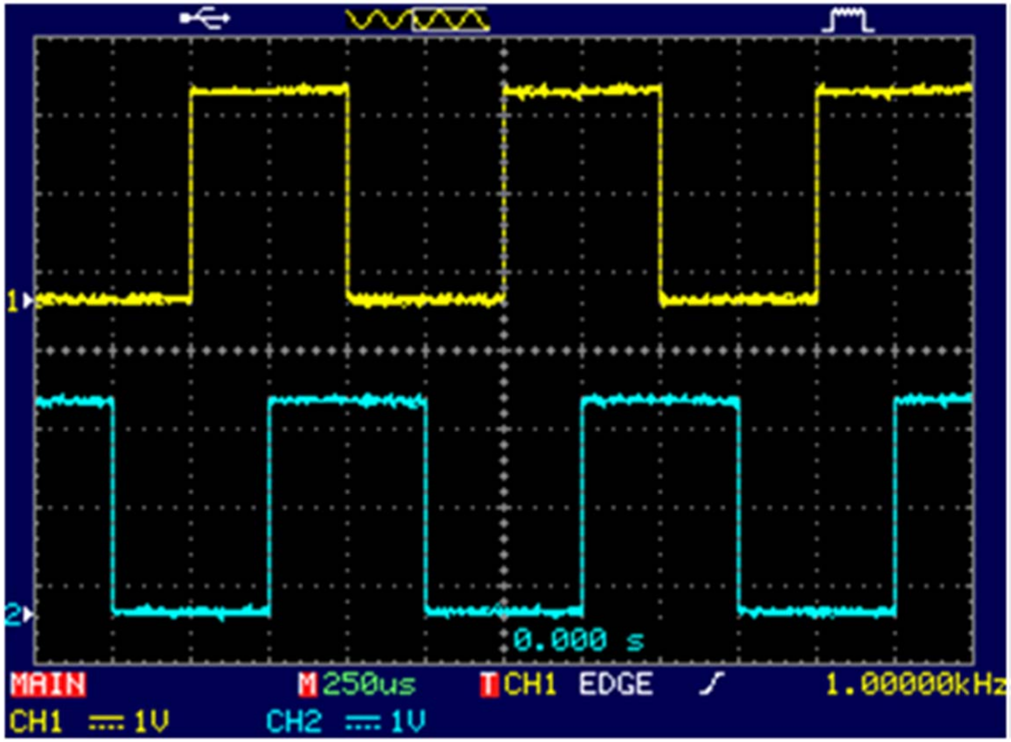
Experimental Set-up for Phase Angle Measurements, φ_x



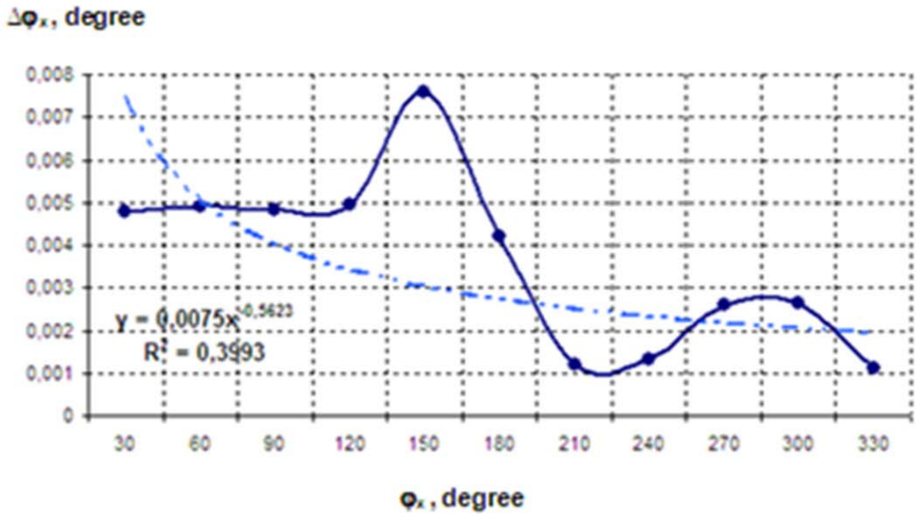
Measuring Equipment for φ_x Measurement

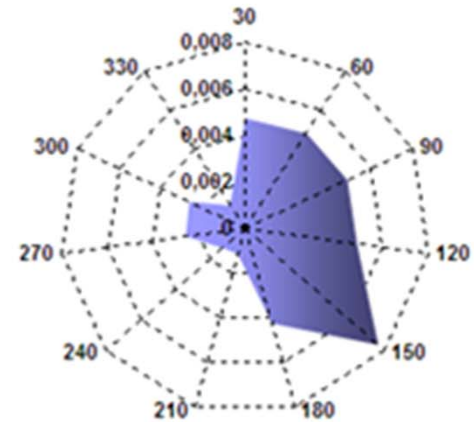


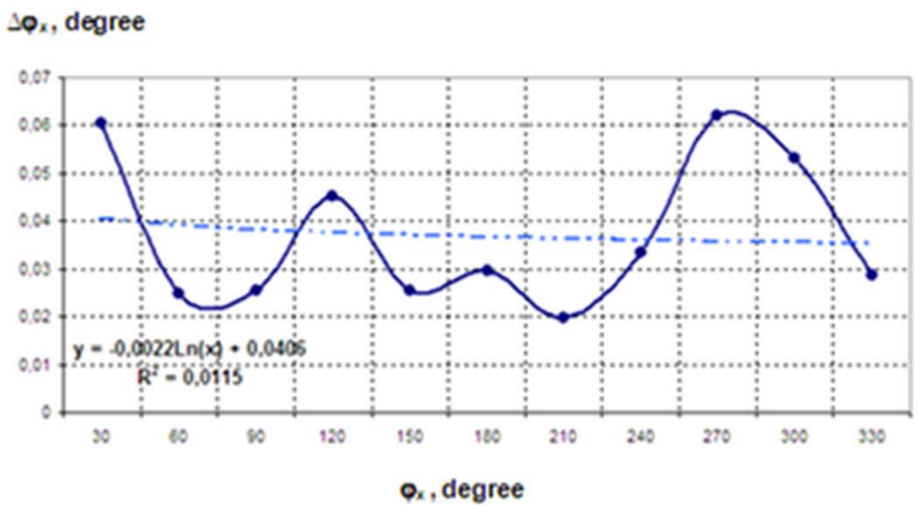
Rectangular Waveform Signals ($120^0\ \varphi_x$ at 1 kHz)

