Sensors & Sensor Systems: Design and Development for Smartphones, and IoT

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Contents

- Introduction
- Sensor types and classification
- Advanced Design Approach
- Examples
- From “Smart” to “Intelligent”
- Summary

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Sensor Market

- 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 IoT Sensors Market is expected to reach **USD 38.41 Billion** by 2022, growing at a CAGR of **42.08%** between 2016 and 2022

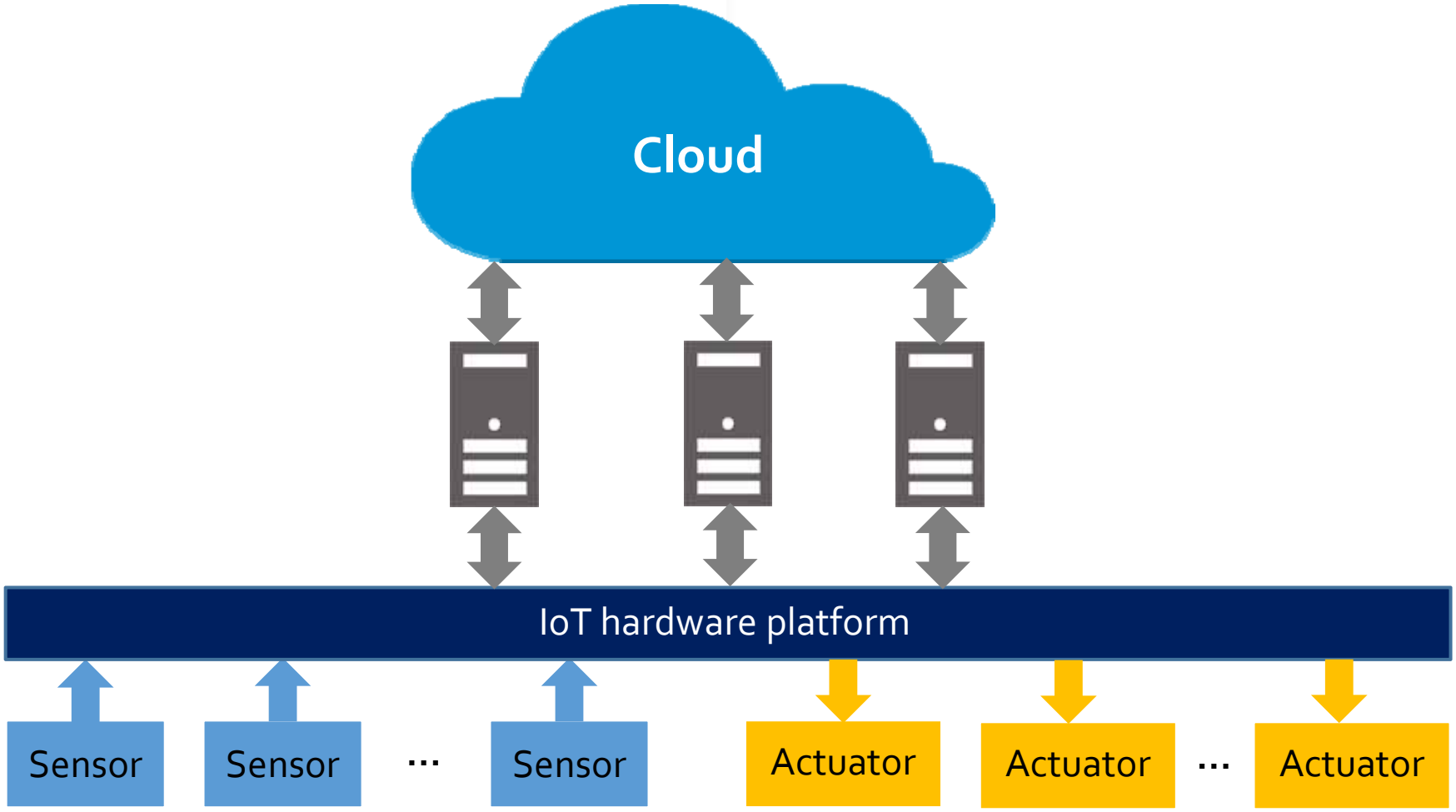
25 B devices with sensors.

(Gartner - Projections for 2020)

IFSL

Excelera

IoT Architecture

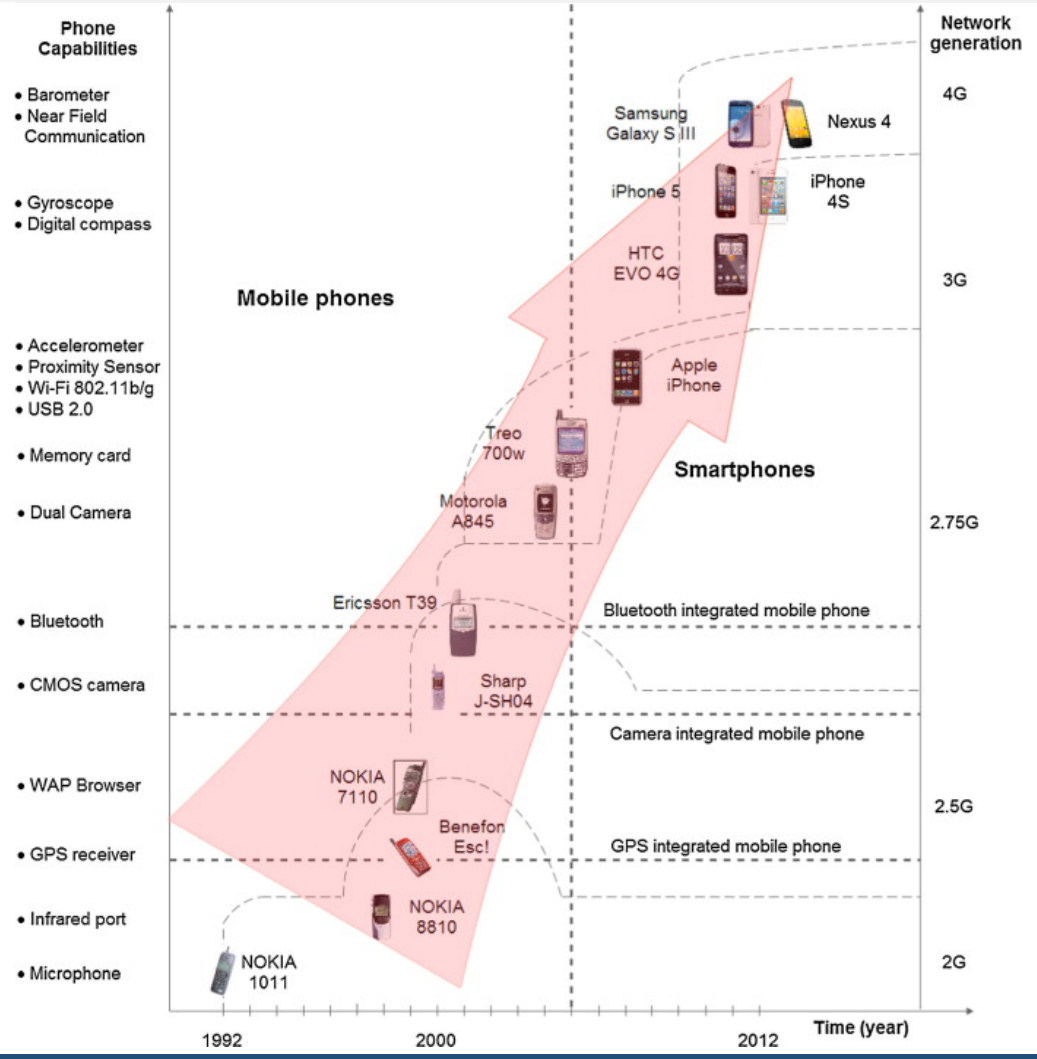


Factors Driving the Growth of IoT Sensors

Development of:

- Cheaper sensors
- Smart sensors
- Small sensors

Evolution of Mobile Phones



Evolution of Sensors in Smartphone

5 sensors

iPhone Edge

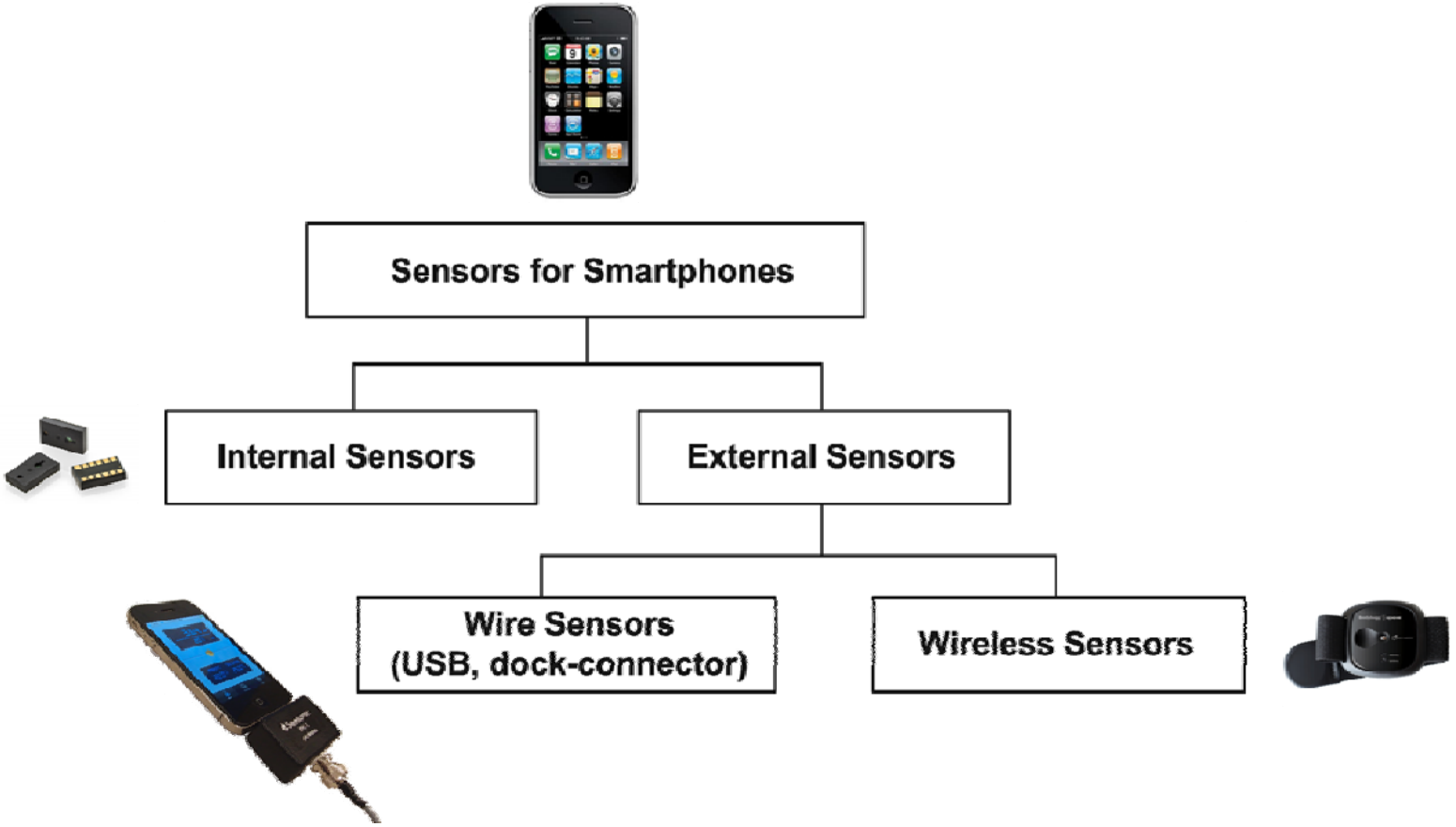
12 sensors

Samsung S5/iPhone 6 - 2014

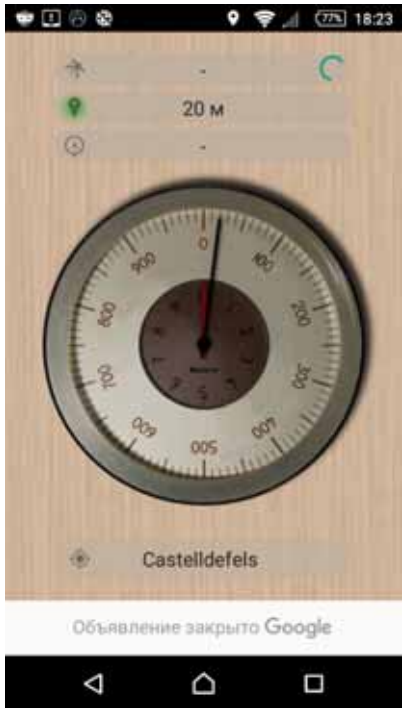
19 sensors ?

Galaxy S12/iPhone 9/9+ - 2021 ?

Smartphone Sensors Classification



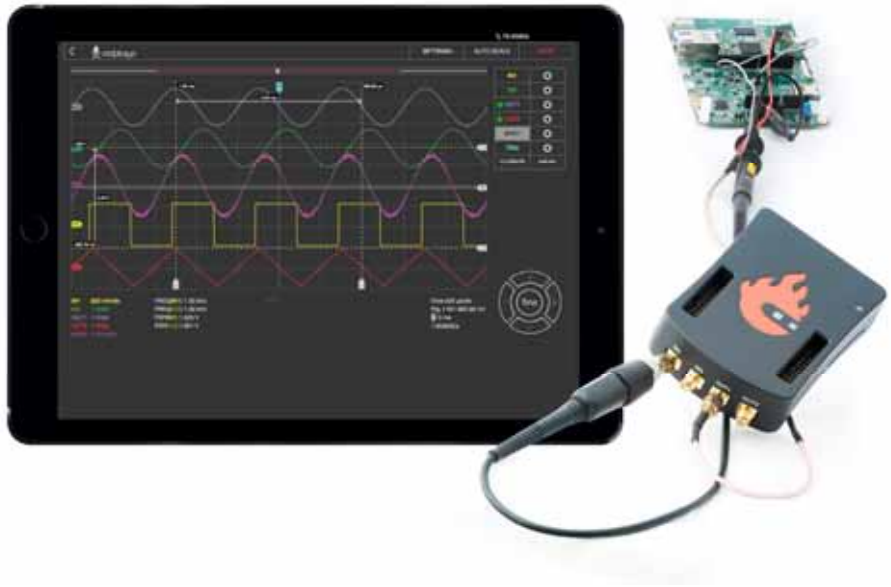
Smartphone Apps: Altimeters (1)



Smartphone Apps: Altimeters (2)

Smartphone Apps: Altimeters (3)

“Smartphone” for Engineers



- Oscilloscope & Signal Generator
- Logic Analyzer
- Spectrum Analyzer
- LCR Meter
- Bode Analyzer
- SCPI Controller

Which Sensors are in your Smartphone ?

Agenda

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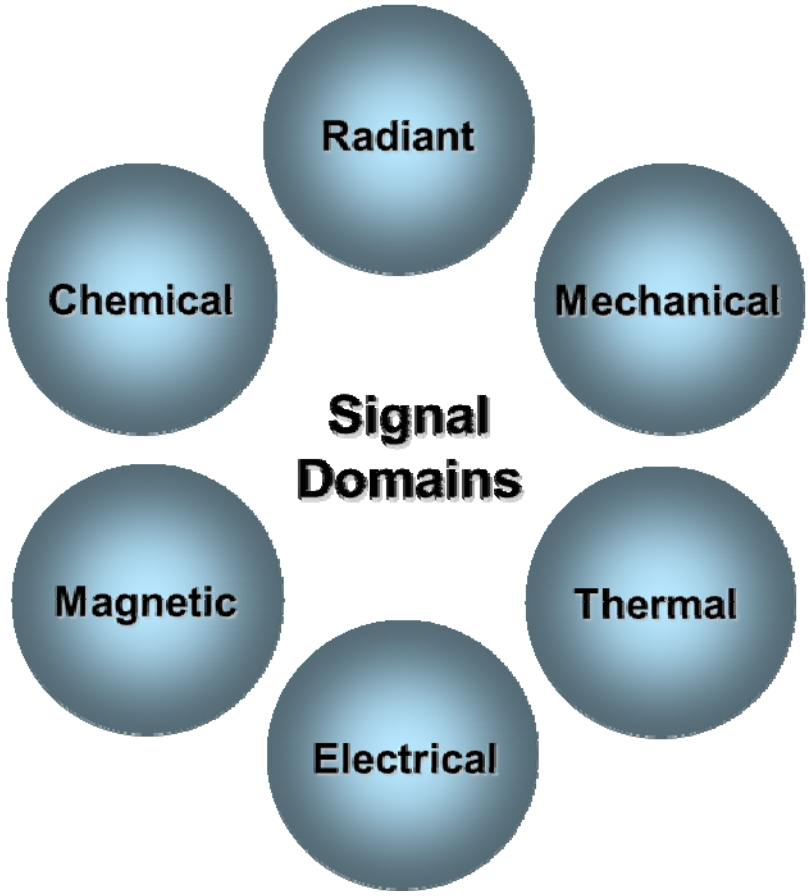
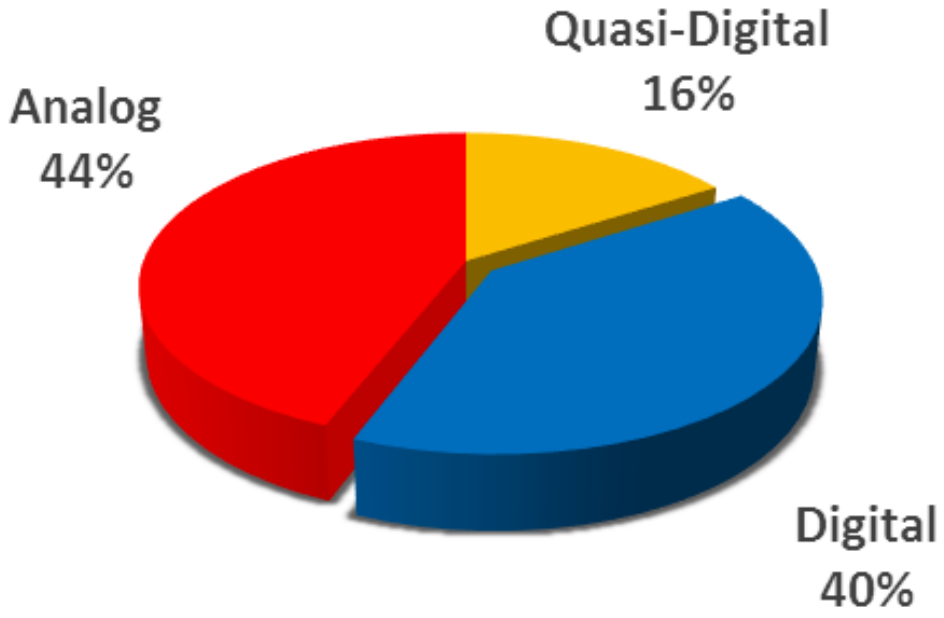
Sensor Definition

