

Energy-Efficient Capacitance-to-Digital Converter Based on Universal Sensors and Transducers Interface (USTI-MOB)

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Abstract: This article presents a highly digital Universal Sensors and Transducers Interface (USTI-MOB) with low power consumption, working in the capacitance measurement mode. The state-of-the art review of capacitance-to-frequency (time parameters) converters and commercially available capacitance-to-digital converters is provided. The proposed ASIP has the input capacitance range from 50 pF to 0.1 μ F and average relative error $< \pm 0.3$ %. The USTI-MOB has 1.5 mW power consumption at +1.8 V supply voltage, and use a 4 MHz quartz oscillator. The IC has three popular serial interfaces: I2C, SPI and RS232/USB. Due to high metrological performances and technical characteristics the energy-efficient USTI-MOB is well suitable for such application as sensor systems for IoT, wearable and mobile devices. The ICs can also work with any quasi-digital capacitance converters, in which the capacitance is converted to frequency, period, time interval, duty-cycle or pulse width of square wave signals.

Keywords: Capacitance-to-digital converter, USTI-MOB, Capacitive sensors, Capacitance sensor interface, Capacitance-to-time converter, Capacitance-to-frequency converter.

1. Introduction

According to the modern market study the global capacitive sensors market was valued at US \$ 25.11 billion in 2019 and is expected to reach US \$ 34.50 billion by 2025 at compounded annual rate of growth of 5.5 %. The increase in application in the consumer electronics industry is driving the capacitive sensor market in the forecast period.

Capacitive sensing technology is witnessing swift developments to meet the advanced user interface requirements of modern applications. The increasing preference for capacitive sensors, due to their more exceptional durability, high sensitivity and measurement accuracy than resistive or inductive

sensors are major factors, which drive the growth of the market studied.

The most of existing capacitive sensors do not require any special additional materials or processes beyond those of the basic CMOS technology [1]. Due to the low production cost and large range of applications, the capacitive sensors are widely used in various sensing applications including SOI-MEMS accelerometers, gyroscopes, displacement sensors, flow sensors, humidity and moisture sensors, level sensors, pressure sensors, proximity sensors, angular and linear position sensors, hazardous gas sensors, pH sensors and biosensors. It also used in biochemical analysis, biotelemetry, lab-on-chip and for monitoring of biomolecular reactions. The values of capacitive

sensors can range from less than one pF up to hundreds of pF or even to nF.

One of the main benefit of the use of capacitive sensors is that the sensing elements itself is a passive component, which does not consume any static power, and consequently, it is very suitable for different low-power applications [2], for example, wearable and bioimplantable devices, IoT sensors and transducers, etc. The major of the power consumption comes from the electronic readout circuit used to digitize the sensor capacitance. Hence, a capacitance-to-digital converter (CDC) needs to have high energy efficiency, while having high metrological performances.

This article presents an extension of the work reported in [3-5] showing measurements from the developed Universal Sensors and Transducers Interface (USTI-MOB) IC, working in the direct capacitive sensors interfacing mode.

2. Capacitance-to-Digital Converters: State-of-the Art

2.1. Sensor Circuit Topology

Dependent on the sensing element electrical configuration, the following circuit topology can be categorized: single-ended and differential grounded sensors (i.e. sensors in which one of the electrodes is grounded); single-ended and differential floating sensors (i.e. sensors in which neither of the electrodes is grounded), [6] and differential capacitive sensor Wheatstone bridge. The appropriate topology should be selected according to applications. Some of them require the capacitance between one input node and ground, others need the capacitance value between one input nodes excluding parasitic capacitance to ground.

2.2. Capacitance Readout Circuits

A readout circuit to measure the capacitance value is needed to convert the capacitance change into an analog parameters (voltage, current or phase shift between voltage and current) or frequency-time (quasi-digital) parameters of electrical signals. The CDCs classification scheme in term of readout circuits is shown in Fig.1.