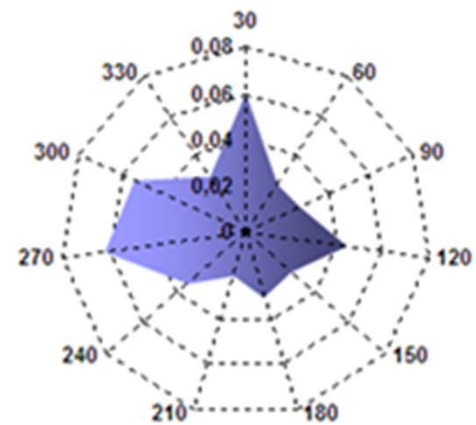


Phase Shift Measurement Absolute Error at 10 Hz and 100 Hz

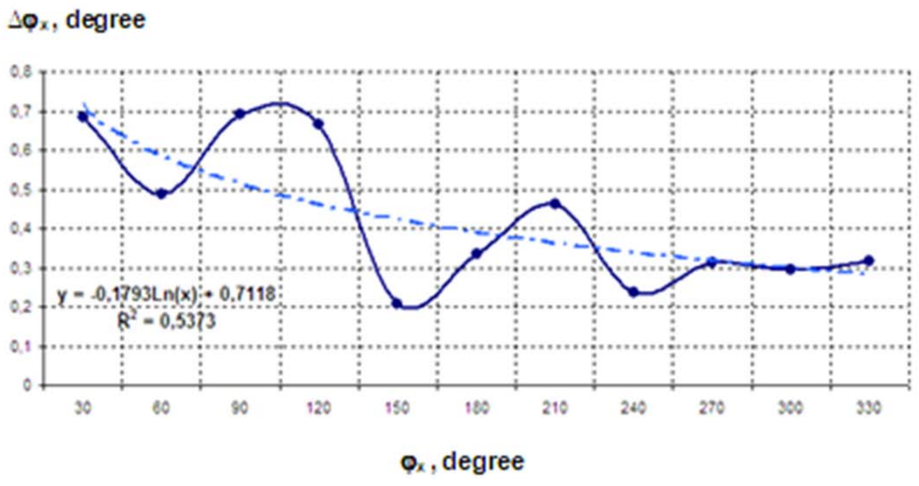


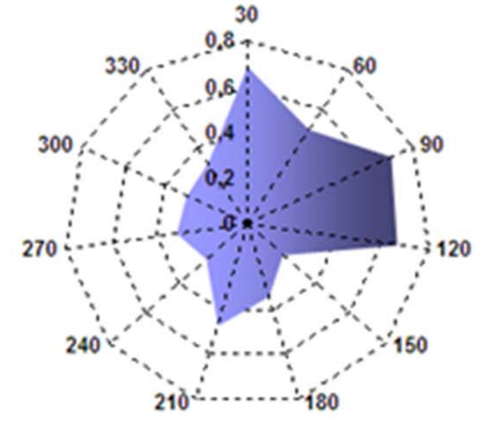


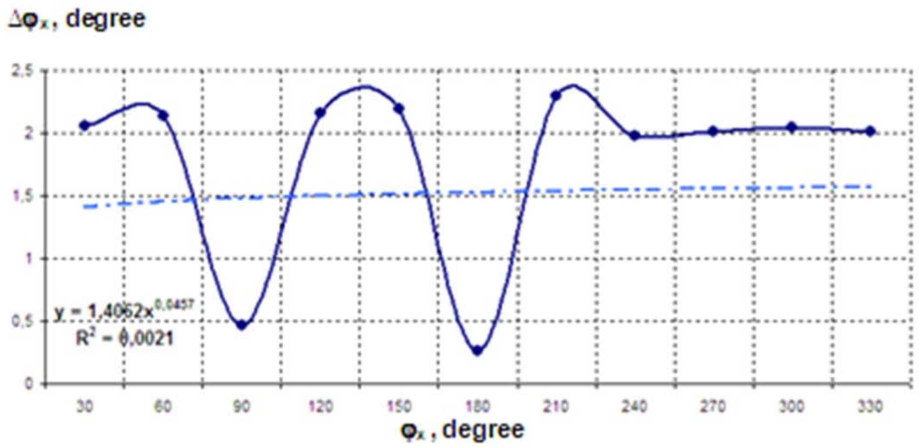


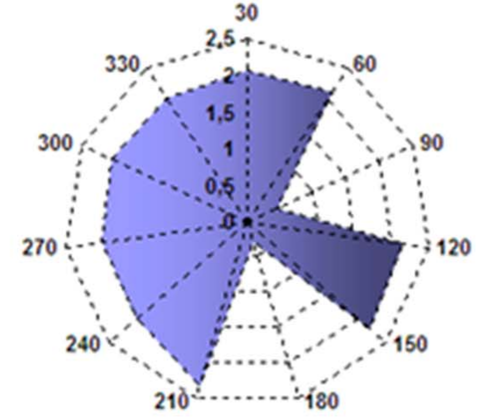


Phase Shift Measurement Absolute Error at 1 kHz and 4 kHz

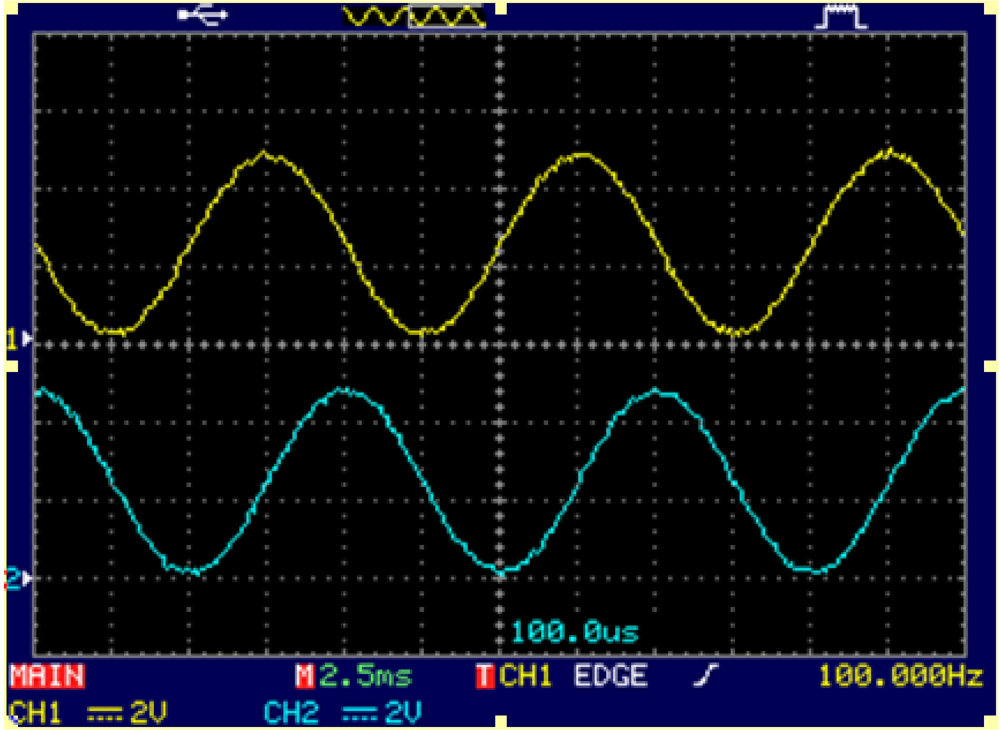




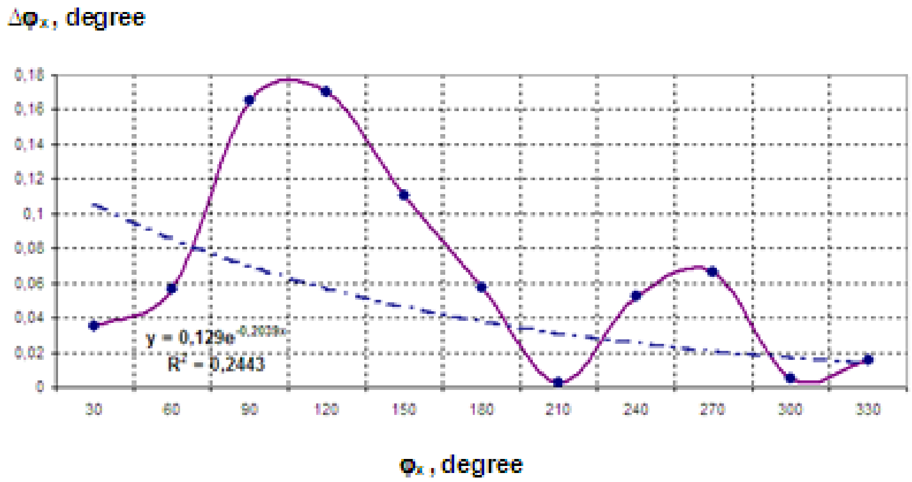


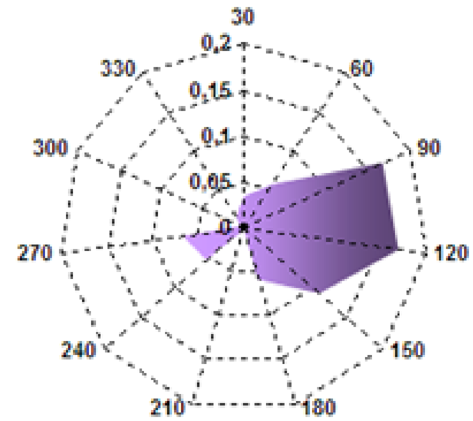


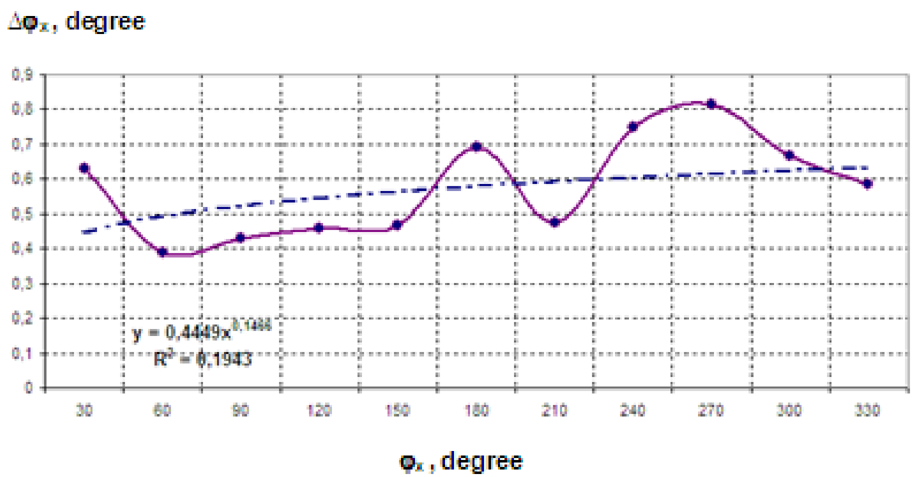
Sine Waveform Signals (90^0 φ_x at 100 Hz)