Sensor is a device that detects events or changes in the environment, and transform signals from different energy domains to the electrical domain then provides a corresponding output



Sensor Outputs



International Frequency Sensor Association (IFSA), Study, 2016

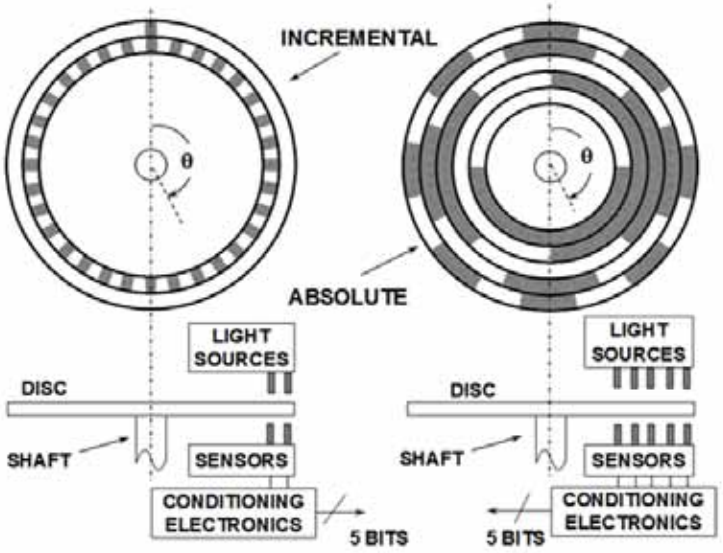
Analog & Quasi-Digital Sensors

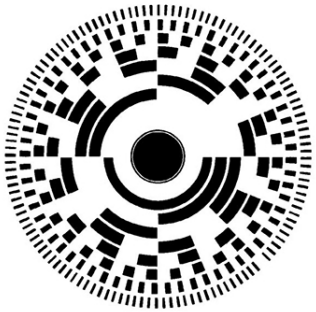
Analog sensor - sensor based on the usage of an amplitude modulation of electromagnetic processes

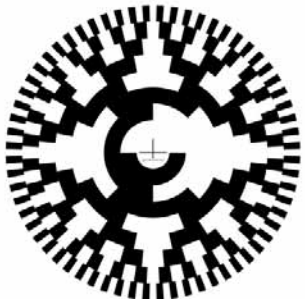
Quasi-digital sensors are discrete frequency-time domain sensors with frequency, period, duty-cycle, time interval, pulse number or phase shift output

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

Angular Position Encoders

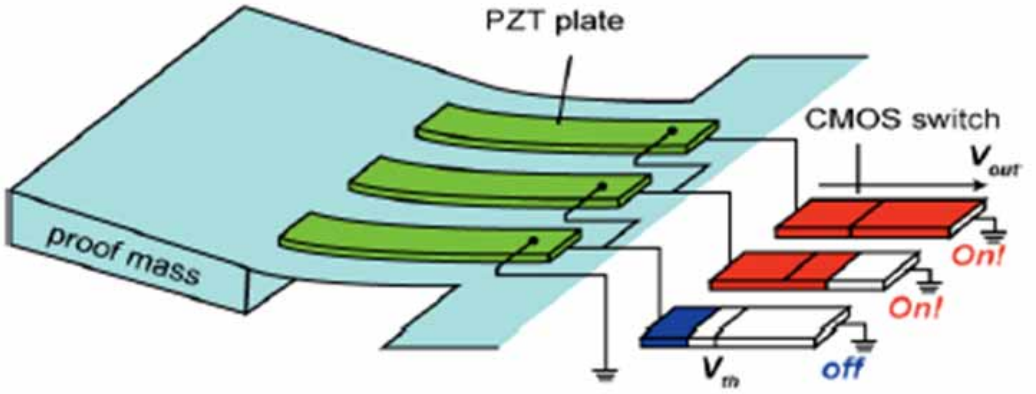






decimaal	Gray-code
0	0000
1	0001
2	0011
3	0010
4	0110
5	0111
6	0101
7	0100
8	1100
9	1101
10	1111
11	1110
enz.	enz.

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.

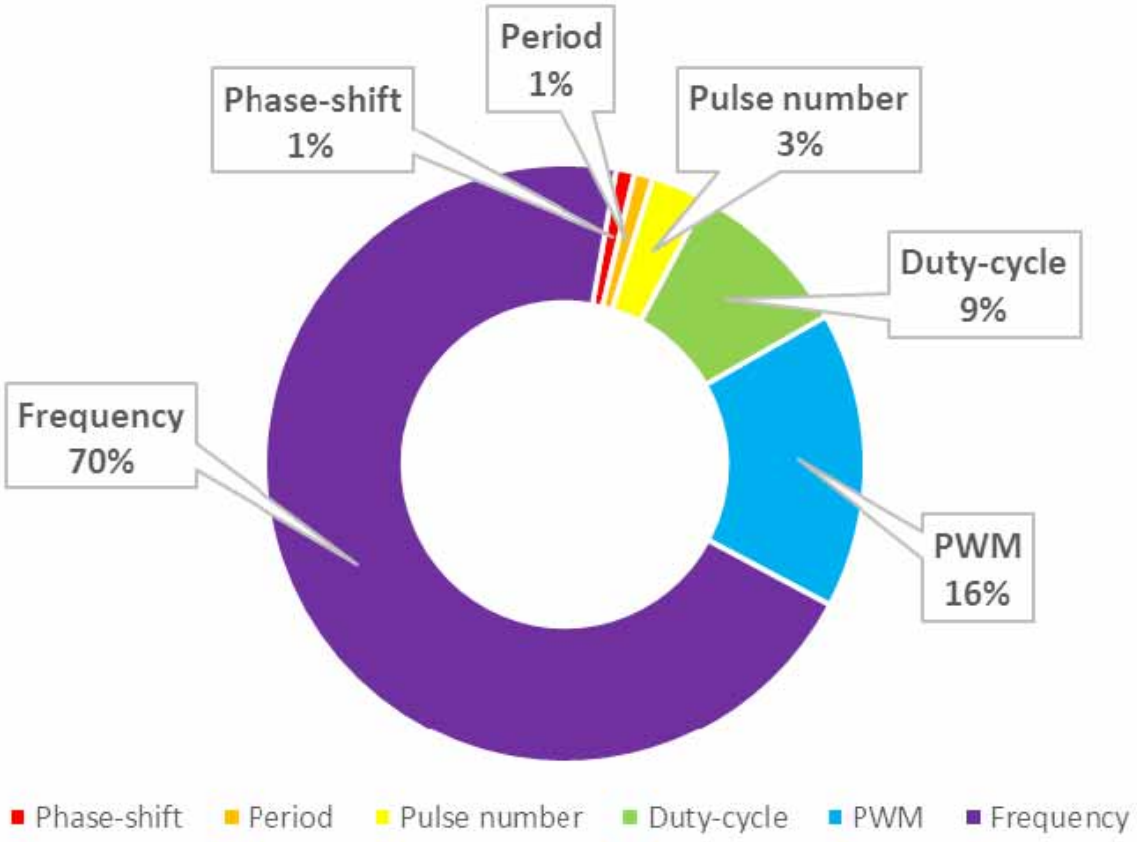
Digital Sensors

- 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.

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

Quasi-Digital Sensors Types

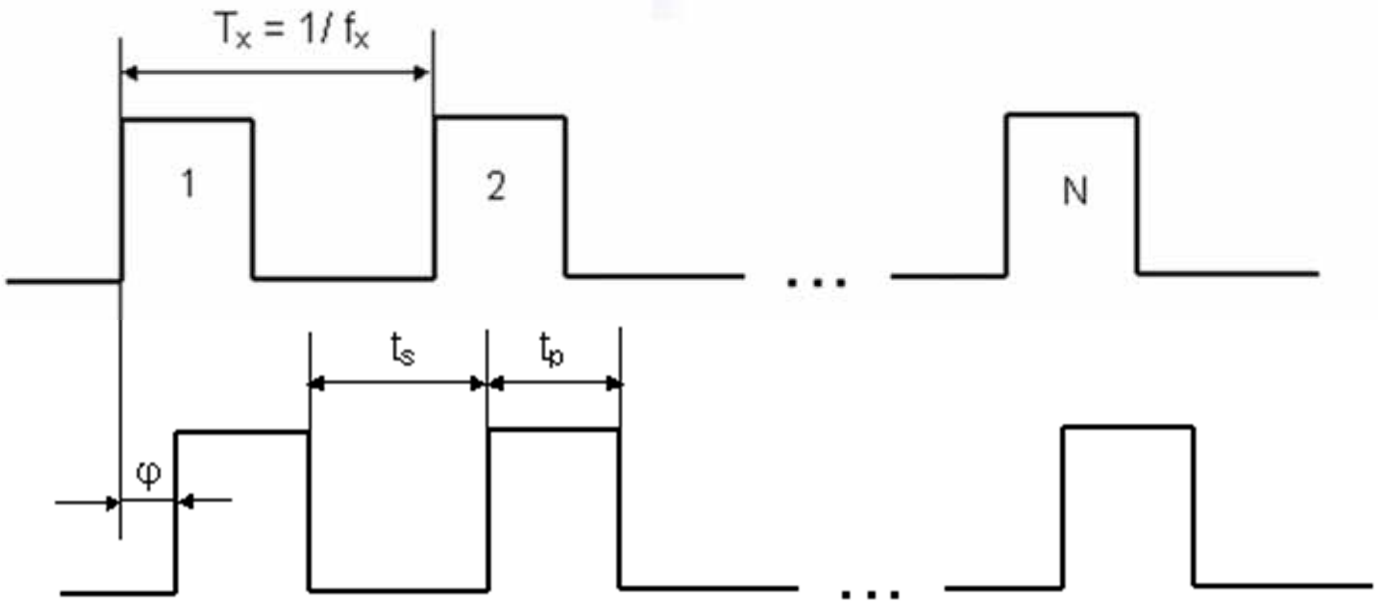


International Frequency Sensor Association (IFSA), Study, 2015

The First Quasi-Digital Sensors

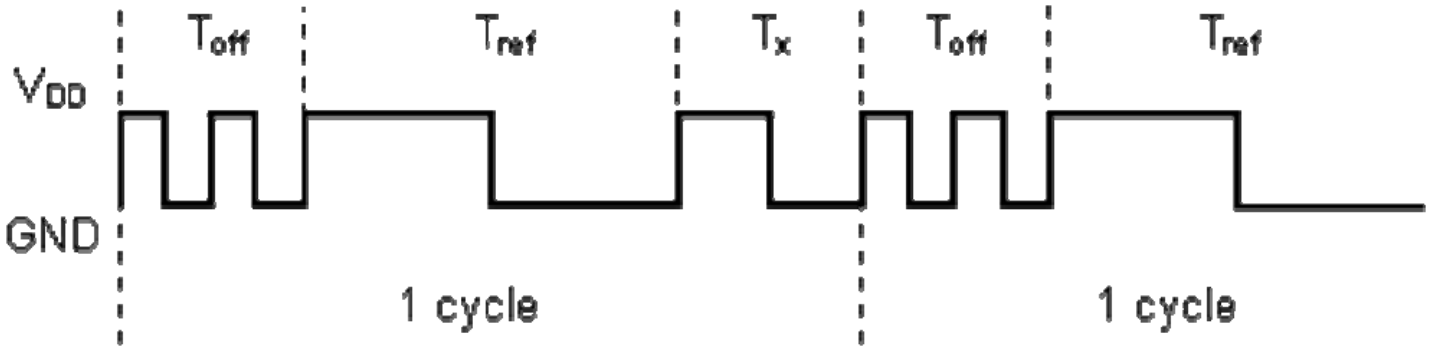
- **1930** - string distant thermometer (Pat. No.61727, USSR, Davydenkov N., Yakutovich M.)
- **1931** - string distant tensometer (Pat. No. 21525, USSR, Golovachov D., Davydenkov N., Yakutovich M.)
- **1941** - ADC for the narrow time intervals (Pat. No. 68785, USSR, Filipov V.N. and Negnevitskiy S.B.

Informative Parameters

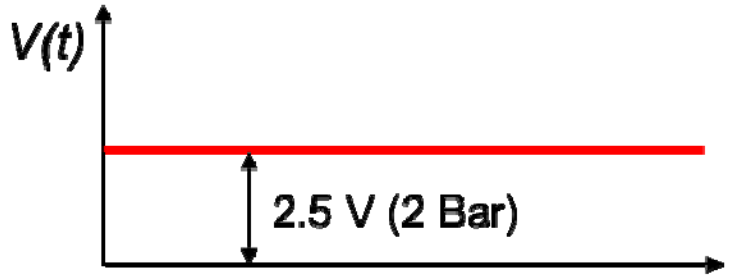


- Duty-cycle: $D.C. = t_p/T_x$
- Duty-off factor: $1/D.C. = T_x/t_p$
- PWM signal: t_s/t_p ratio at T_x = *constant*

Period-Modulated Output

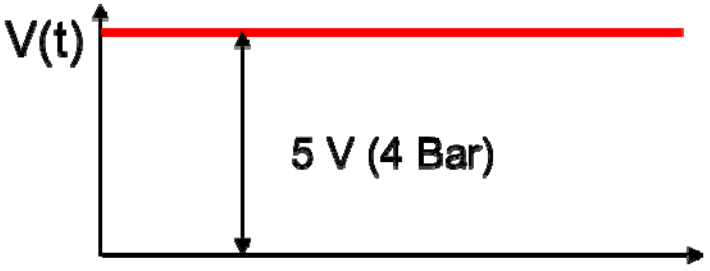


Voltage Output



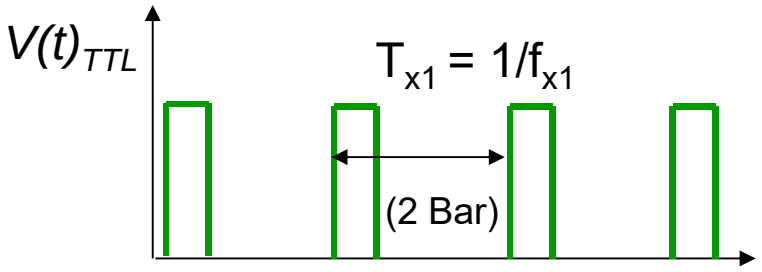
(a)

$V_1 < V_2$

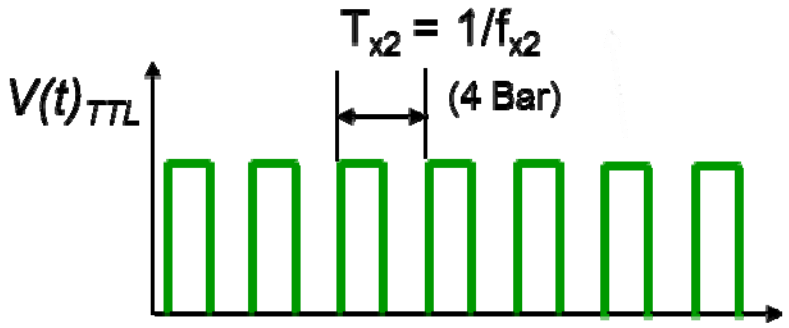


(b)