2.2.1. Capacitance-to-Voltage Conversion

Many of the readout circuits are capacitance-to-voltage converters (CVCs) operating through charge transfer techniques, and followed by analog-to-digital converters (ADC) [7] of the following typos: cyclic, incremental, $\Sigma\Delta$, dual-slope and successive approximation register (SAR)-type ADCs [8-13] to cope-off between performance and power consumption. However, each type of ADC has some difficult requirements to be implemented. Such approach requires complex signal conditioning and analog components (amplifiers, filters, analog multiplexers, etc.) increasing the design complexity, power consumption, chip area and cost. It needs analog and mixed designs, which are significantly complex for CMOS standard technologies below 40 nm and less. Moreover, the initial capacitance-to-voltage conversion essentially limits the input capacitance range due to of output voltage saturation.

The technology scaling is especially beneficial for digital circuits [14, 15]. The reduced parasitic capacitance improves both: power consumption and speed performances. Analog circuits, however, are less scalable and suffer more when going to nm.

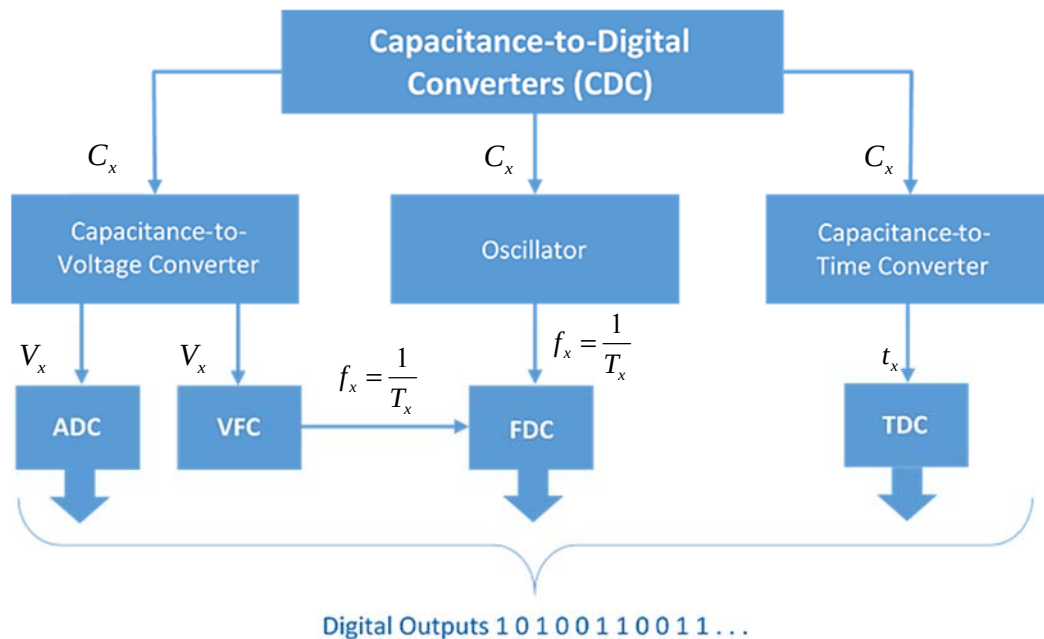
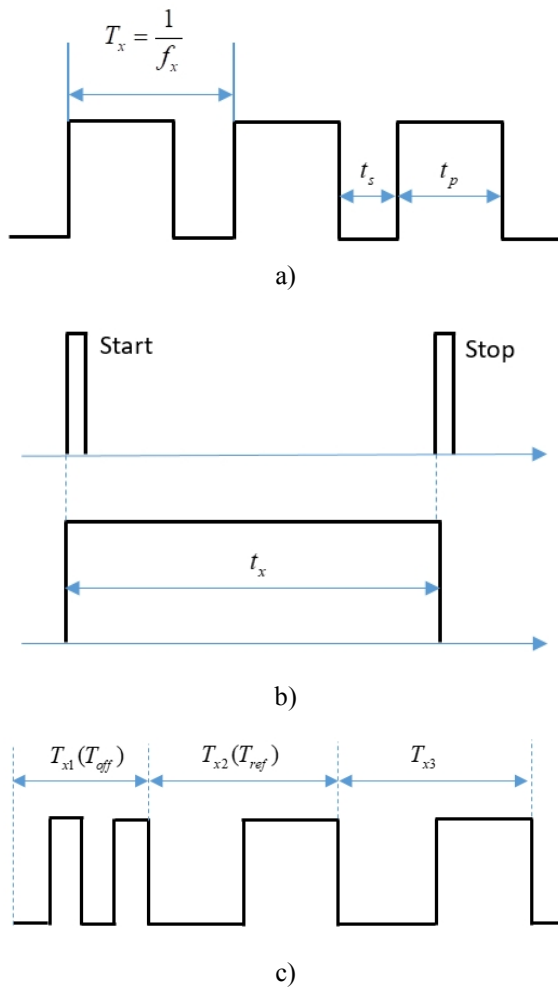