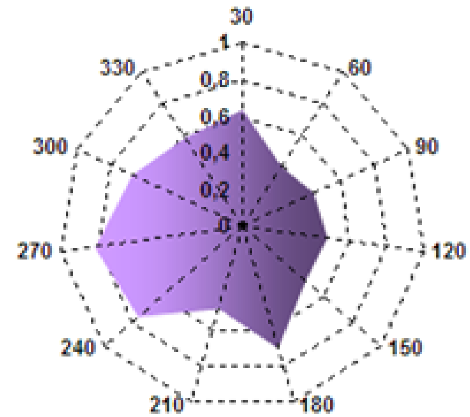


Phase Shift Measurement Absolute Error at 100 Hz and 1 kHz









Maximum Absolute Errors

Waveform	Frequency, Hz	Max. Absolute Error, ^{0}
Sine	100	± 0.17
	1 000	± 0.8
Rectangular	10	± 0.008
	100	± 0.06
	1 000	± 0.7
	4 000	± 2.3

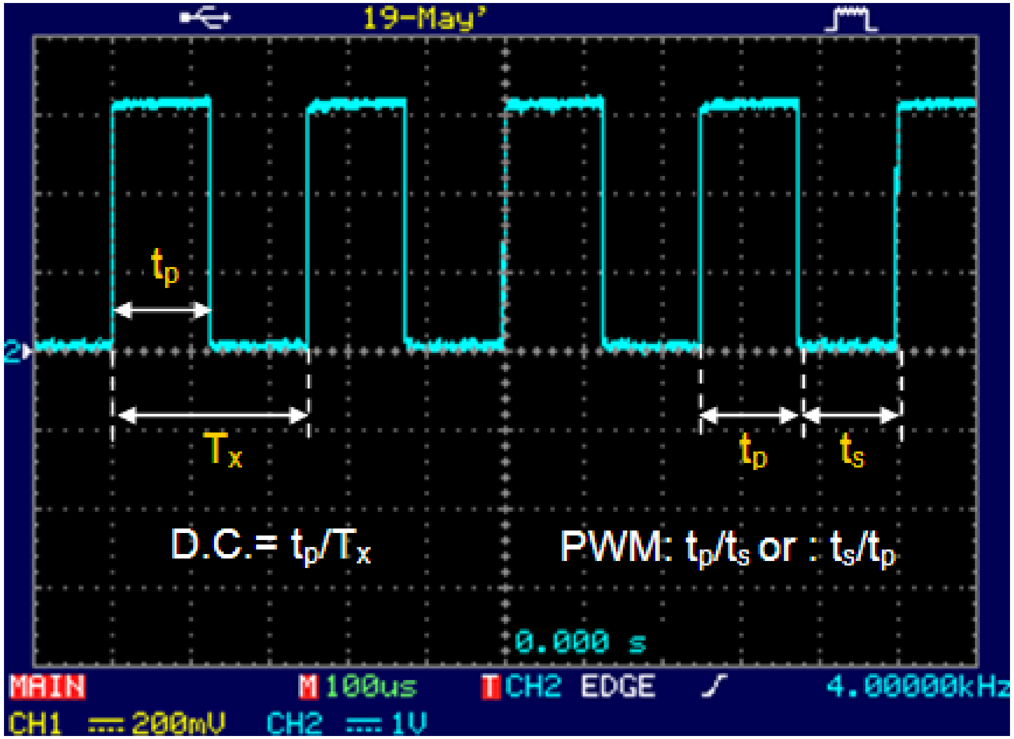
Commands for RS232, I2C and SPI Interfaces

M02 ; Select phase shift measurement mode
S ; Start measurement
C ; Check result status: ‘r’ if ready or ‘b if busy
R ; Get result in BCD ASCII format

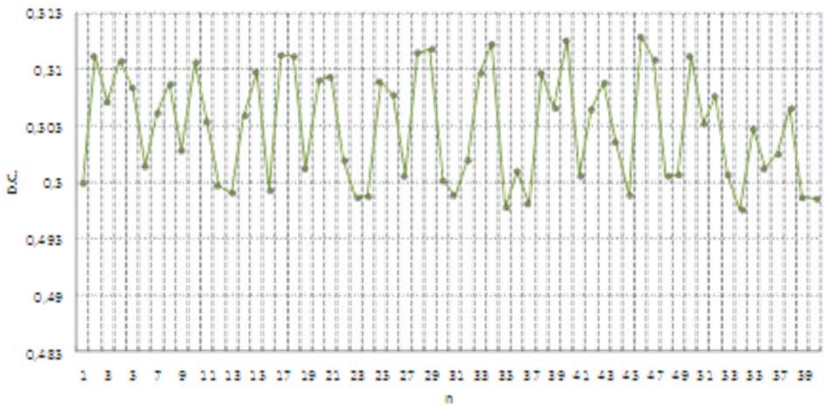
<06><02> ; Select phase shift measurement mode
<09> ; Start measurement
<03> ; Check result status: ‘0’ if ready or not ‘0' if busy
<07> ; Get measurement result in BCD format

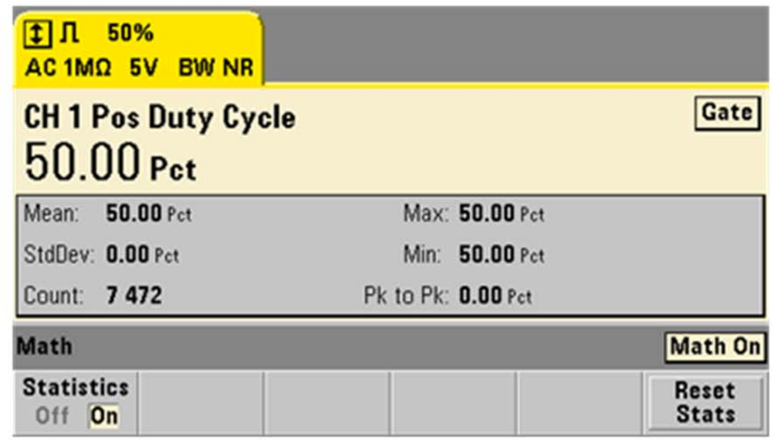
<06><02> ; Select phase shift measurement mode
<09> ; Start measurement
<03><FF> ; Check result status: ‘0’ if ready or not ‘0' if busy
<07><FF> ; Get measurement result in BCD format