Frequency Output



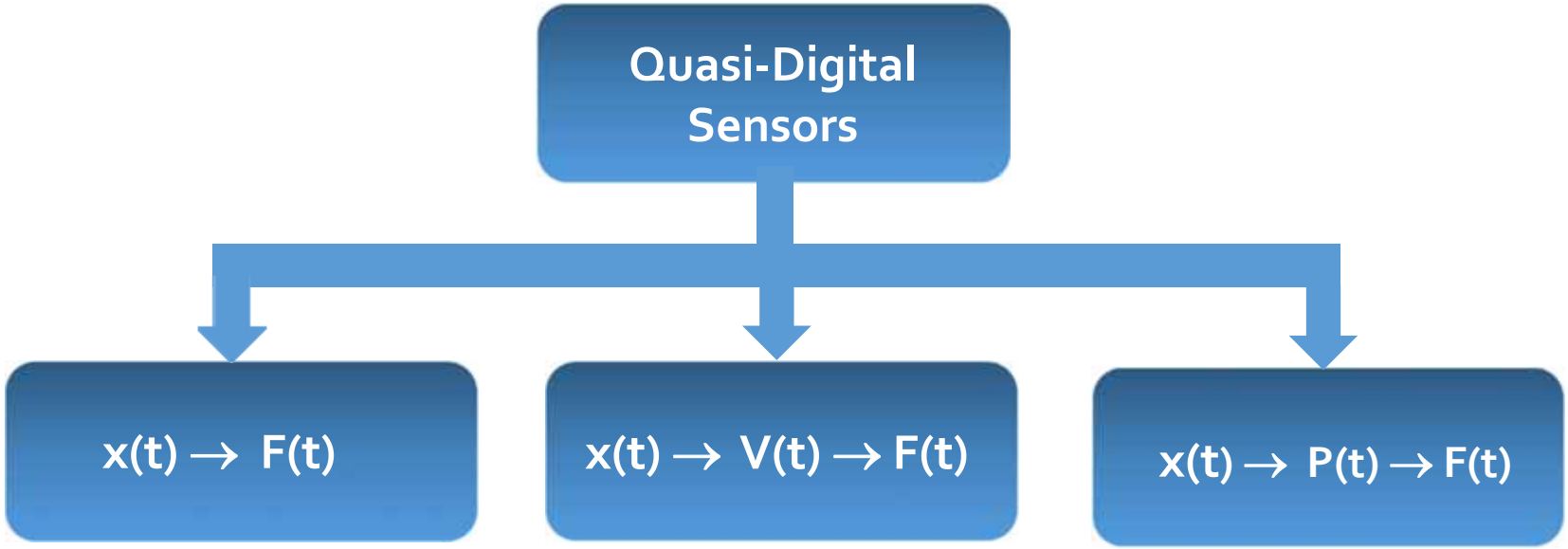
(a)



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

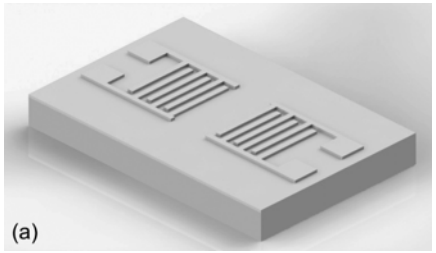
(b)

Quasi-Digital Sensors Classification



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

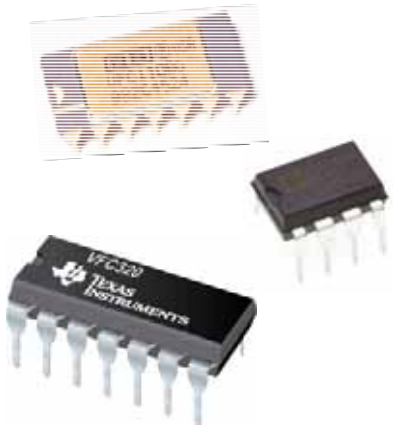
x (t) → F (t) Conversion



- Sensors themselves generate a frequency output
- Electronic circuitry might be needed for amplification of impedance matching
- One group of such sensors is based on resonant structures (piezoelectric quartz resonators, SAW (surface acoustic wave) dual-line oscillators, etc.), another group is based on the periodic geometrical structure of the sensors (angle encoders)

Examples: inductive, photo impulse, string, acoustic and scintillation sensors

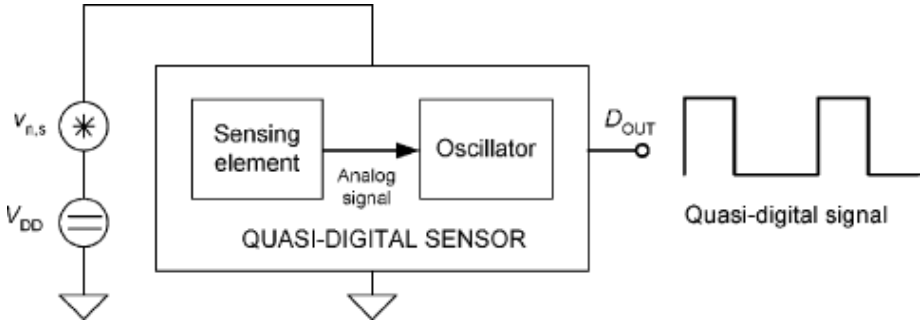
x (t) → V(t) → F (t) Conversion



- It is rather numerous sensors group
- Simple voltage-to-frequency or current-to-frequency conversion circuit can be used

Examples: Hall sensors, thermocouple sensors and photo sensors based on valve photoelectric cells

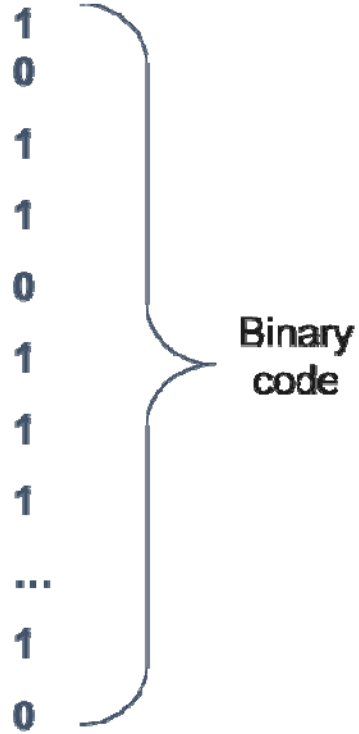
x (t) → V(t) → P (t) Conversion



- Sensors of this group (electronic-oscillator based sensors) are rather manifold and numerous
- Sensor element itself is the frequency determining element

Examples: inductive, capacity and ohmic parametric (modulating) sensors

Digital Sensors Outputs



- Serial interfaces RS232/485/422, USB
- Parallel interfaces (8-, 16-, 32-bits)
- Sensor buses: SPI, I2C, I3C, CAN, SMBus, LIN, etc.

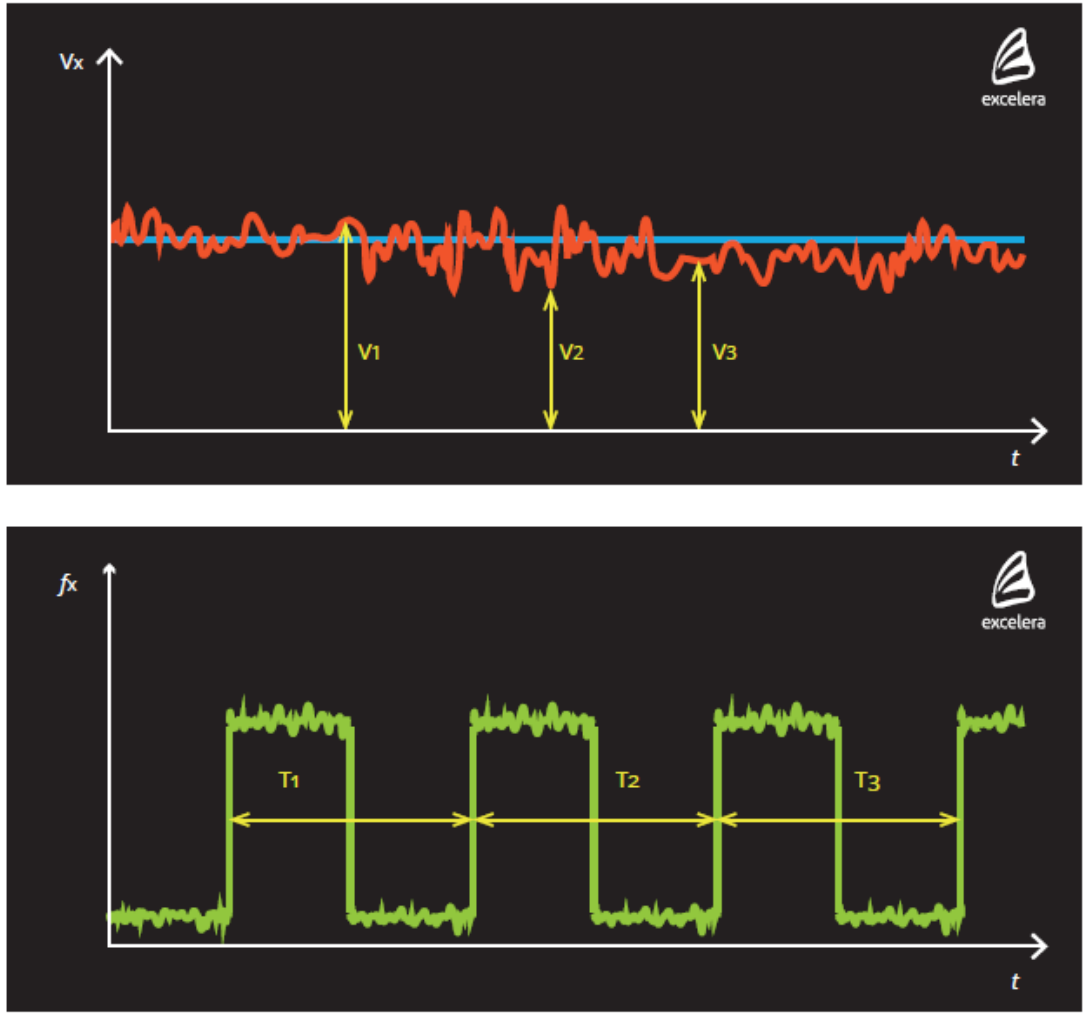
Quasi-Digital Sensors Advantages

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

High Noise Immunity

- Objective property due to a frequency modulation
- Frequency signal can be transmitted by communication lines to much greater distance
- Only two-wire line is necessary for transmission of such signal
- Data transmitting does not require any synchronization
- Frequency signal is ideal for high noise industrial environments

High Noise Immunity (cont.)



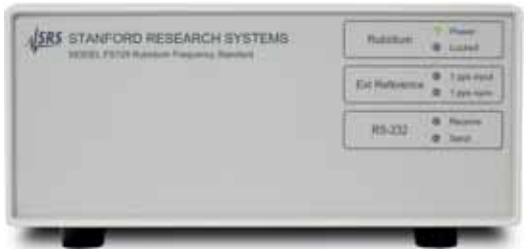
High Power Signal

- Section from a sensor output up to an amplifier input is the heaviest section in a measuring channel for signal transmitting from a power point of view
- Losses, originating on this section can not be filled any more by any signal processing
- Output powers of frequency sensors, as a rule, are considerably higher

Wide Dynamic Range

- Dynamic range is not limited by supply voltage and noise
- Dynamic range of over 160 dB can be easily obtained

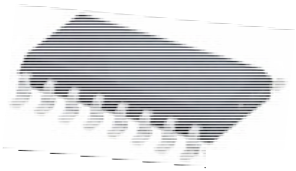
High Accuracy of Reference



- Crystal oscillators can be made more stable, than the voltage reference:
  - non-compensated crystal oscillator has up to $(1 \div 50) \cdot 10^{-6}$ error
  - temperature-compensated crystal oscillator has up to $10^{-8} \div 10^{-10}$ error
- Minimum possible error for frequency measurements with the help of quantum frequency standard is 10^{-14}, minimum possible quantization step for time interval is 10^{-12} seconds

Simplicity of Interfacing

VS.



- Parasitic electromotive force (emf), transient resistances and cross-feed of channels in analog multiplexer at the usage of analog sensors are reasons for errors
- Frequency modulated signal is not sensitive to all listed factors
- Multiplexers for frequency output sensors and transducers are very simple and do not introduce any errors

Multiparametricity

- One sensor's output - two informative parameters: a frequency is proportional to the physical quantity X and duty-cycle at the same output is proportional to the physical quantity Y
- Today there are some examples
- It is the future of multiparametric, multifunctional and combo sensors

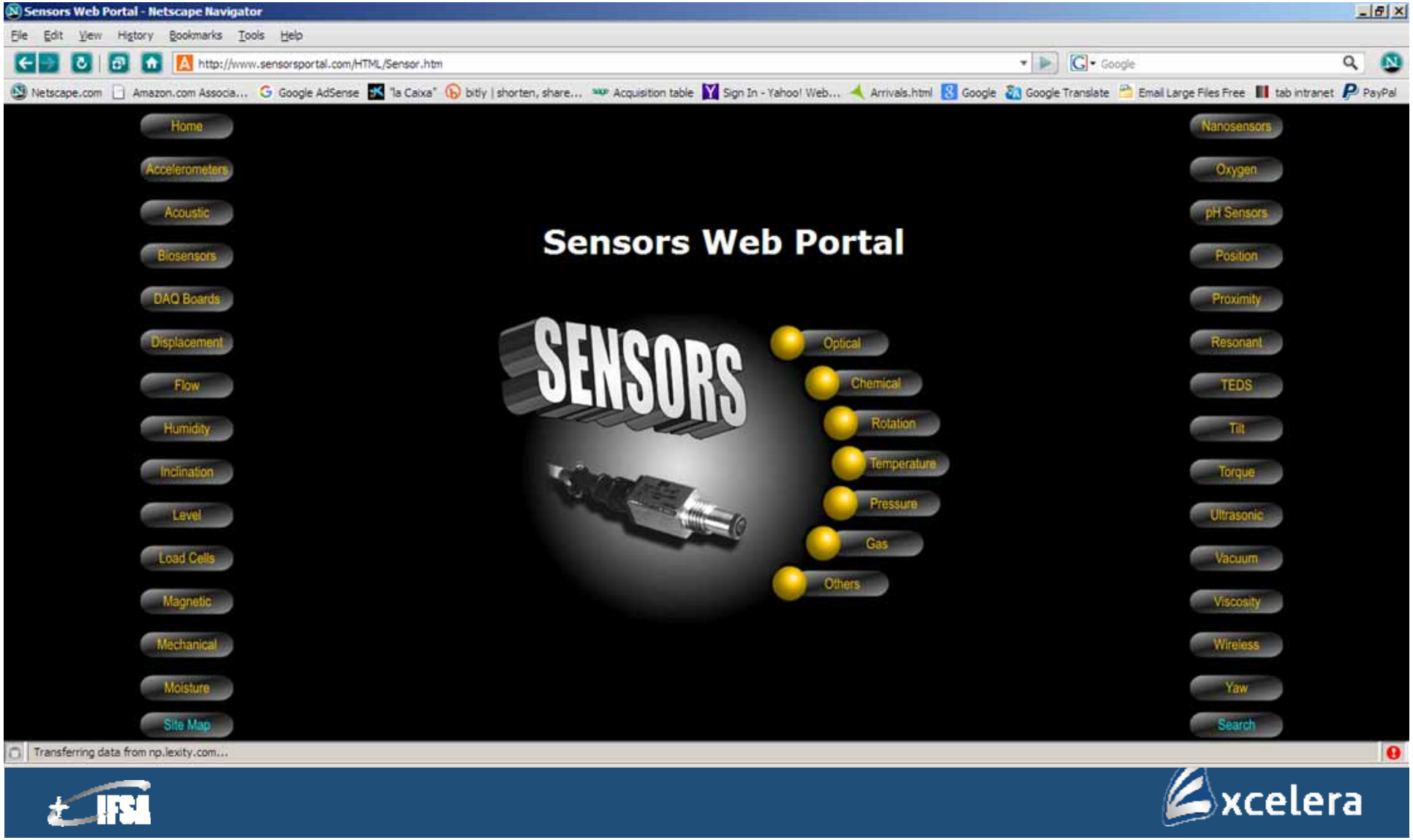
Self- Adaptability

- Versatility between accuracy and speed (time of measurement or conversion time)
- Trade-off between accuracy and power consumption

Quasi-Digital Output vs. Analog and Digital Sensor Outputs

No.	Parameter/Feature	Analog and Digital Sensors (based on ADC)	Quasi-digital Sensors
1.	**Accuracy (relative error), %**	Up to ±0.01 % (full scale)	Up to ±0.0001 % and better (all range)
2.	**Dynamic range**	Up to 100 dB	130 dB and more (not limited by the supply voltage and noise)
3.	**Resolution**	Up to 16-24 bits	24-32 bits and more (unlimited and scalable)
4.	**Level of integration (CMOS standard technological processes)**	Problems below 100 nm	No any problem even in 14 nm
5.	**Minimal number of output lines**	4 (for digital sensors + ground)	2 (signal + ground)
6.	**Multisensing (max number of parameters in one sensor's output)**	1 parameter	2 parameters
7.	**Electromagnetic noise immunity**	Low	Excellent
8.	**Reliability**	Lower	Higher
9.	**Signal/Noise Ratio**	Lower	Higher
10.	**Remote sensing distance (wire)**	Low	High
11.	**Interfacing, integration and multiplexing of sensor's output**	Complex and costly	Easy and cheap
12.	**Signal conditioning**	Front-end, amplification and filtering	Simple

Quasi-Digital Sensors on SWP



Quasi-Digital Sensors on DigiKey

- There are a lot of quasi-digital sensors: accelerometers, magnetic, temperature, rotary and linear position, colour, light, rotational speed, humidity, pressure, dust, distance, proximity, QCM (chemical) sensors and rotary encoders
- There are more than 100 models of Voltage-to-Frequency Converters (VFC) from *Analog Devices*, *Texas Instruments*, *Microchip Technologies*, etc.