Fig. 1. Capacitance-to-Digital Converters (CDCs) classification scheme (VFC – Voltage-to-Frequency Converter; FDC – Frequency-to-Digital Converter; TDC – Time-to-Digital Converter).

2.2.2. Frequency-Time Parameters of Signals

Frequency-time parameters of electrical signal, which are using in capacitance readout circuits are the following: frequency (f_x), period (T_x), pulse width (t_p) and pulse space (t_s), time interval between start- and stop-pulses (t_x), duty cycle and duty-off factor. The pulse width modulated (PWM) signal has an informative parameter determinate as the ration of pulse width (t_p) to pulse space (t_s) at the constant period (T_x). The main frequency-time informative parameters are shown in Fig. 2 (a-b).

At period modulation, the capacitance sensor information is converted to the full length of one or more non-equals periods (Fig. 2 (c)). The period modulated signal is used in some converters based on a three signal auto-calibration technique [16-18]. The period modulated-based interfaces are asynchronous and have a measurement time and a resolution generally dependent on the sensor capacitance [19]. On the other hand, the other frequency-time-based solutions are synchronous circuit needing a clock line to synchronize the interfacing operation, while their measurement time and resolution are typically independent from the sensor capacitance [19].



2.2.3. Capacitance-to-Time Conversion

In comparison with the CDCs based on ADCs, the CDCs based on TDCs for time interval between start- and stop-pulses, pulse width and pulse space, have mainly digital components. However, as it was written in [20, 21] the TDC requires a fast digital counters and a high frequency stable reference clock in order to achieve the reasonable resolution and low quantization error, which results in increased power consumption.

A coarse-fine TDC based on the asynchronous sampling method was described in [22]. This TDC lets to eliminate the quantization error in counter and has low power consumption.

The TDC with continuous sampling for biomedical sensing has been proposed by Huang H.-Y., *et al* [23]. It has a low power consumption and small chip area.

A differential capacitance-to-digital converter with the 22 pF capacitance range was proposed by Lee H., *et al* [24]. It is also based on the TDC, which convert time interval between start- and stop-pulses to digital code. The TDC contains time splitter, chopper and stretchers.

Symbol	Description	Unit
T_x	Period	[s]
$f_x = 1/T_x$	Frequency	[Hz]
t_s	Pulse width	[s]
t_s	Pulse space	[s]
$D.C. = t_s/T_x \times 100$	Duty cycle	[%]
$k = 1/D.C. = T_x/t_p$	Duty off factor	-
t_x	Time interval	[s]
t_p/t_s at $T_x = \text{const}$	PWM signal	-

PWM – pulse-width modulation

$$T_{x1} \neq T_{x2};$$

$$T_{x2} \approx T_{x3}.$$

Fig. 2. Frequency-time parameters of electrical signals, which are using in capacitance readout circuits: (a) Period, frequency, pulse width and pulse space; (b) Time interval between start- and stop-pulses; (c) Period modulated signal.

Any time interval measurements [22-24] between start- and stop-pulses or pulse width/space, are, in the nature, a single time interval measurements and introduce additional significant error due to a jitter.

The time-based Capacitance-to-Digital Converters based on a new design methodology for parasitic cancellation with a simple calibration technique were presented by Hassan A.H. *et al* and Fouad A. *et al* in [25] and [26] respectively. The maximum relative error is not more than $\pm 3\%$, and capacitance range from 0.17 to 15 pF [26]. However, as it was marked in [27], the signal-to-noise ratio of this device is as low as 45.14 dB due to error accumulation in the two conversion steps.