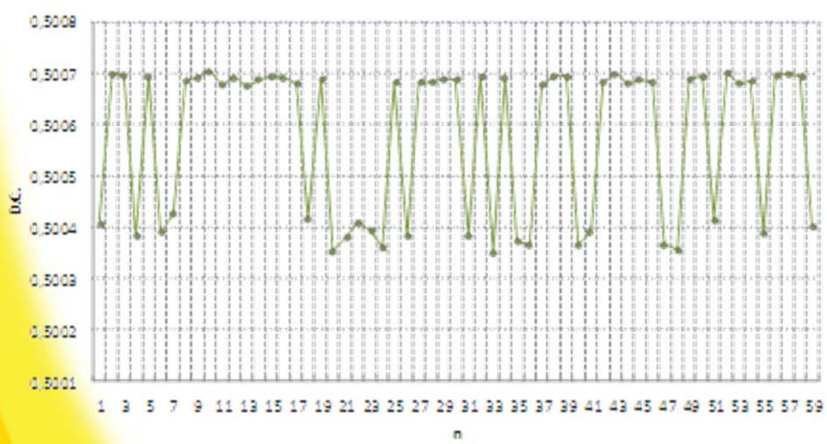
Duty-Cycle and PWM Signal

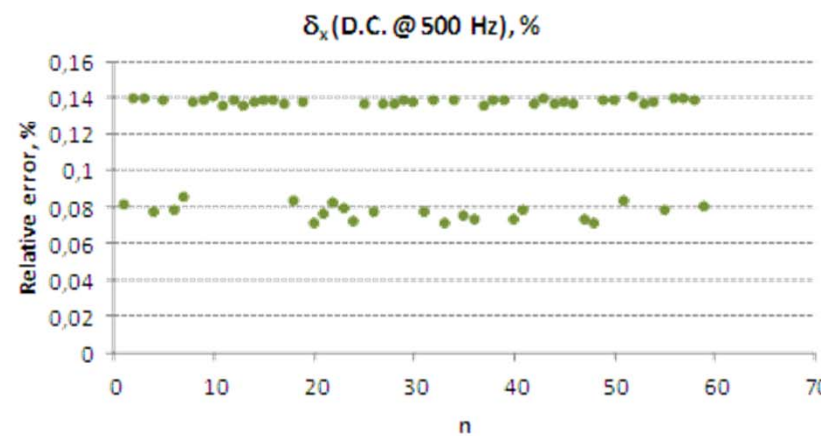


Duty-Cycle Measurement at 100 kHz and 500 Hz





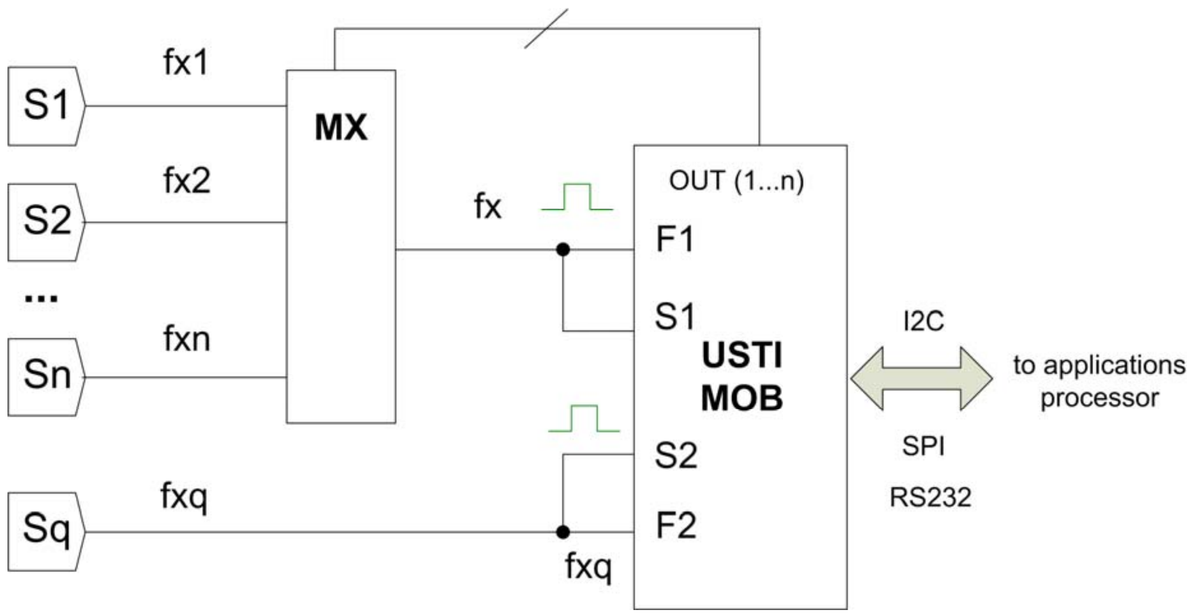




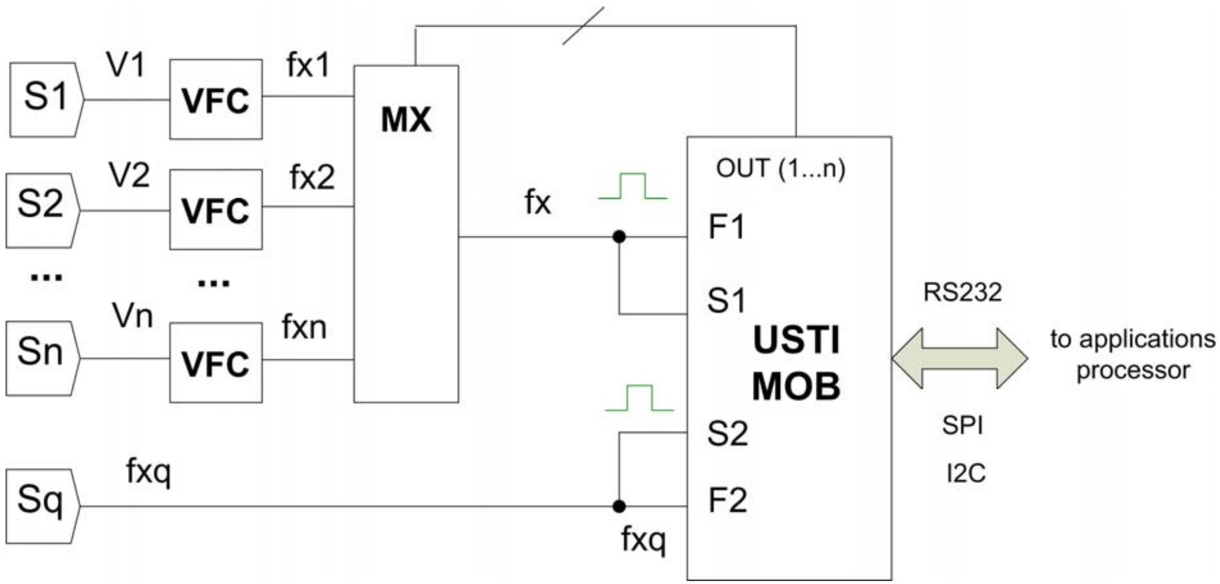
Duty-cycle Values vs. Frequencies

Frequency, kHz	Duty-cycle, %
< 0.5	1 ... 99.3
1	1.5 ... 98
10	15 ... 80
20	30 ... 71
30	46 ... 60
> 40	50

Multisensor System for Smartphones and Tablets



Analog Sensors Interfacing



Measurement Time Calculation

$$T_{meas} = t_{conv} + t_{comm} + t_{calc}$$

$$\begin{cases} t_{conv} = \dfrac{1}{f_x} \quad if \quad \dfrac{N_\delta}{f_0} \prec T_x \\ t_{conv} = \dfrac{N_\delta}{f_0} + (0 \div T_x) \quad if \quad \dfrac{N_\delta}{f_0} \geq T_x \end{cases}$$

where $N\delta = 1/\delta$ is the number proportional to the required programmable relative error δ

The calculation time depends on operands and is as usually

$t_{calc} \leq 20$ ms

Communication Time

- **For RS232 interface:** $$t_{comm} = 10 \cdot n \cdot t_{bit}$$

  where t_{bit} = 1/300, 1/600, 1/1200, 1/2400, 1/4800, 1/9600, 1/14400, 1/19200, 1/28800, 1/38400 or 1/76800 is the time for one bit transmitting; *n* is the number of bytes (*n* = 13÷24 for ASCII format).