Quasi-Digital Sensors Manufactures

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

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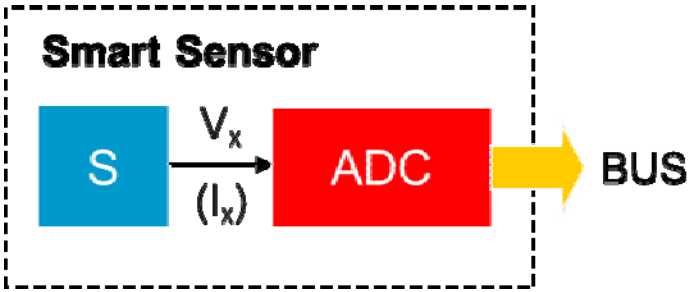
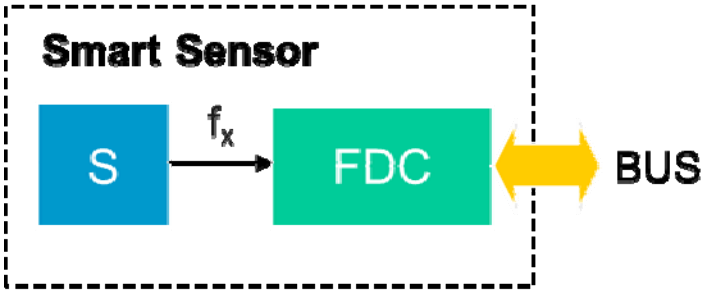
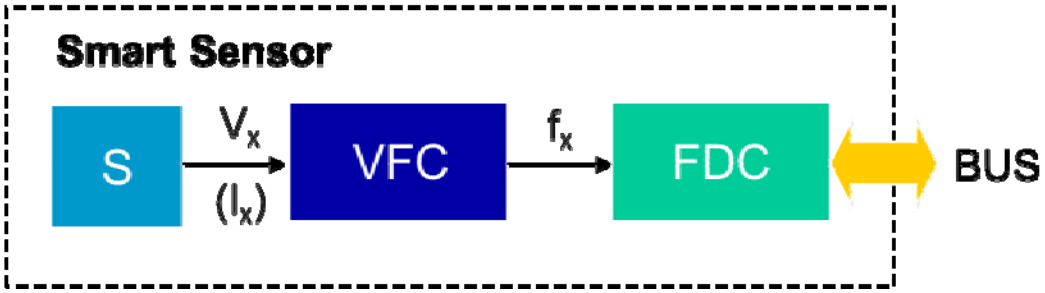
Sensor Systems Design Approaches



- Classical approach



- Advanced approaches



VFC Advantages

- Needs less integration area and power consumption
- Analog circuitry (the VFC and analog signal conditioning circuits) to be located close to the signal source
- Digital circuitry (frequency-to-digital converter) to be located elsewhere
- Resolution can be increased almost indefinitely

Manufactures of Integrated VFCs

Modern VFCs' Performances

- There are a lot of commercially available types of integrated VFCs to meet many requirements (0.012 % integral nonlinearity)
- Ultra-high speed 1 Hz-100 MHz VFC with 0.06 % linearity
- Fast response (3 μs) 1 Hz-2.5 MHz VFC with 0.05 % linearity
- High stability quartz stabilized 10 kHz – 100 kHz VFC with 0.005 % linearity
- Ultra-linear 100 kHz – 1 MHz VFC with linearity inside 7 ppm 0.0007 %) and 1 ppm resolution for 17-bit accuracy applications
- 1.8 … 1.2 V single supply; 0.4 mW … 70 μW power consumption

Analog-to-Digital Converters

Converter Type	Maximum speed	Typical resolution, bit	Noise Immunity	Relative Cost
Successive Approximation	Medium (10 kHz to 1 MHz)	6-16	Little	Low
Integrating	Slow (10 Hz to 30 Hz)	12-24	Good	Low
VFC-based	Medium (160 kHz to 1 MHz)	16-24 or more	Excellent	Low
Sigma-Delta	Slow to Medium (Up to 1 MHz or higher)	16 or more	High	Low
Flash	Very Fast (1 MHz to 500 MHz)	4-8	None	High

Integrated FDC

- USP-30 one-chip specialized microprocessor (1980)
- IC of ALU for time interval measurements (1989)
- K512PS11 - frequency-to-digital converter (1990)
- USIC - universal sensor interface chip (1996)
- Single-chip (FPGA) interpolating time counter
- ASIC of single channel frequency-to-digital converter (1999)
- Frequency-to-digital converter from *AutoTEC*
- Time-to-Digital Converter (TDC) from *ams* (*Acam-messelectronic GmbH)*

FDC ICs Disadvantages

- All ICs except TDCs are based on conventional methods of measurement, hence, quantization error is dependent on measurand frequency f_x, many of ICs have redundant conversion time
- They cannot be used with all existing modern frequency-time domain sensors due to low accuracy or/and narrow frequency ranges
- They do not cover all frequency–time informative parameters of electric signals

µC-based Realization's Disadvantages

Neither

nor

C/C++

- Low metrological performance due to classical methods for frequency measurements
- All advanced conversion methods are patented
- Firmware realization contains many time-dependent pieces of code and must be written in *Assembler*
- Additional program related errors can be easily introduced during the design

Excelera's Products

UFDC-1

universal frequency-to-digital converter

UFDC-1M-16

32x faster than UFDC-1

Development boards

(fully functioning DAQ system)

USTI

(high performance sensors & transducers interface)

USTI-EXT

for extreme conditions

USTI-MOB

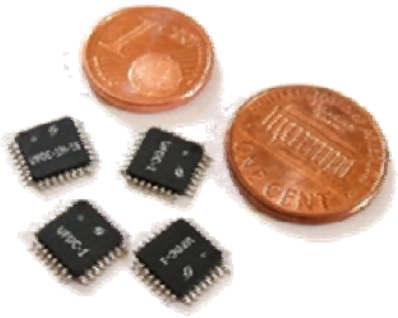
for mobile devices

Applications: Smart sensors, ADC, Industry, automotive, IoT

Universal Frequency-to-Digital Converter (UFDC-1)

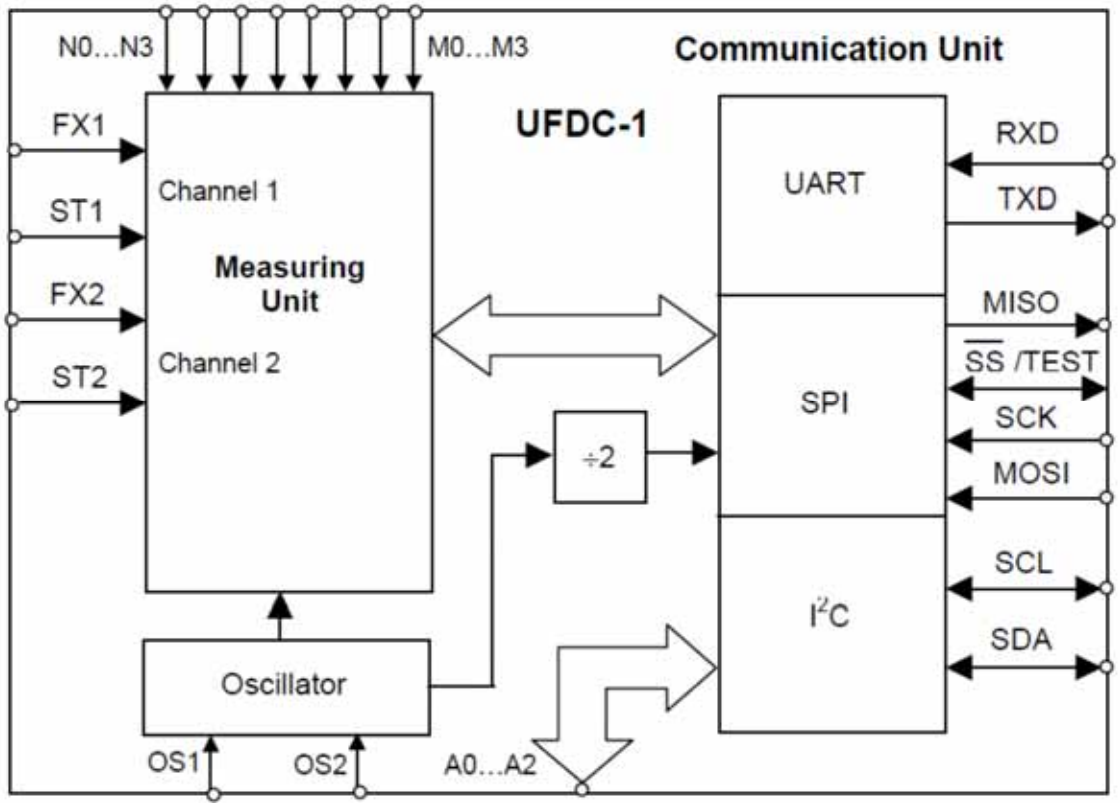
- High, programmable accuracy
- Scalable resolution
- 2 channels, 16 measuring modes for different frequency-time parameters and one generating mode ($f_{osc}/2$ = 8 MHz)
- Based on four patented novel conversion methods
- It has very wide applications

Features



- Frequency range from 0.05 Hz up to 7 MHz without prescaling and 112 MHz with prescaling
- Programmable accuracy (relative error) for frequency (period) conversion from 1 up to 0.001 %
- Relative quantization error is constant in all specified frequency range
- Non-redundant conversion time
- Quartz-accurate automated calibration
- RS232/485, SPI and I^2C interfaces

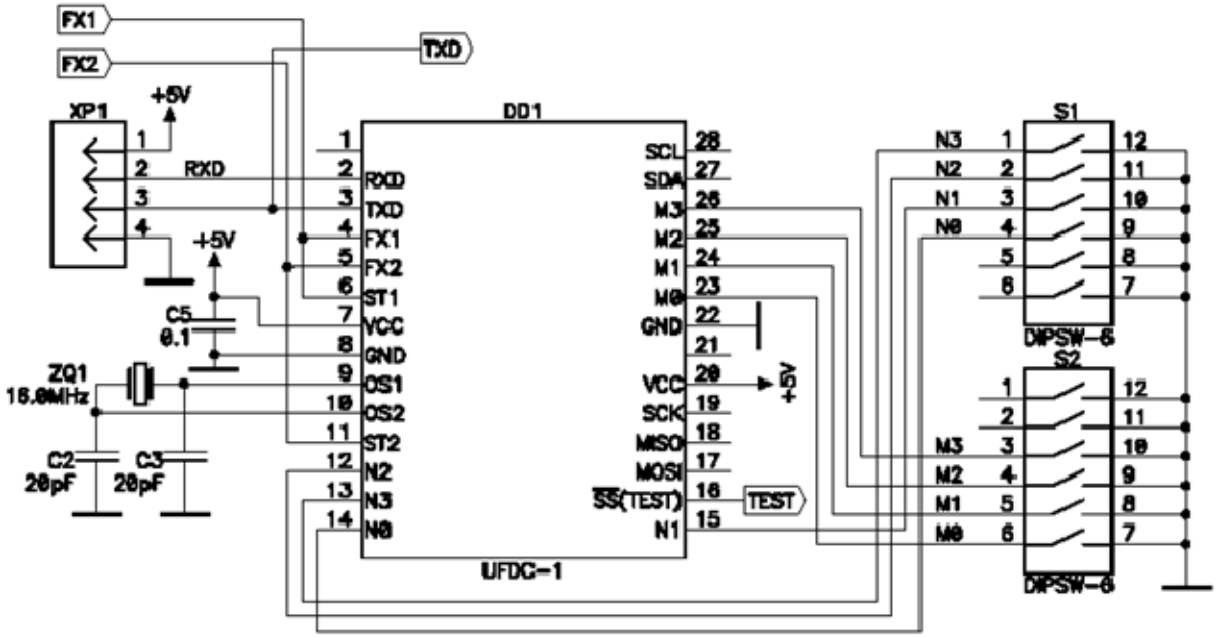
UFDC-1 Block Diagram



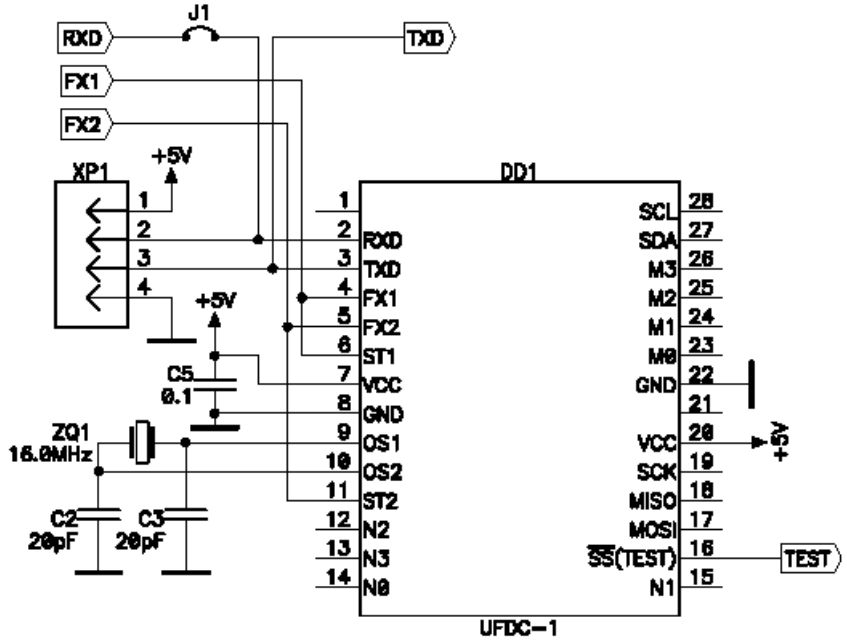
Measuring Modes

- Frequency, f_{x1} 0.05 Hz – 7 MHz directly and up to 112 MHz with prescalling
- Period, T_{x1} 150 ns – 20 s
- Phase shift, φ_x 0 - 360° at $f_x \leq 300$ kHz
- Time interval between start- and stop-pulse, τ_x 2.5 μs – 250 s
- Duty-cycle, D.C. 0 – 1 at $f_x \leq 300$ kHz
- Duty-off factor, Q 10^{-8} – 8×10^6 at $f_x \leq 300$ kHz
- Frequency and period difference and ratio
- Rotation speed (*rpm)* and rotation acceleration
- Pulse width and space interval 2.5 μs – 250 s
- Pulse number (events) counting, N_x 0 – 4×10^9

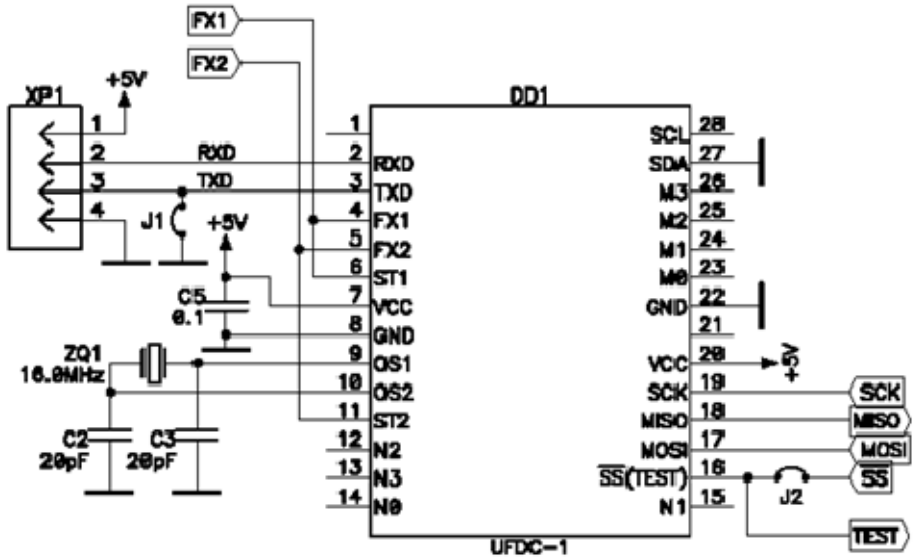
UFDC-1: Master Mode (RS232)



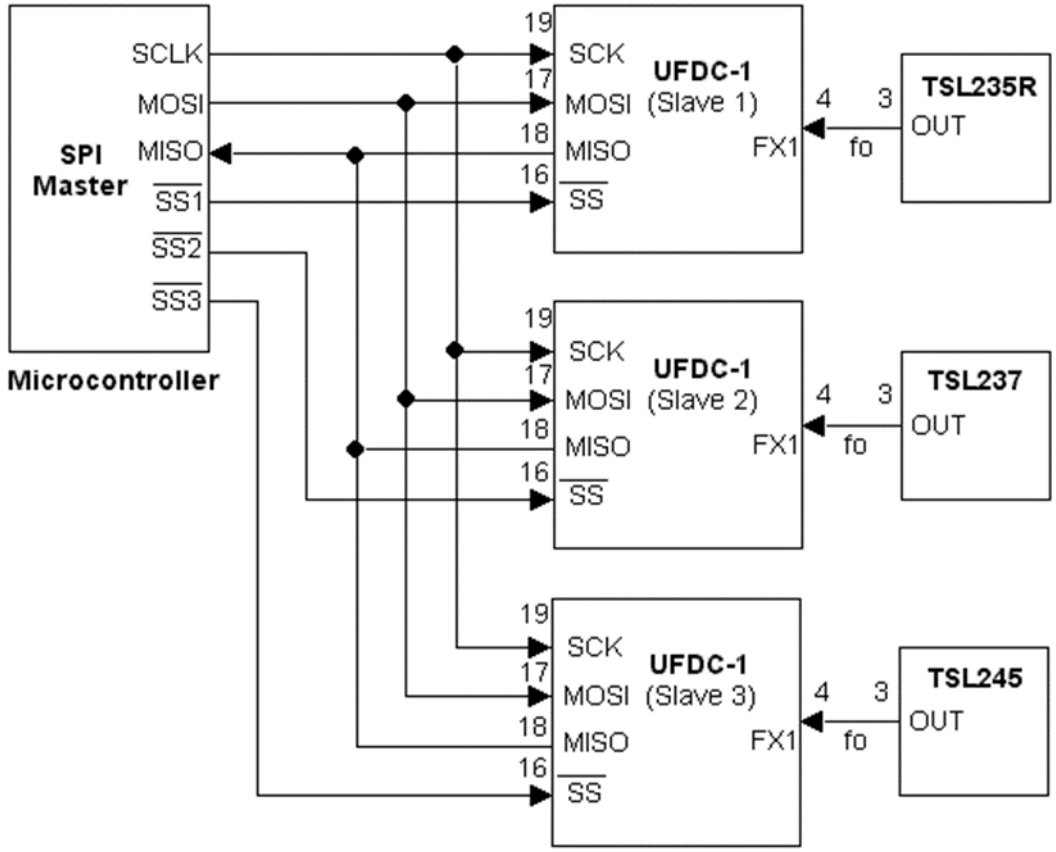
UFDC-1: Slave Mode (RS232)