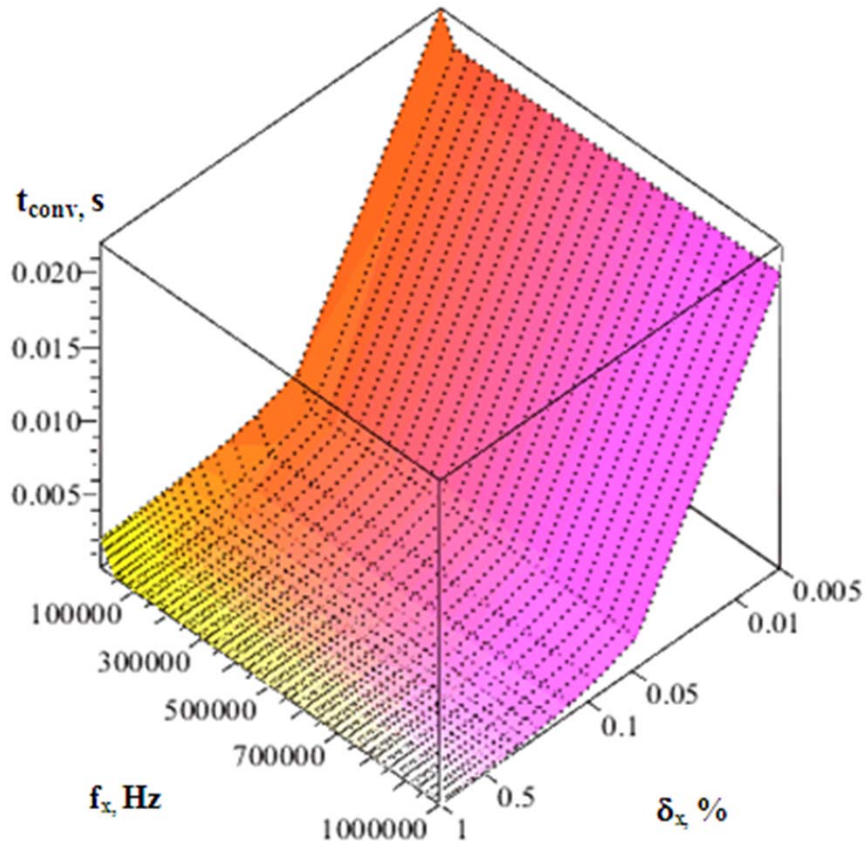
- **For SPI interface:** $$t_{comm} = 8 \cdot n \cdot \frac{1}{f_{SCLK}}$$

  where f_{SCLK} = 28 kHz is the serial clock frequency; *n*=12÷13 is the number of bytes: for BCD (*n*=13) or binary (*n*=12) formats

- **For I²C interface:** $$t_{comm} = 8 \cdot n \cdot \frac{1}{f_{SCL}}$$

  where f_{SCL}= 20 kHz is the serial clock frequency *n*=12÷13 is the number of bytes for measurement result: BCD (*n* = 13) or binary (*n* =12).

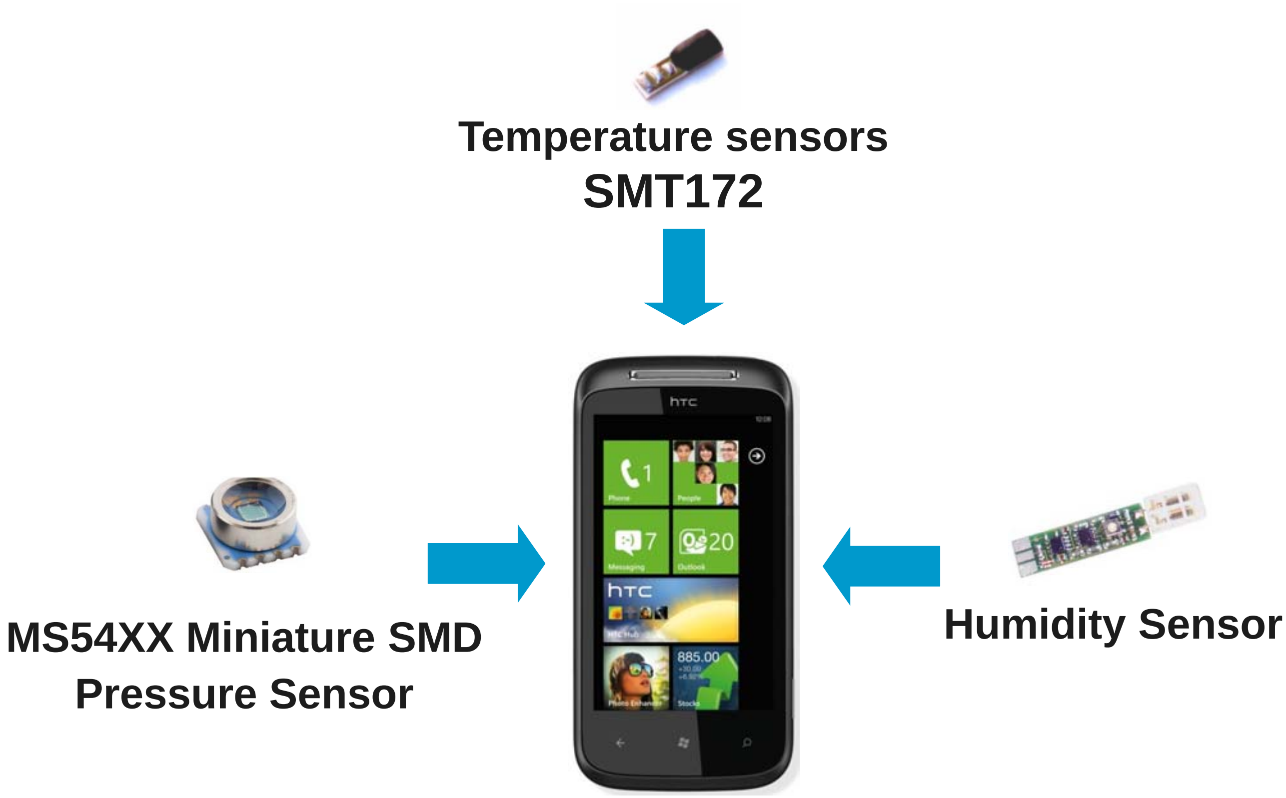
Dependence of t_{conv} (δ_x, f_x) in the frequency range from 0.5 to 1 MHz



Sensors Systems Examples

1. Introduction: Markets and Definitions
2. Modern Challenges
3. Sensor Systems Design: Introduction
4. Advanced Sensor Systems Design
5. Sensors Systems Examples
6. The Future and Summary

Smartphone based Weather Station



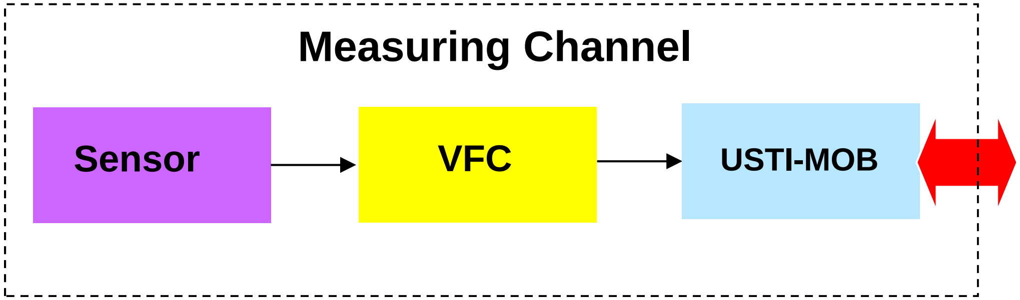
Commands for USTI-MOB (I2C Interface)

<06><00>	; Frequency measurement in the 1st channel (humidity)
<02><02>	; Set up the conversion error 0.25 %
<09>	; Start a measurement
<03>	; Check result status: '0' if ready or not '0' if busy
<07>	; Get result in BCD format

<06><14>	; Duty-cycle measurement in the 2nd channel (temperature)
<09>	; Start a measurement
<03>	; Check result status: '0' if ready or not '0' if busy
<07>	; Get result in BCD format

<06><12>	; Resistance-bridge B_x measurement mode (pressure)
<10><13>	; Set the charging time 20 ms
<09>	; Start measurement
<03>	; Check result status: '0' if ready or not '0' if busy
<07>	; Read conversion result

Measuring Channel



Relative Error's Components:

$\pm\delta_s$, %

$\pm\delta_{VFC}$, %

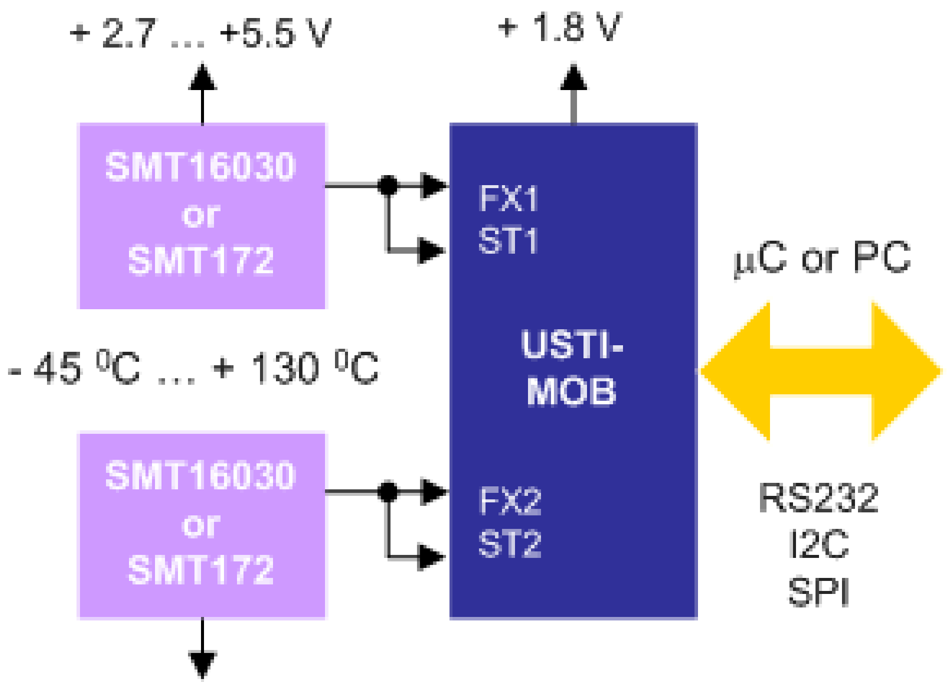
$\pm\delta_q$, % - quantization error

$\pm\delta_o$, % - reference error

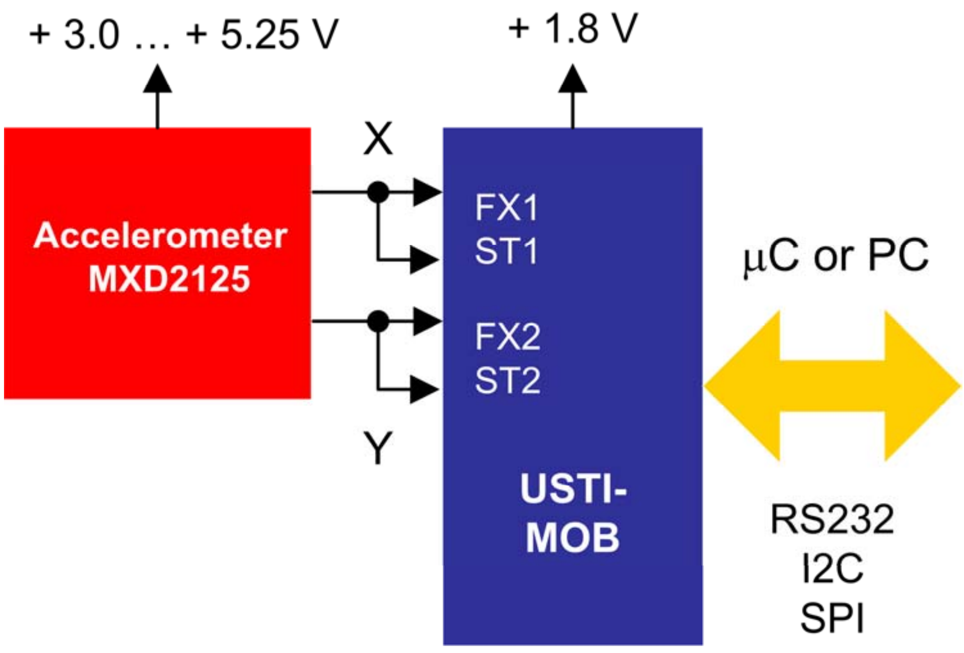
Main considerations:

- USTI-MOB's relative error (δ_q) must be in one order less (or at the lease in 5 times less than the sensor's error)
- The reference error for calibrated USTI-MOB is $\delta_o=\pm0.00001$ %