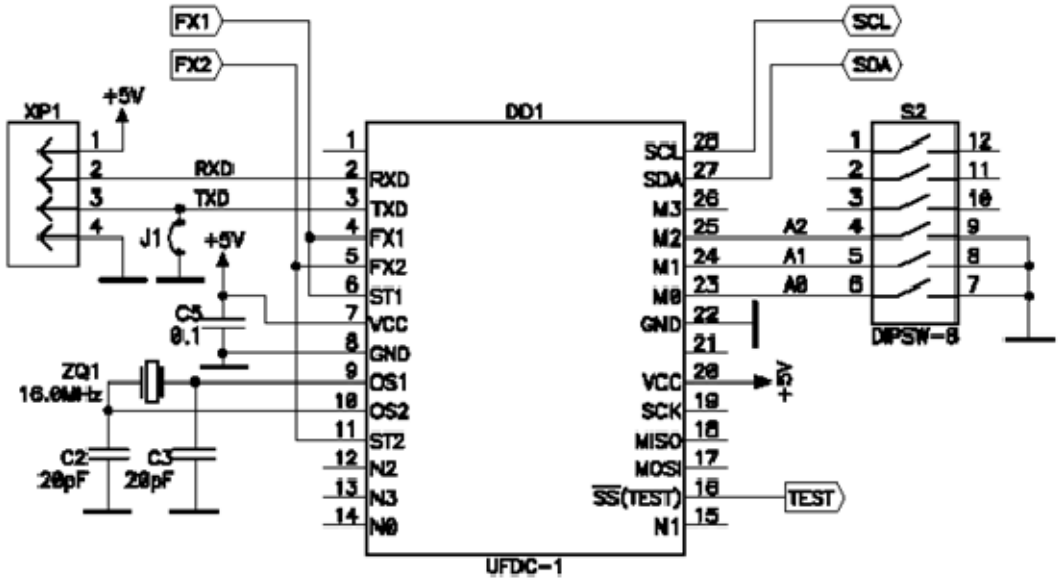
UFDC-1: 3-wire Serial Interface (SPI)



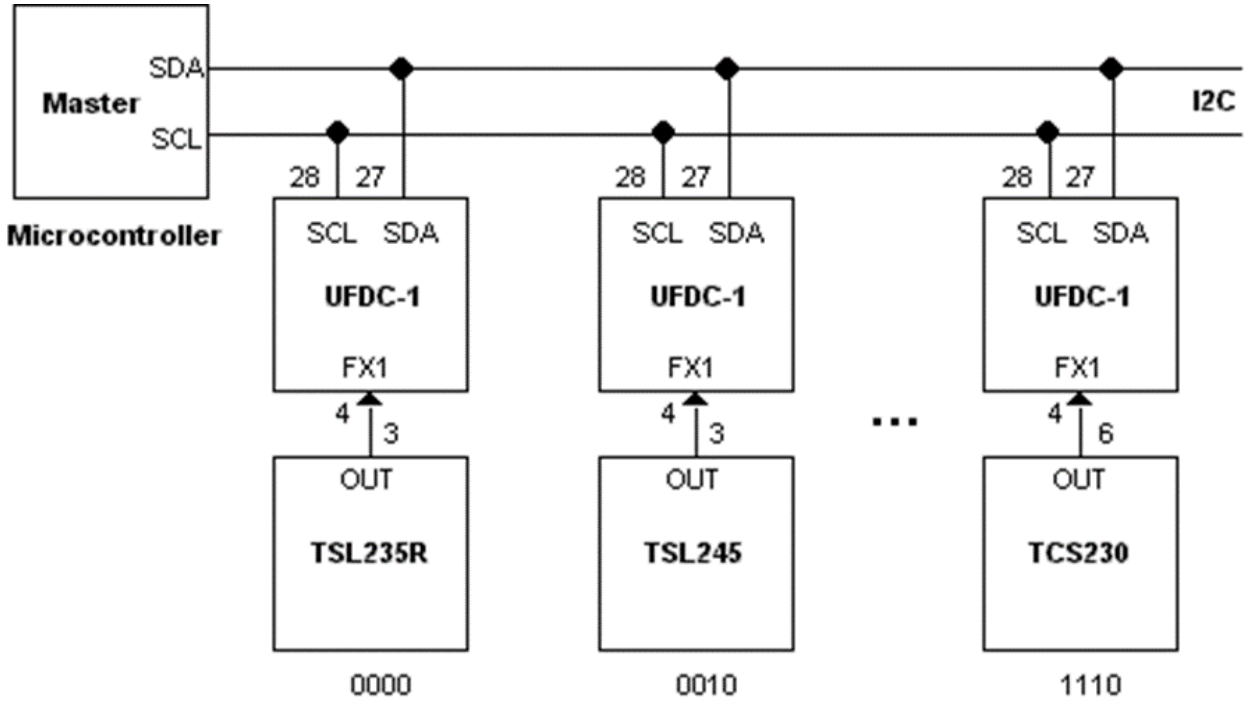
SPI Interface to ams Opto Sensors



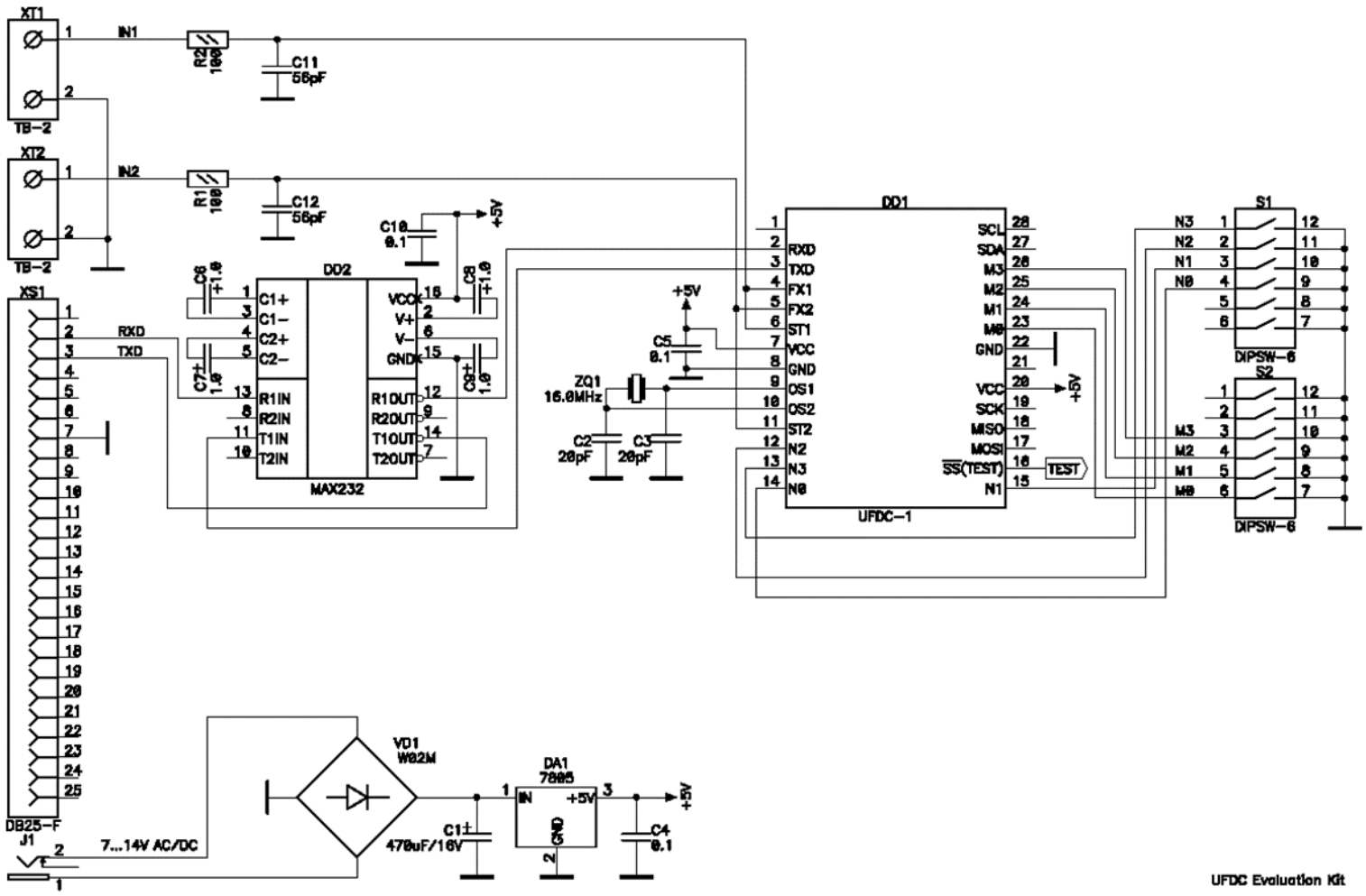
UFDC-1: 2-wire I²C Interface



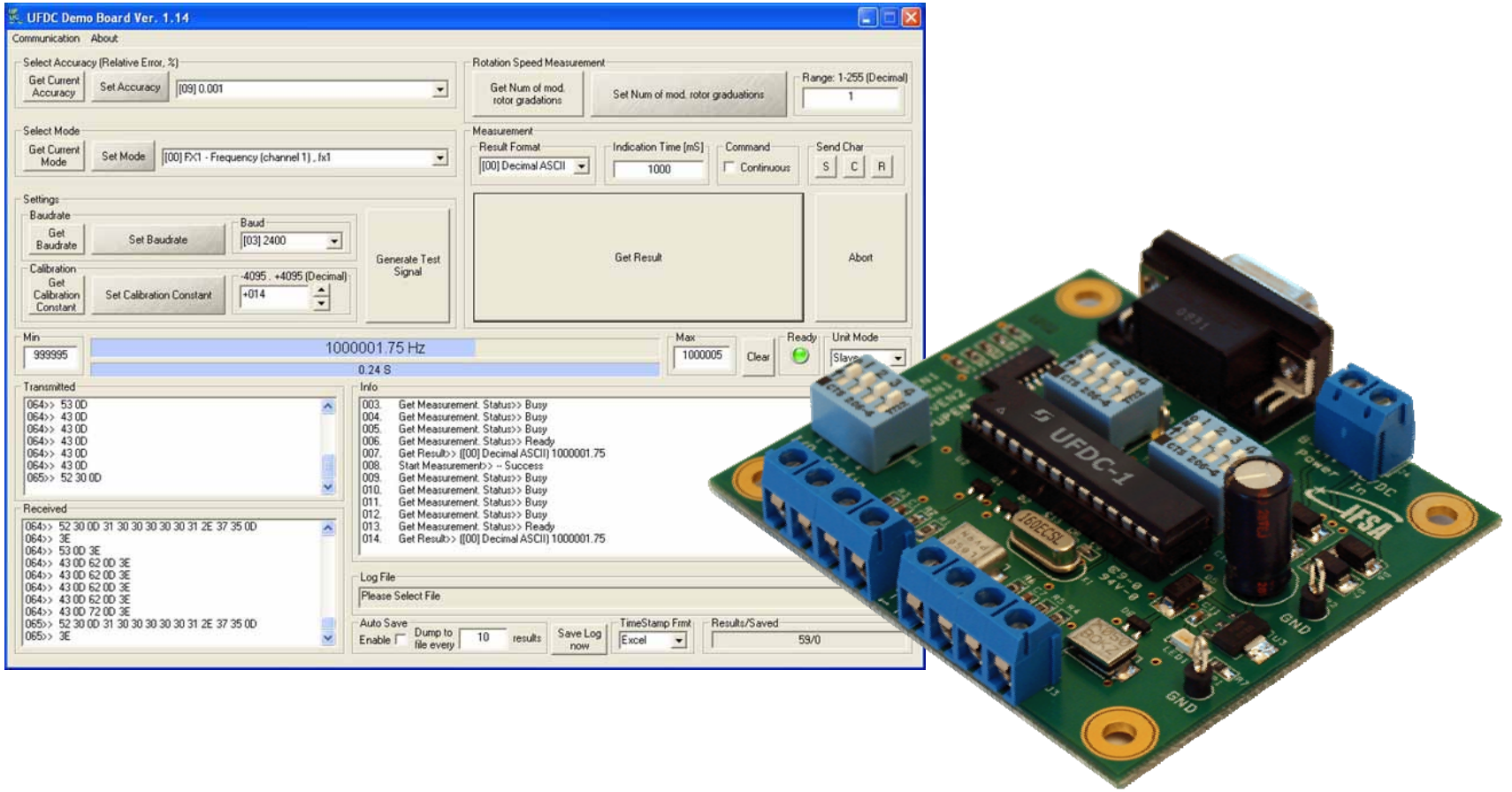
I²C Interface to ams Opto Sensors



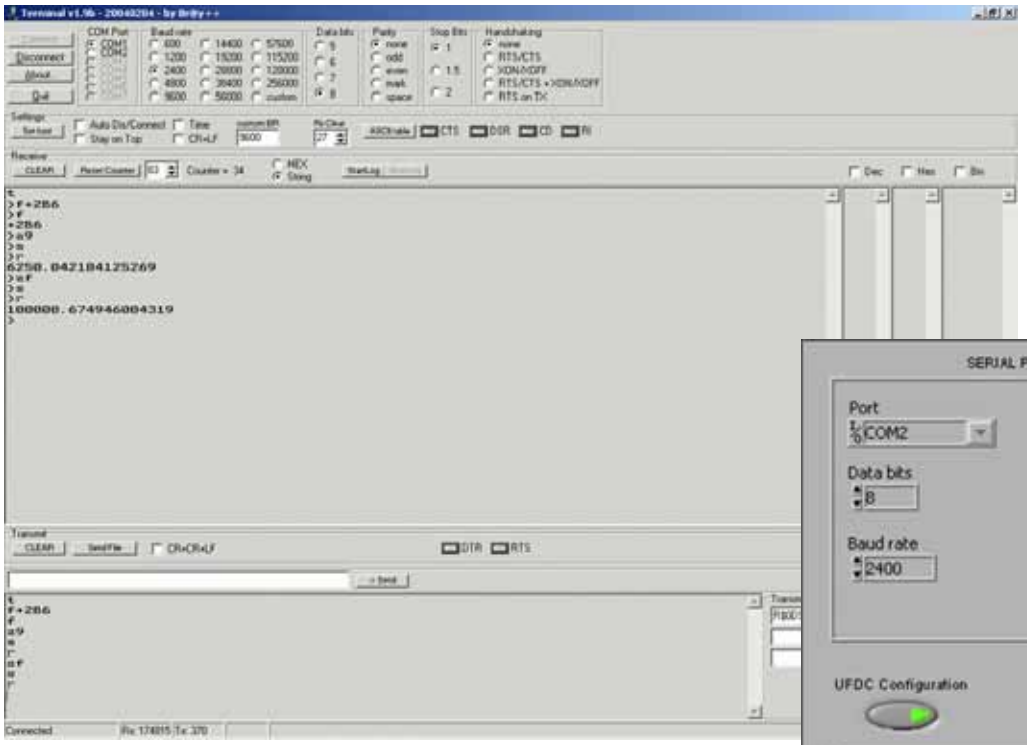
Development Board Circuit Diagram

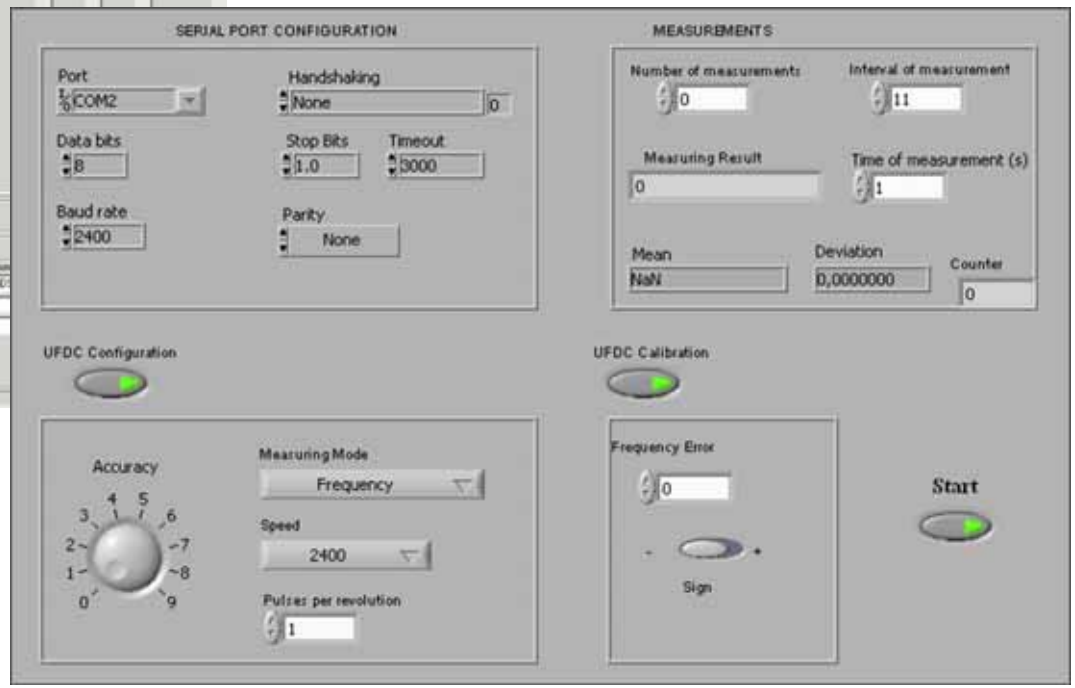


Development Board for UFDC-1/UFDC-1M-16

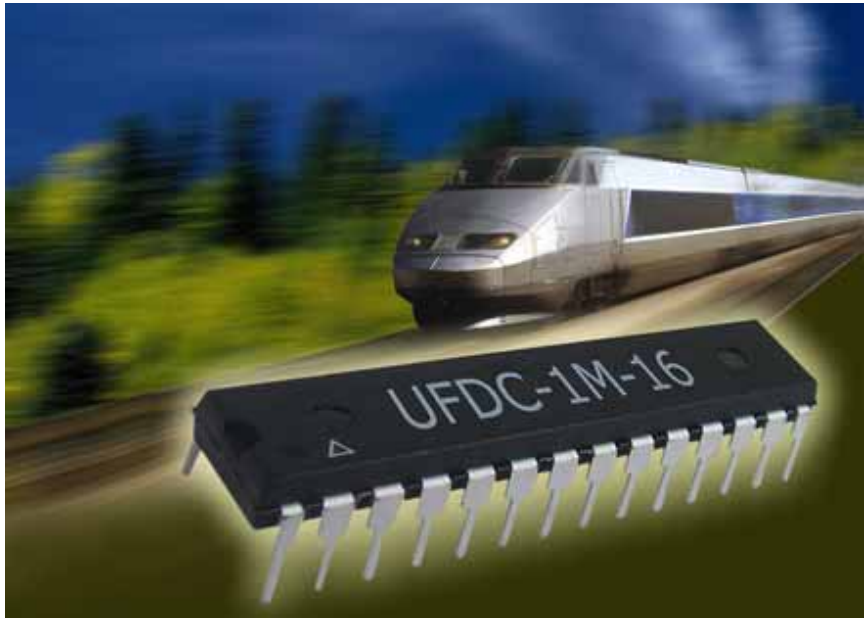


Software: Terminal V1.9b and LabView



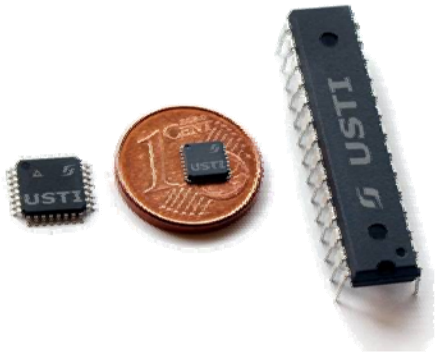


UFDC-1M-16



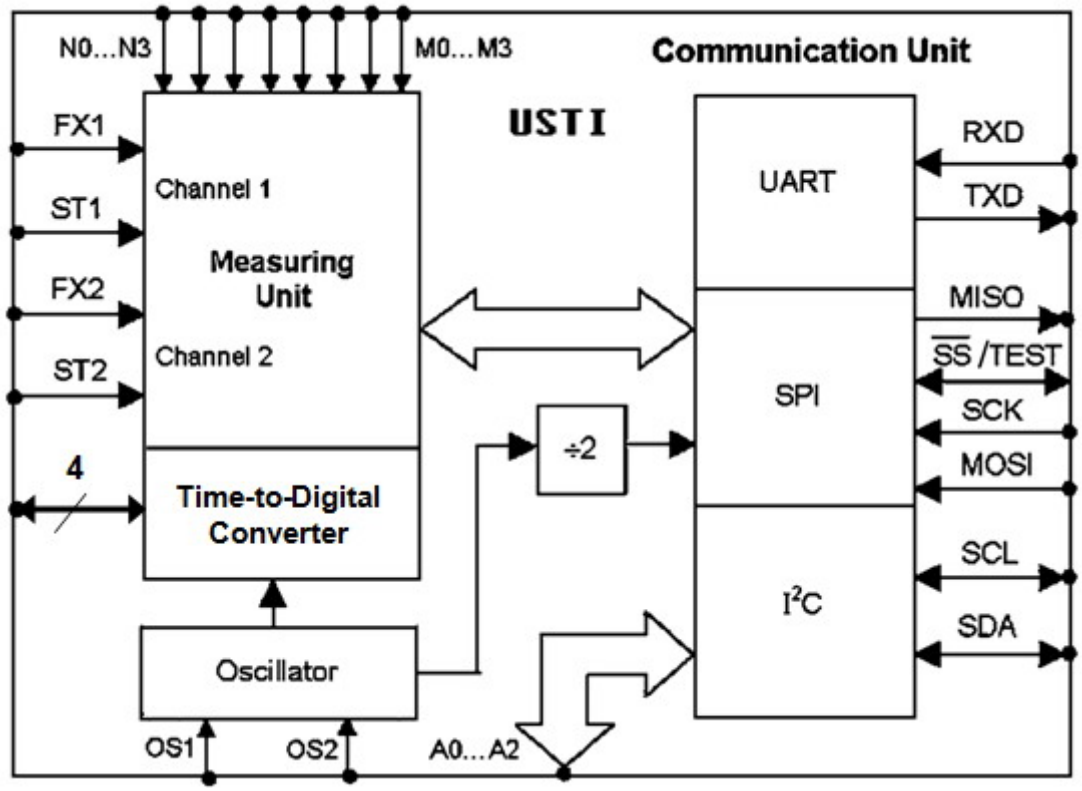
- Non-redundant conversion time: from 6.25 µs to 6.25 ms
- Internal reference frequency 16 MHz
- Frequency range: 1 Hz to 7.5 MHz (120 MHz with prescaling)

USTI



- All UFDC's modes plus a frequency deviation (absolute and relative) measuring mode
- Improved metrological performances: extended frequency range up to 9 MHz (144 MHz with prescaling), programmable relative error up to 0.0005 %, etc.
- Two channel measurements for every parameters
- Improved calibration procedures
- Resistance, capacitance and resistive bridge measuring mode

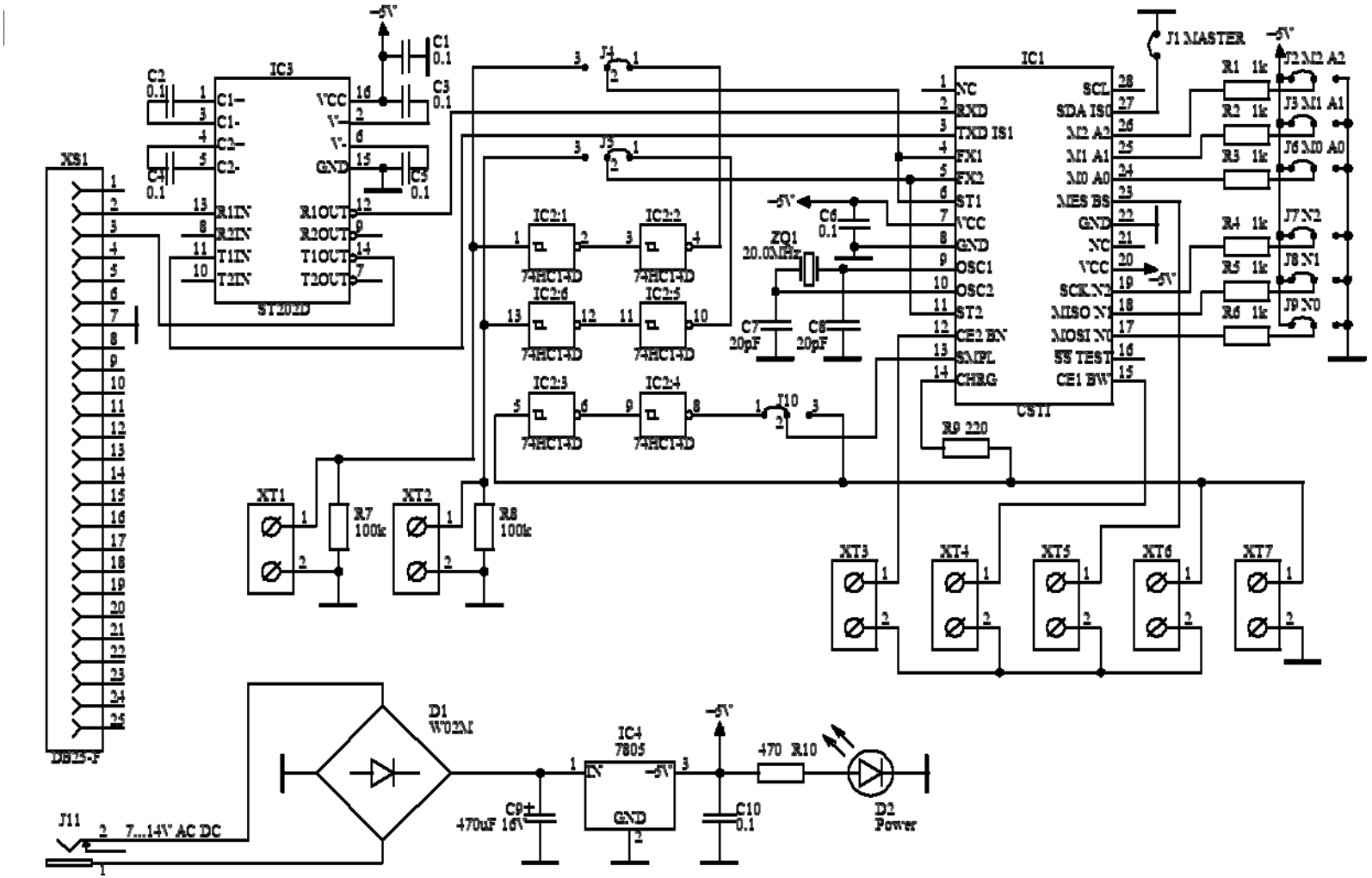
USTI Block Diagram



Comparative Table of UFDC-1 & USTI

Parameter	UFDC-1	USTI
Programmable relative error, %	± (1…0. 001)	± (1…0. 0005)
Maximal frequency range, MHz **- without prescaling** **- with prescaling**	7.5 120	9 144
Reference frequencies, MHz	0. 5 / 16	0. 625 / 20
Generating mode, MHz	8	10
Frequency deviation measurement mode	No	Yes
TEDS Support	No	Yes
2-channel conversion for	Frequency and period	All parameters
Number of measuring modes	16	26

USTI Development Board Circuit Diagram



USTI-EXT

-55 °C ... +150 °C
USTI-
EXT
USTI-
EXT
26 measuring modes for all frequency-time parameters,
rotational speed, capacitance Cx, resistance Rx, resistive bridges
Frequency range, 0.05 Hz ... 7.5 MHz (120 MHz);
Programmable relative error, % 1 .... 0.0005 %
Conversion speeds 6.25 us ... 12.5 ms
SPI, I2C, RS232 (master and slave, up to 76 800 baud rate)
Packages: 32-lead, 7x7 mm TQFP and 32-pad, 5x5 mm (QFN/MLF)

USTI-EXT Features

- Similar metrological performance as UFDC-1M-16
- Wide functionality as in USTI
- Active supply current < 12 mA
- Applications: automotive industry, avionics, military, etc.

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 and 4 x 4 mm MLF packages, TQFP and PDIP

USTI-MOB Applications

- Smartphones
- Tablets
- IoT: sensor hubs; hardware platforms
- WSN
- Wearable devices

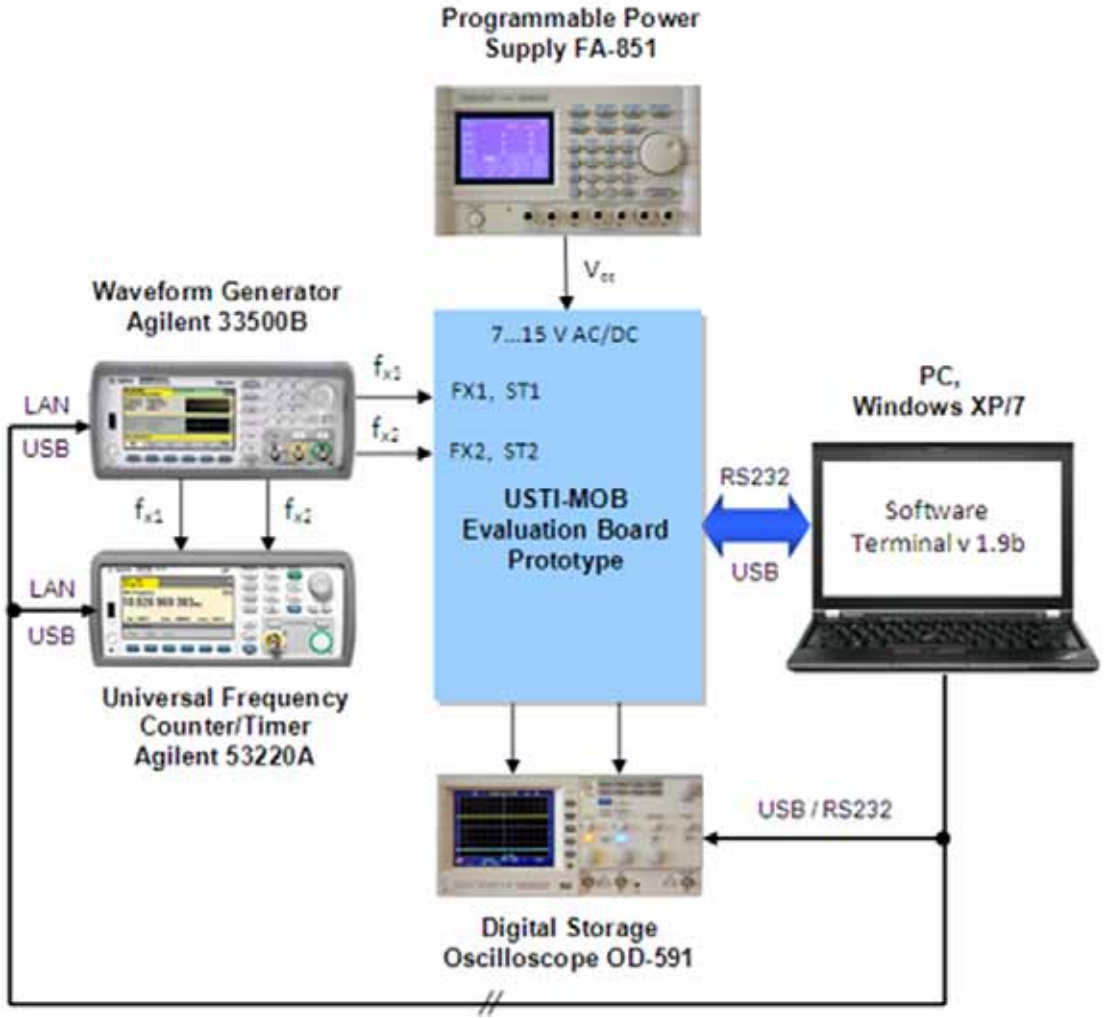
Comparative Table of USTI & USTI-MOB

Parameter	USTI-MOB	USTI
Programmable relative error, %	±(1…0. 0009)	±(1…0.0005)
Frequency range of measurement, Hz	0.25 ... 1.95×10^{6}	0.05 ... 9×10^{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