Low Power Consumption Temperature Sensor Systems



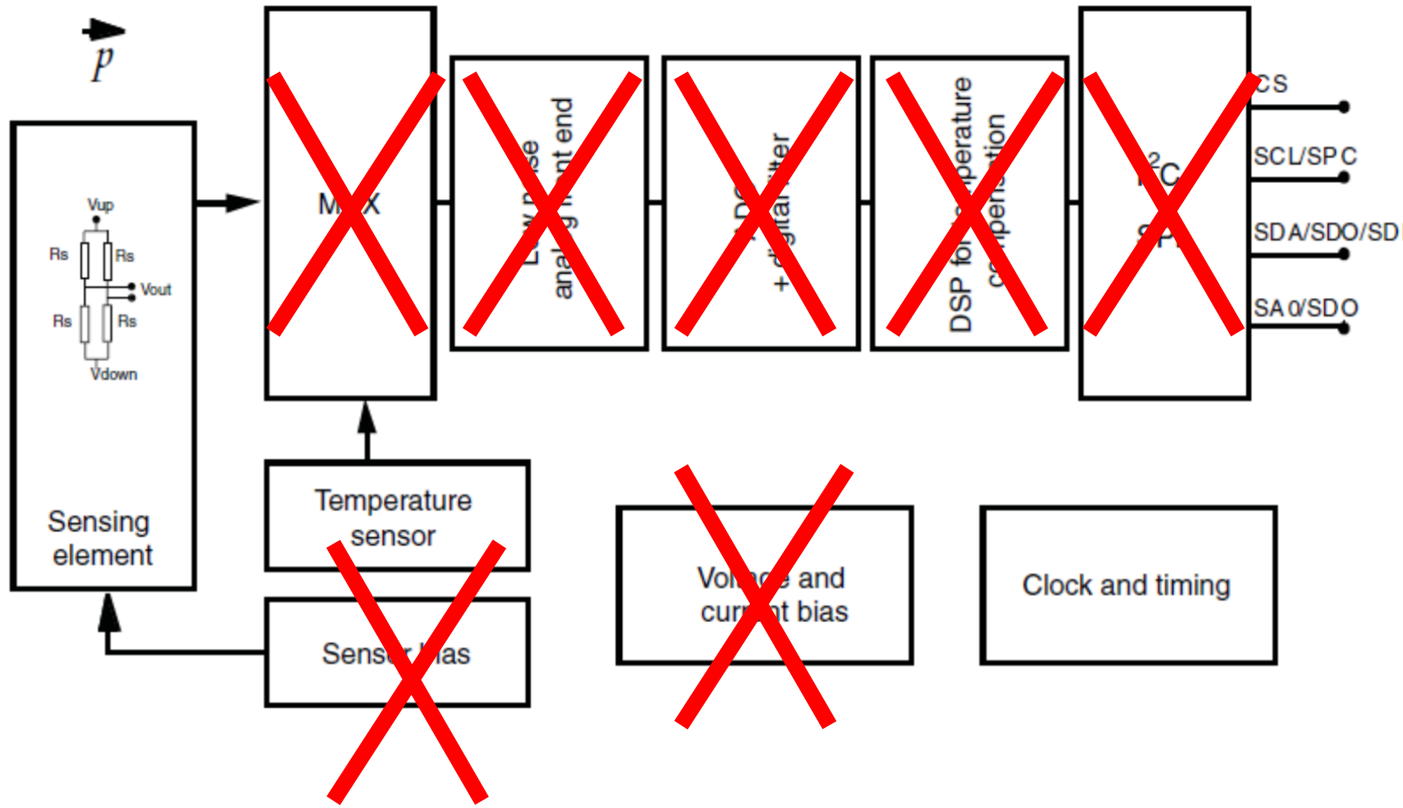
Accelerometer Sensor Systems



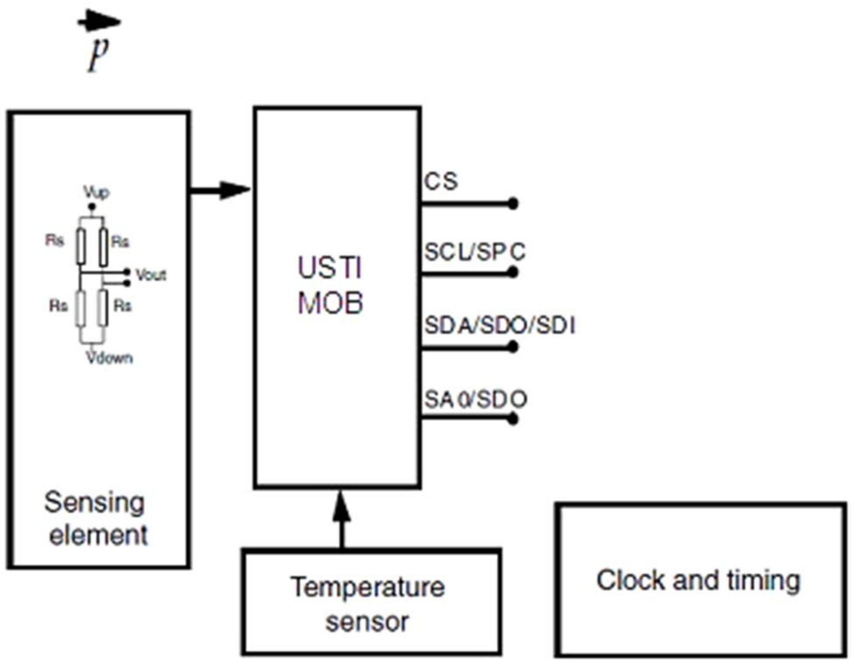
Commands for RS232 Interface

M04	; Select duty-cycle measurement mode
S	; Start measurement
C	; Check result status: ‘r’ if ready or ‘b if busy
R	; Get result in BCD ASCII format

Barometric Pressure Sensor (I)



Barometric Pressure Sensor (II)



USTI-MOB Custom Design

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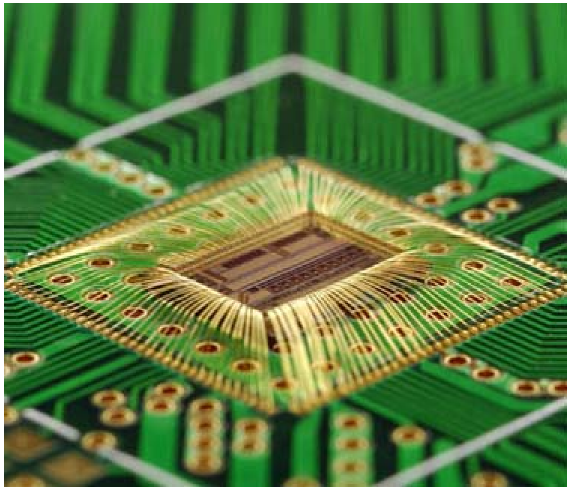
simplify, go faster!

- Extended functionality
- New measuring modes
- Customized units of measurements
- Improved metrological performance and communication interfaces

The Future



- USTI-WSN
- ASIC or IC
- SoC/SiP

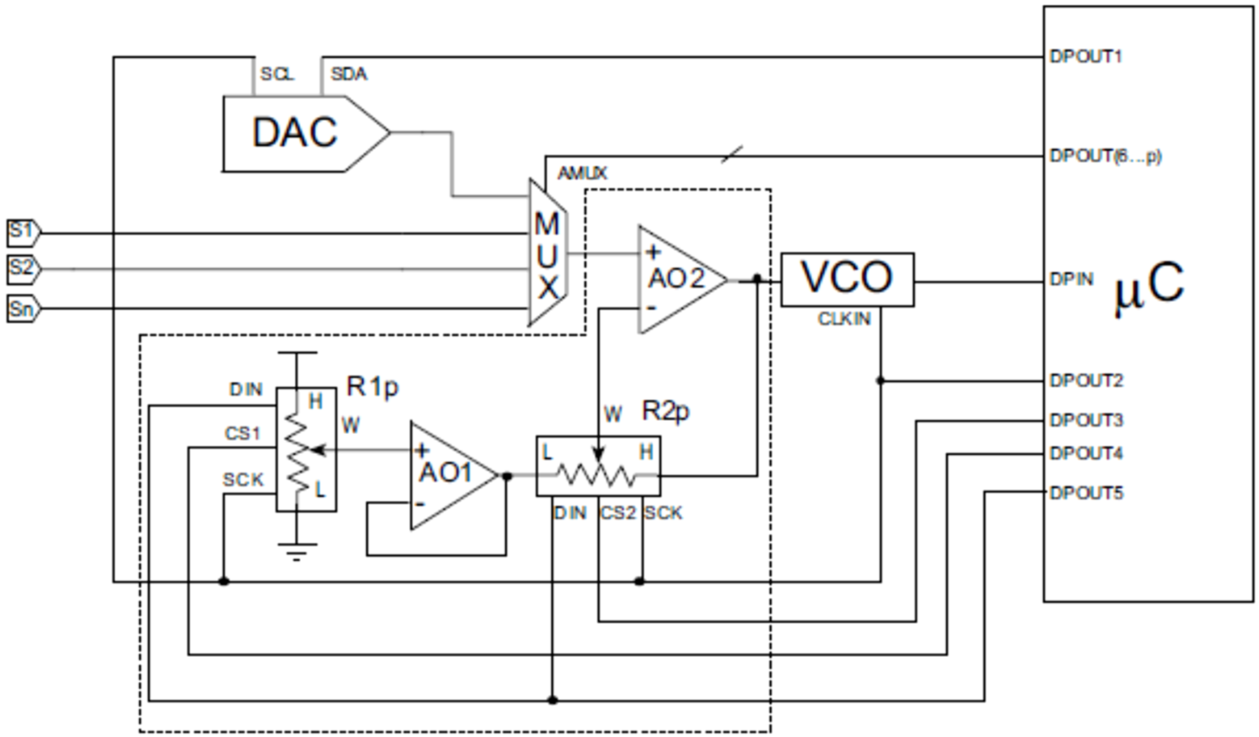
USTI-WSN

- The same metrological performance and functionality as USTI IC
- Includes RF-CMOS 2.4 GHz radio transceiver
- IEEE 802.15.4, ZigBee, IPv6/6LoWPAN, RF4CE, SP100, WirelessHART and ISM applications
- Supply voltage is 1.8 V
- Current consumption is less than 18.8 mA in active mode
- 64-pad QFN package

Traditional Approach

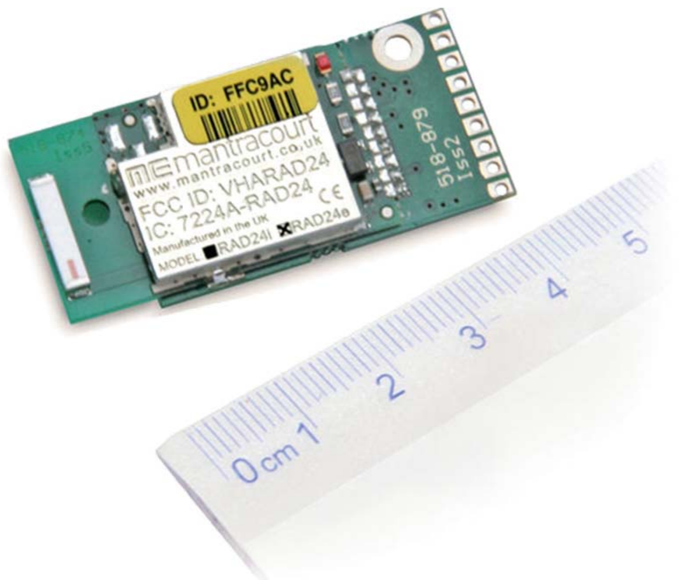
- Analog sensors with voltage or current outputs
- Analog multiplexer
- Multichannel ADC

Sensor Node Interface



A. Bayo, N. Medrano, B. Calvo, S. Celma, A Programmable Sensor Conditioning Interface for Low-Power Applications, *Proc. of the Eurosensors XXIV*, 5-8 September, 2010, Linz, Austria, Procedia Engineering, Vol. 5, 2010, pp. 53–56.