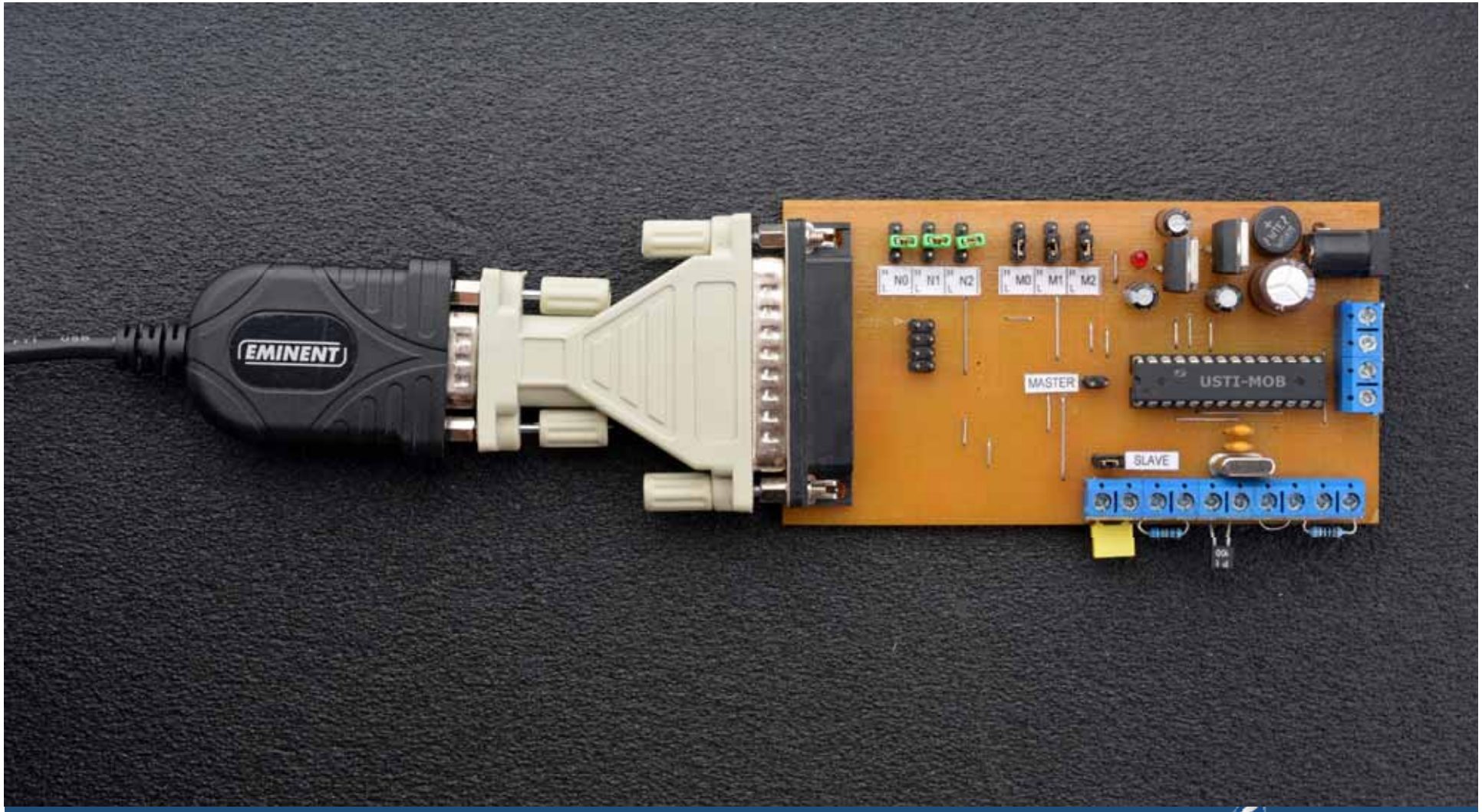
Current Consumption Comparison

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

Experimental Set-Up for Frequency-time Parameters



Development Board Prototype: R_x mode

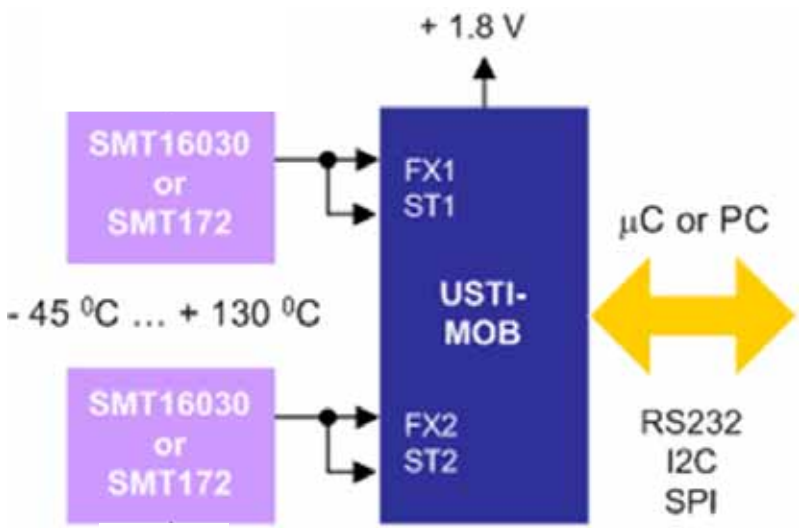


Measuring Equipment

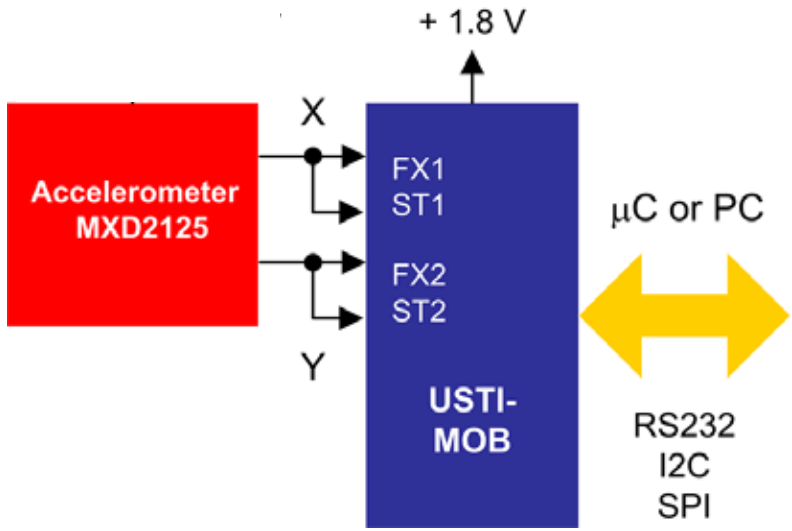
Contents

- Introduction
- Sensor types and classification
- Advanced Design Approach
- From “Smart” to “Intelligent”
- Examples
- Summary

Sensor Systems Examples



2-channel temperature sensor system

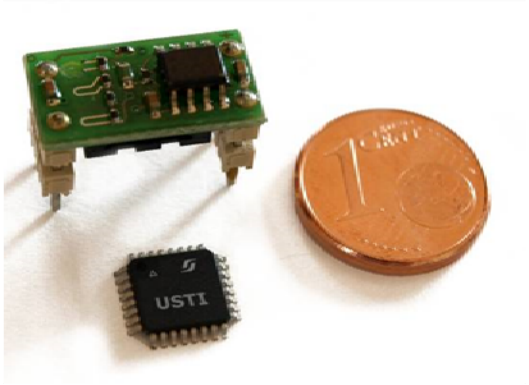


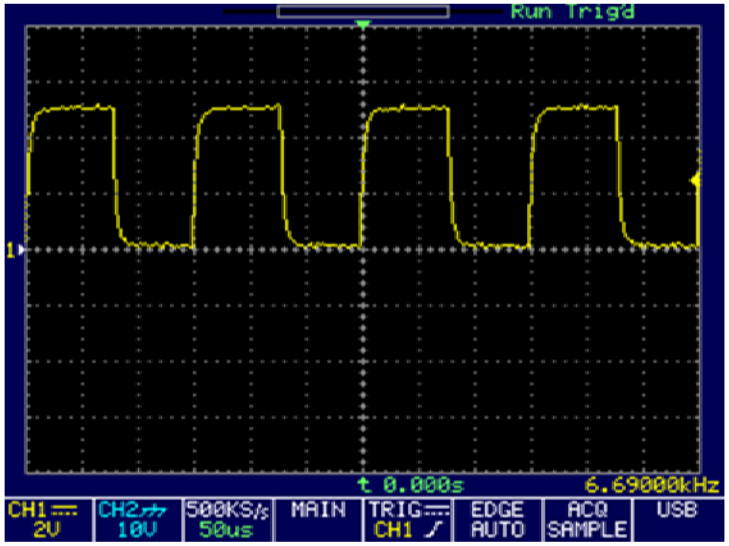
2-axis accelerometer system

Commands (RS232):

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

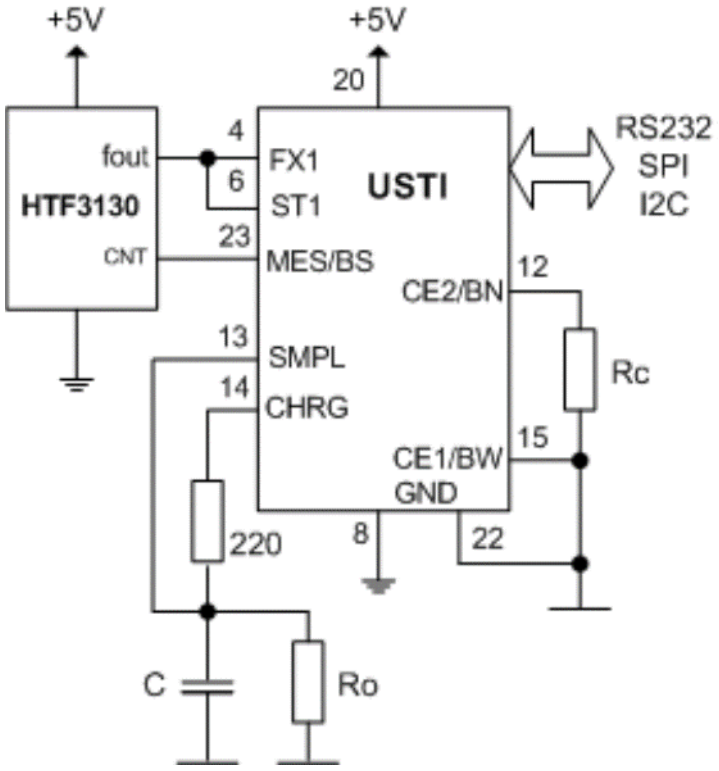
Example: Humidity Sensor





Oscillograms on humidity sensor's output at 58 % RH

Example. Hardware

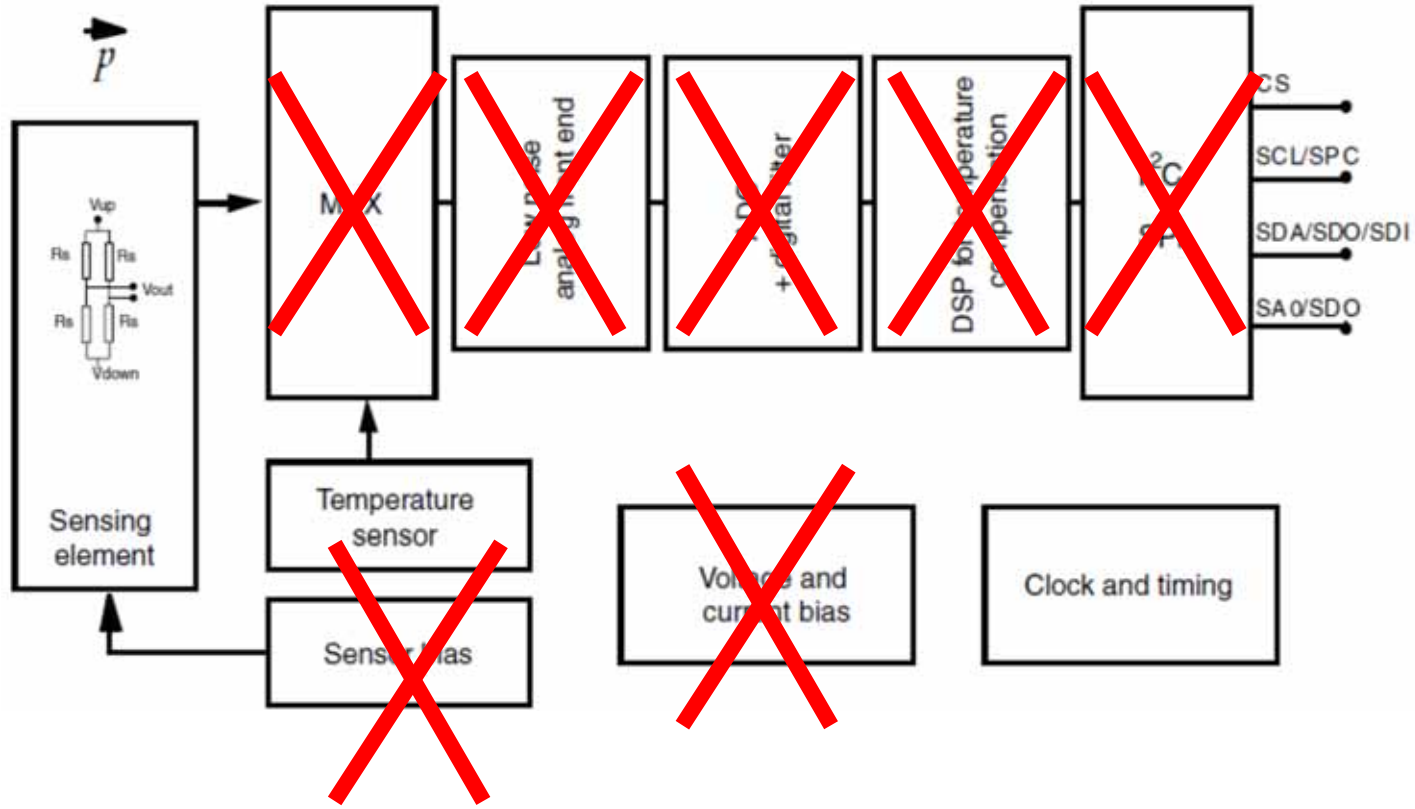


Example. Software

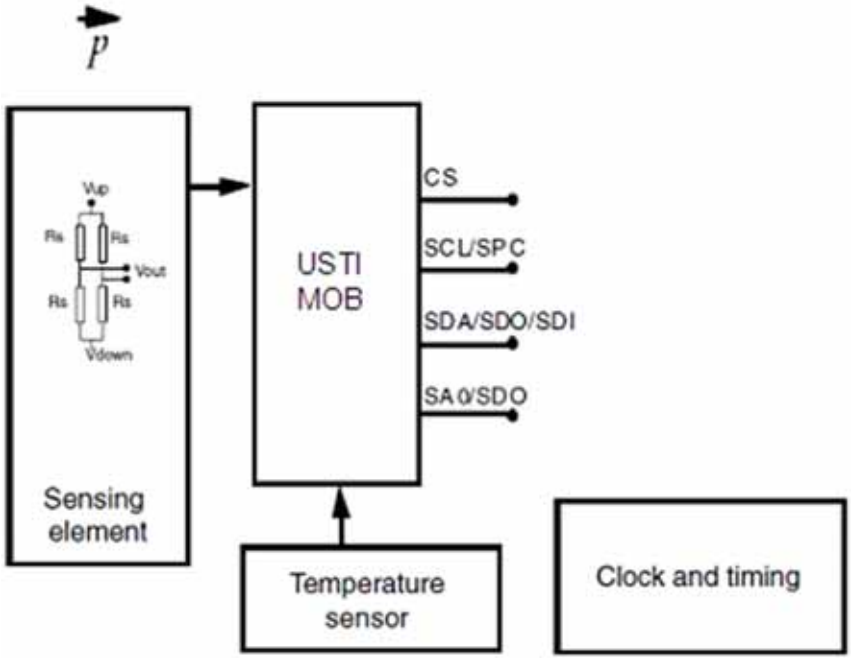
```
>M00          ; Set up a frequency measurement mode in the 1st channel
>A02          ; Set up the relative error 0.25 %
>S            ; Start a frequency measurement (humidity)
>C            ; Check result status: returns 'r' if ready or 'b' if busy
>R            ; Read a result of frequency measurement (humidity)

>M10          ; Set a resistance Rx measurement mode
>E263000.0    ; Set the reference value of Rc =263 kΩ
>W1B          ; Set the charging time 100 ms
>S            ; Start a resistive measurement (temperature)
>C            ; Check result status: returns 'r' if ready or 'b' if busy
>R            ; Read a result of resistive measurement (temperature)
```

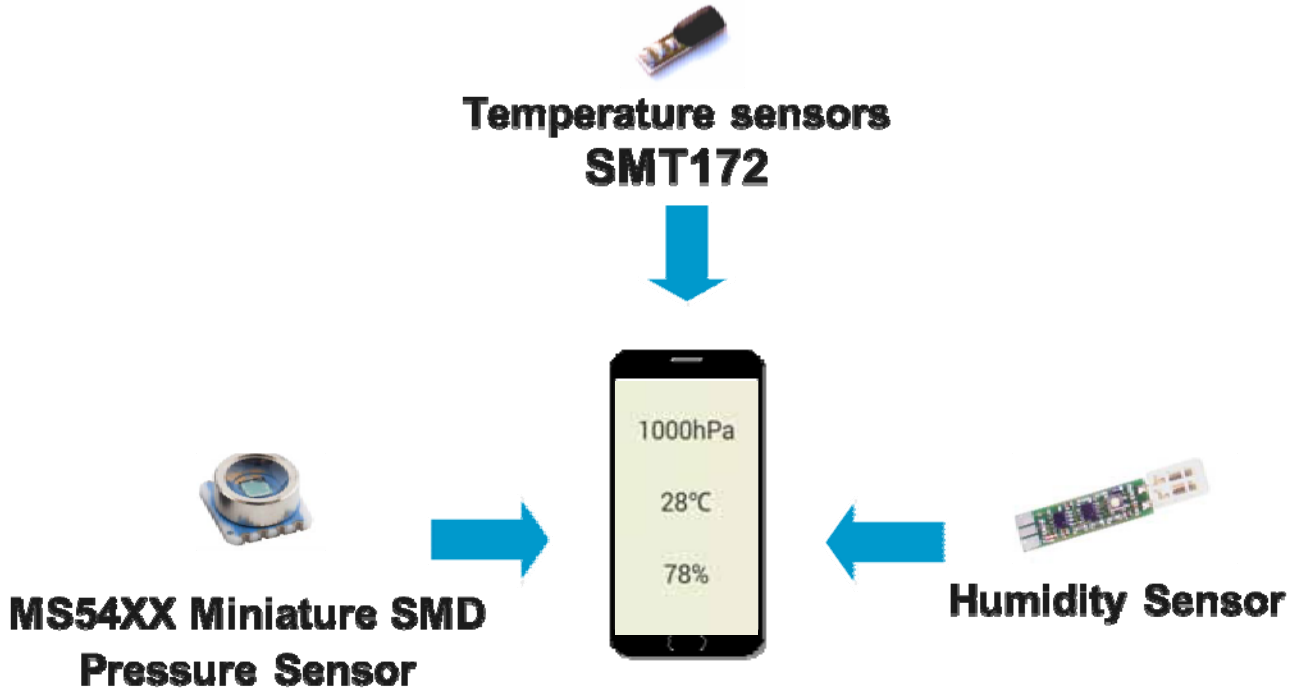
Barometric Pressure Sensors



Pressure Sensor based on USTI-MOB



Smartphone based Weather Station



WSN Application: USTI-MOB vs. T24-PA

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

mEmantracourt
Advanced Intelligent Instrumentation

IFSA

Excelera

Price Comparison: USTI-MOB vs. ADC

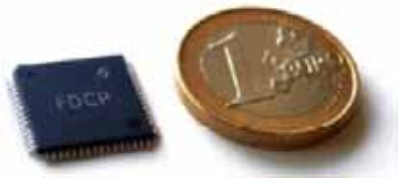
ICs	Manufacturers	Price, $ US (in quantities of 1, 000)
ADS1278, 24-bit, 8 channels, SPI	Texas Instruments	23.95
USTI-MOB, 3 channels, SPI, I2C, RS232 + any digital multiplexer (8 channels or more)	Excelera, S.L.	16.95
	Saving:	23.95-16.95 = 7.00

Texas Instruments

UFDC and USTI Custom Designs

- Extended functionality
- New measuring modes
- Customized units of measurements
- Improved metrological performance
- Communication interfaces, for example, SMBus, CAN, I3C, etc.
- IEEE 1451 standard compatibility
- Various self-adaptation functions

FDC with Parallel Interface (FDCP)



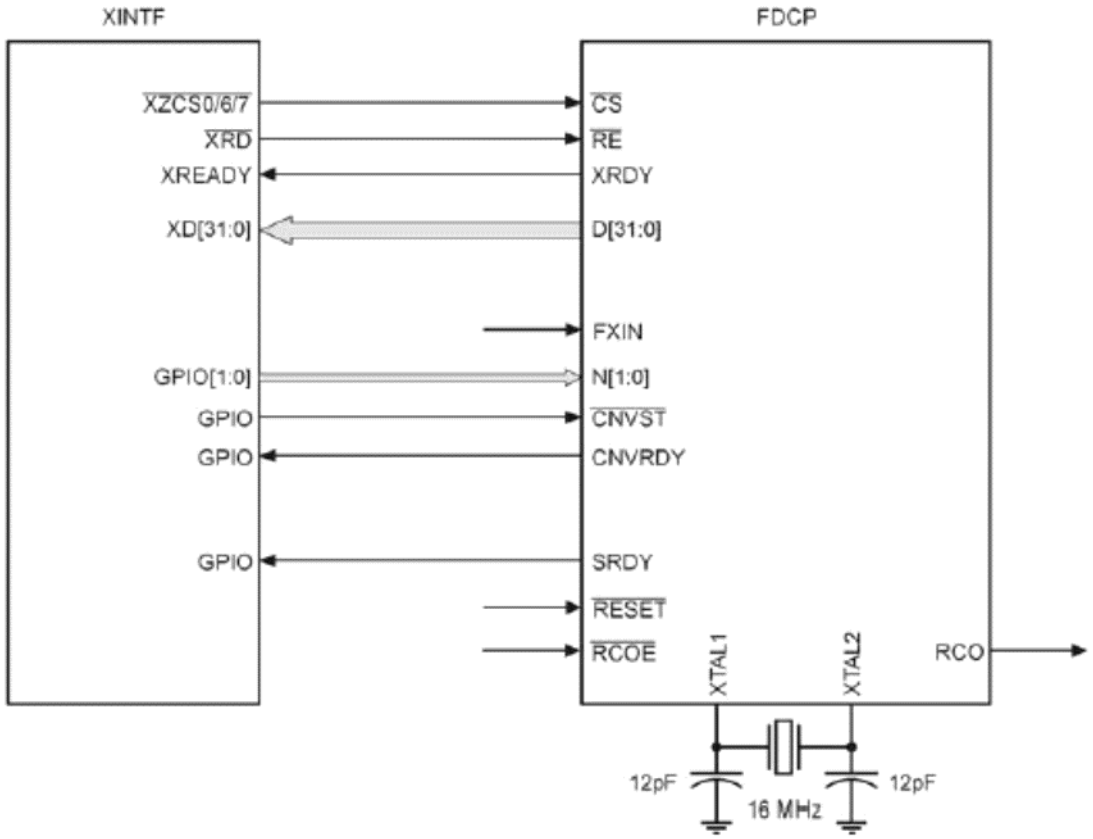
- Fully digital, low-power CMOS IC
- Non-Redundant conversion time 6.7 µs to 1.6.ms
- One generating output (f_0=32 MHz)
- 64-lead TQFP package 14 × 14 mm
- Parallel output: two 16-bit words N_x and N_r
- Slave communication mode

$$f_x = \frac{N_x}{N_r} \times f_0 \qquad T_x = \frac{N_r}{N_x \times f_0},$$

FDCP Performance & Characteristics

Parameter	Value
Minimal converted frequency, Hz	≥ 500
Maximal converted frequency, MHz	≤ 16
Programmable relative error, %	1; 0.1; 0.01; 0.002
µC (DSP µP) interface, bit	32
External clock oscillator frequency, MHz	16
Internal clock frequency, MHz	32
Supply current, mA	12
Power supply, V	3.3
Operation temperature range, ^{0}C	-40 … +85

Interfacing with DSC TMS320F28335



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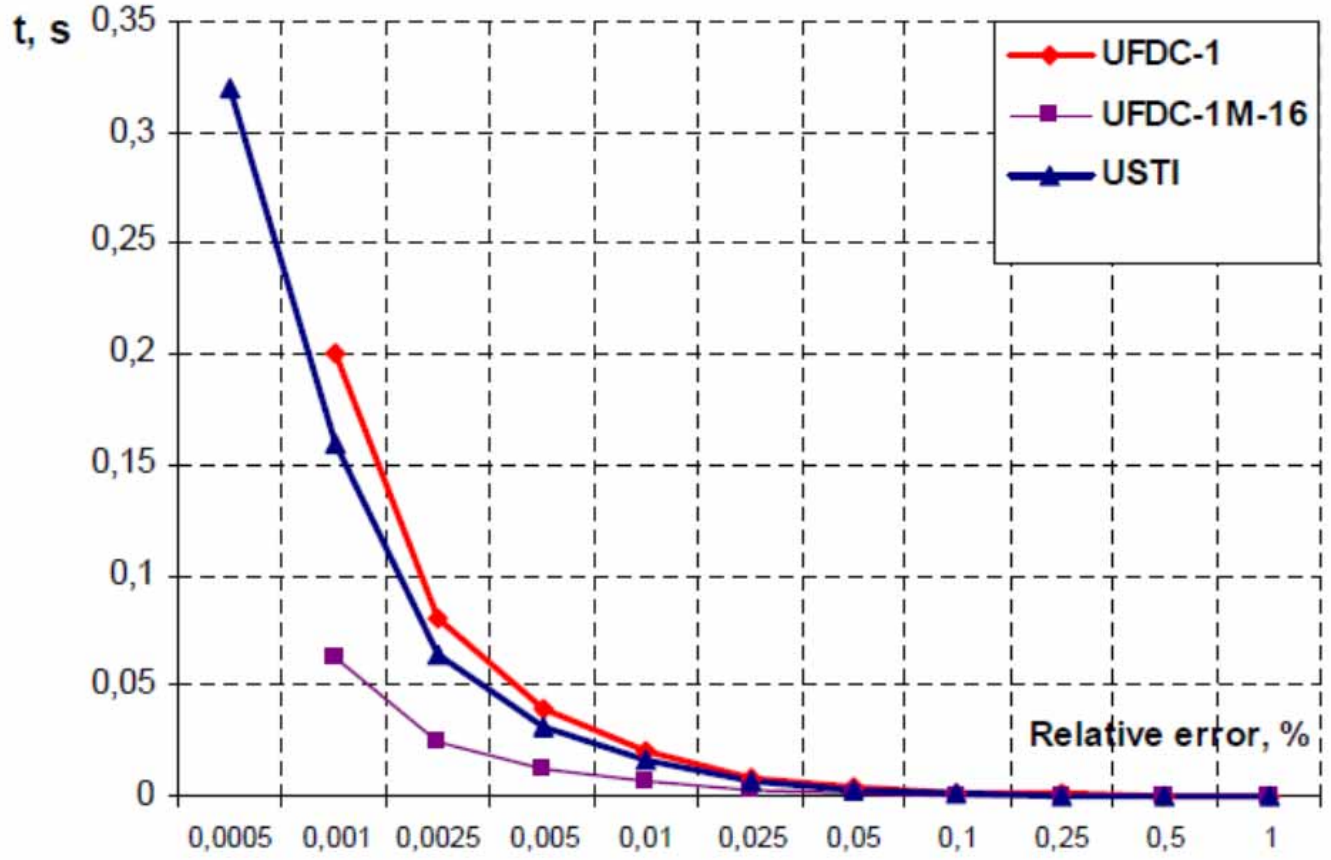
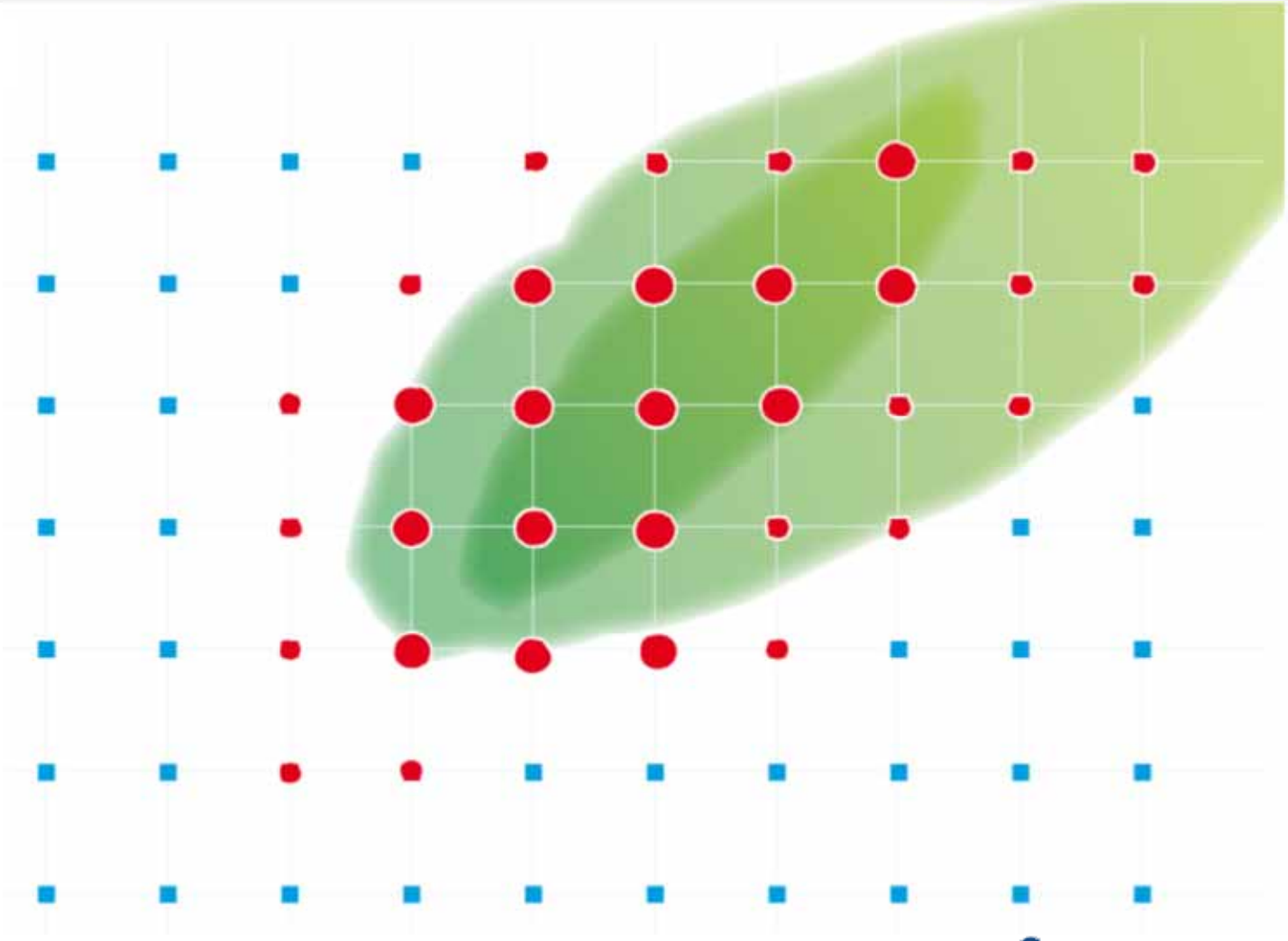
Conversion Time vs. Relative Error



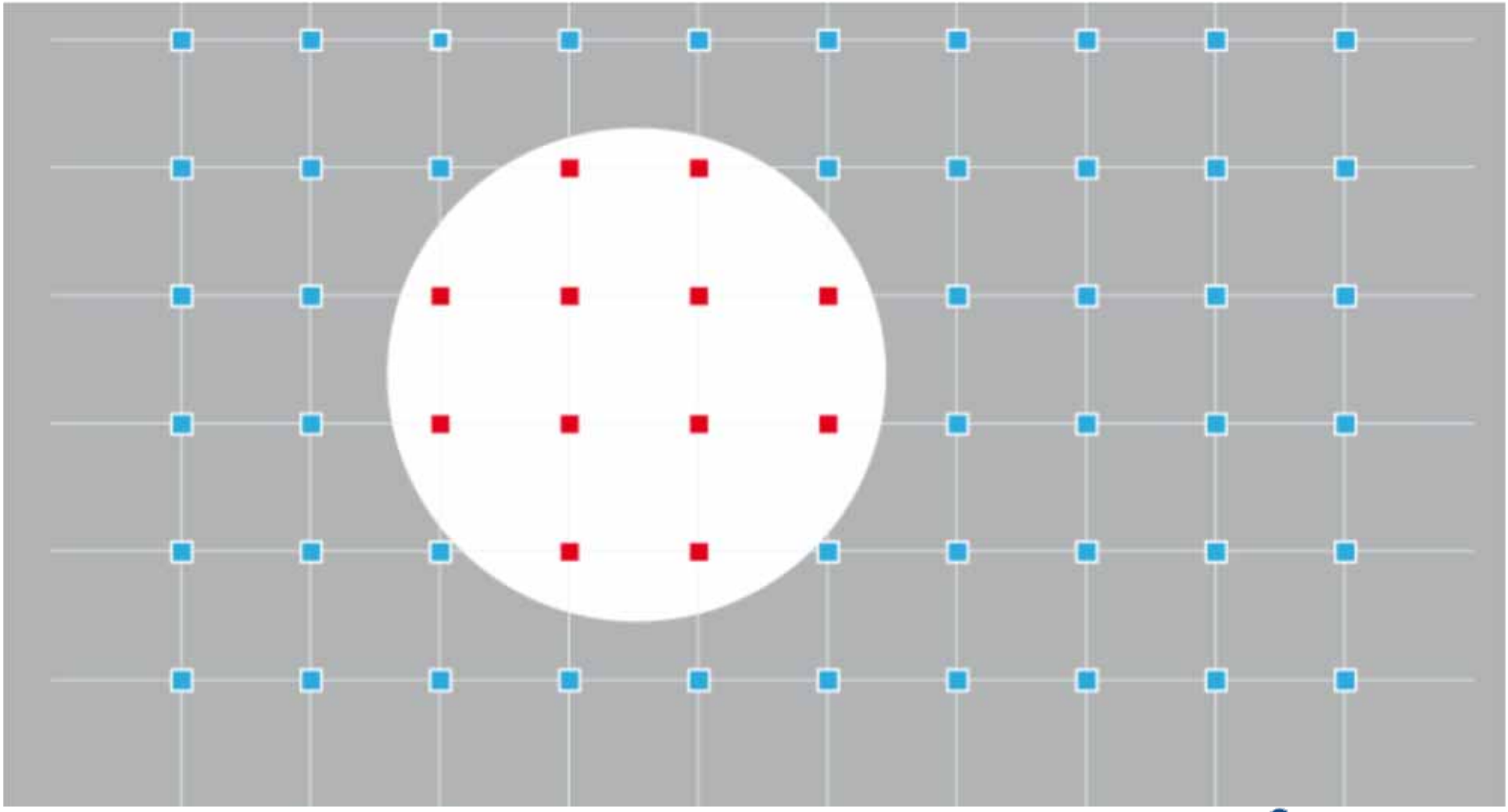
$\delta_x = f(t)$ for 4 Series of ICs

Relative error, δ_x %	$N_\delta = 1/\delta_x$	UFDC-1 (at f_0=500 kHz)	UFDC-1M-16 (at f_0=16 MHz)	USTI (at f_0=625 kHz)	USTI-EXT (at f_0=16 MHz)
		t_{conv}, s			
1	100	0.0002	0.00000625	0.00016	0.00000625
0.5	200	0.0004	0.0000125	0.00032	0.0000125
0.25	400	0.0008	0.000025	0.00064	0.000025
0.1	1000	0.002	0.0000625	0.0016	0.0000625
0.05	2000	0.004	0.000125	0.0032	0.000125
0.025	4000	0.008	0.00025	0.0064	0.00025
0.01	10000	0.02	0.000625	0.016	0.000625
0.005	20000	0.04	0.00125	0.032	0.00125
0.0025	40000	0.08	0.0025	0.064	0.0025
0.001	100000	0.2	0.00625	0.16	0.00625
0.0005	200000	-	-	0.32	0.0125

Example 5. Smart City



Example 5. Smart City



Reading & Practice

IFSA Publishing

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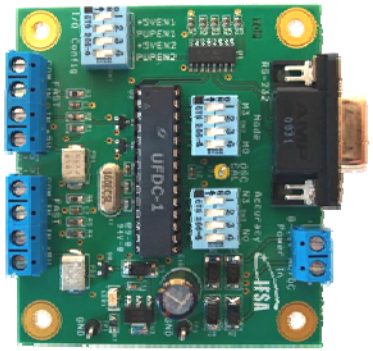

http://www.sensorsportal.com/HTML/BOOKSTORE/Digital_Sensors.htm

Summary

- 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

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Excelera
The right data, at the right time