Wireless Telemetry Pulse Acquisition Module T24-PA



- Frequency range: 0.5 Hz … 3 kHz
- Relative error: 0.15 % …0.25 %
- Frequency, time and RPM measuring modes

Pulse-to-Wireless Converters

mantracourt
Advanced Intelligent Instrumentation

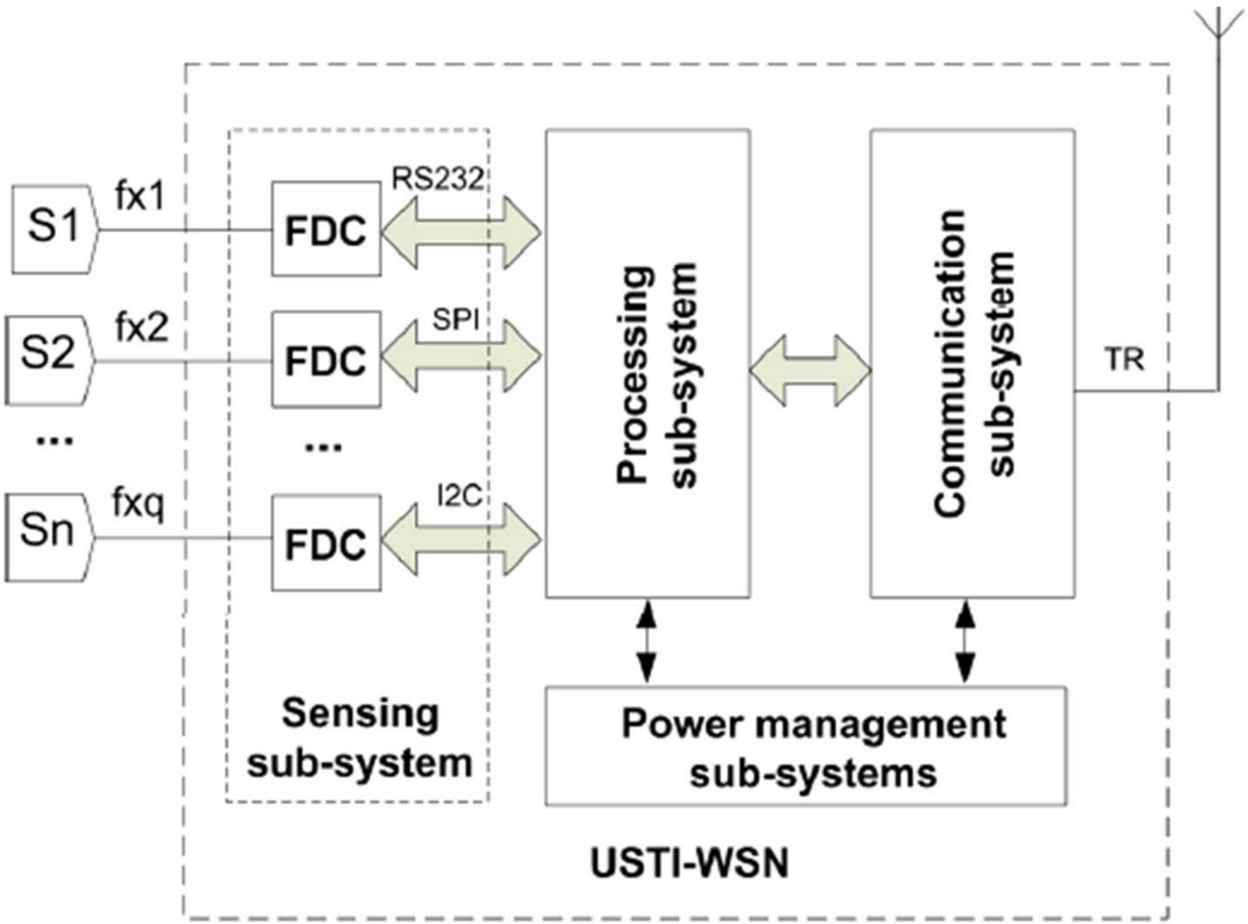
Sensor Node Architecture

- Sensing Sub-system
- Processing Sub-system
- Communication Sub-system
- Power Management Sub-system

Sensor Node Architecture

- Sensing Sub-system
- Processing Sub-system
- Communication Sub-system
- Power Management Sub-system

Node on Chip



S1
fx1
S2
fx2
...
Sn
fxq
FDC
FDC
...
FDC
RS232
SPI
I2C
Sensing sub-system
Processing sub-system
Communication sub-system
TR
Power management sub-systems
USTI-WSN

Comparative Performances

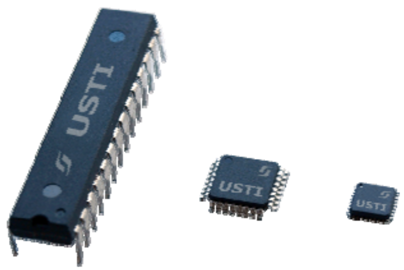
Parameter		
	T24-PA	USTI-MOB IC
Relative error, %	0.15 … 0.25	0.0009
Frequency Range, Hz	0.5 … 3 000	0.25 … 1 950 000
Min.Time interval, s	333E-06 … 2	10E-06 … 250
RPM range (presuming 1 pulse/rev), rpm	30 … 180 000	3 … unlimited
Active Supply Current, mA	35	0.85

Price Comparison

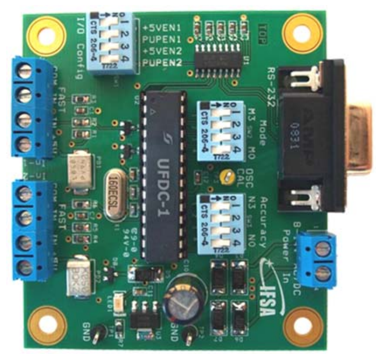
ICs	Manufacturers	Price, $ US (in quantities of 1, 000)
ADS1278, 24-bit, 8 channels, SPI	Texas Instruments	23.95
USTI-MOB, 3 channels, SPI, I2C, RS232 + any digital multiplexer (8 channels or more)	Excelera, S.L.	16.95
	Saving:	23.95-16.95 = 7.00

Series of UFDC and USTI ICs

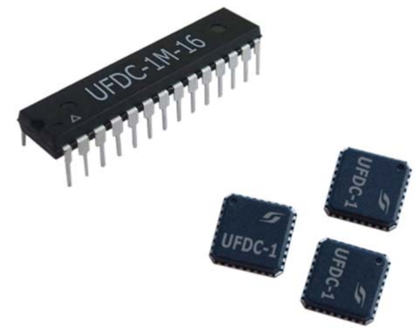
Universal Sensors and Transducer Interface (USTI)



Evaluation boards



Universal Frequency-to-Digital Converter (UFDC-1 & 1M-16)



USTI-EXT for Auto, Aerospace & Defense applications

USTI MOB for ultra-low power applications

xcelera
simplify, go faster!

Current Consumption Comparison

IC	Active Supply Current, mA
USTI-MOB	0.85
USTI	11
USTI-EXT	11
USTI-WSN *	~ 18.8
UFDC-1-16	20
UFDC-1	20

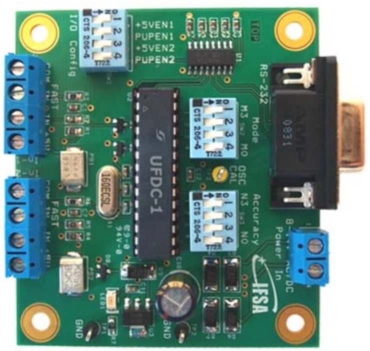
***** - coming soon

Conclusions

- Quasi-digital sensors and digital sensors on its basis are more attractive for mobile devices and IoT because of they let to eliminate current technological limitations
- Proposed advanced design approach lets significantly increase a sensor system integration level and metrological performance
- A lot of different sensors can be integrated by the same way in any mobile devices and IoT without complex sensor fusion algorithms

Reading and Practice

+



http://www.sensorsportal.com/HTML/BOOKSTORE/Digital_Sensors.htm

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Questions & Answers