A precise capacitance-to-pulse width converters for integrated sensors are described in [28, 29] and capacitance-to-duty cycle converters – in [30, 31] in which, the capacitance changes are converted in the pulse width or duty-cycle of a pulse stream respectively. The duty-cycle output converter reported in [30] has narrow capacitance range [1-18 fF], and duty-cycle is varied from 40 to 90 %.

De Marcellis, *et al* has proposed the capacitance interface for differential capacitive sensors, which provides a square wave output in which the difference between pulse width (t_p) and period (T_x) is proportional to the capacitances C1 and C2 [19]. It contains three Operational Amplifiers, one analog mixer and seven resistors discrete components. The capacitance detection range is [2.2 pF ÷ 197 pF]. Nevertheless that the capacitance-to-time converter has the immunity to voltage offset and low sensitivity to noise/disturbs, it is difficult to be realized as a single chip.

2.2.4. Capacitance-to-Frequency Conversion

Dependent on the circuitry, capacitance-to-frequency converters (CFCs) can be divided into two main types: CFC employing a CVC followed by a voltage-to-frequency converter (VFC), and CFCs using different oscillators (liner, non-linear, ring, switched-capacitor harmonic, relaxation, etc.) with direct frequency or period output proportional to the sensor capacitance. This makes the sensor information less sensitive to noise and can be processed in a highly digital way. Non-ideal effects and electromagnetic noises/disturb only affect the amplitude but not frequency of square-wave pulse stream.

The capacitance-to-frequency conversion is well-known for a long time and has become increasingly popular in recent years. It is a well-established technique and represents a universal transduction mechanism for the measurements in which the capacitance changes need to be measured with high accuracy [32].

Krummenacher F. has introduced a high resolution 16-bit capacitance-to-frequency converter in [33]. It has 0.1 pF to 20 pF capacitance range, good linearity (better than 0.1 %) and low power consumption (less than 0.1 mW).

A low power CMOS integrated CFC with on-chip temperature sensor and digital output according to I2C bus, designed for humidity sensors for 20-80 % RH is described in [34]. It has up to 350 pF capacitance range, and about 150 μ W power consumption.

A cost-effective CMOS differential CFC for monitoring biomolecular reactions was proposed by Lee H., *et al* [35]. It has 3 mW power consumption.

Shin D.-Y., *et al* has improved the accuracy of capacitance-to-frequency converter by accumulating residual charges [36]. This CFC has 1.5 – 2.5 pF capacitance range, 0-1 MHz frequency output range and relative error $\pm 0.13\%$.

Ramfos I., *et al* has described a 16-channel CMOS integrated capacitance-to-period converter for capacitive sensor applications [37]. The output signal of the readout is a square wave signal, with period (T_x) linearly proportional to the sensor capacitance C_x . The relaxation oscillator type CFC has 10-140 pF capacitance range and 20 mW power consumption.

A temperature-compensated capacitance-frequency converter with high resolution has been introduced by Matco V., *et al* [32]. The CFC has 0-4 pF capacitance range and 2-45 kHz frequency output range.

2.3. IC of Capacitance-to-Digital Converters

The modern semiconductor industry is driven towards smaller technologies to reduce the power consumption and cost. Many capacitive sensor applications, for example, IoT, sensor networks, mobile (smart phones, tablets, etc.) and wearable devices need a digital output according to the standard interfaces and buses.

An integrated implementation of this sensors together with readout circuit and appropriate FDC or TDC yields better metrological and performances and operational characteristics in term of accuracy, noise immunity and power consumption.

Let consider integrated CDCs commercially available on the modern market. Examples of such interfaces are the 1-2 channel capacitance-to-digital converters for floating capacitors AD7745/AD7746 of Analog Devices [38] and the AD7747/AD7748 [39] converters for grounded capacitors. Additionally, the same company offers the AD7150 [40], which is a low-power (300 μ W) capacitive sensor interface. All these CDC are based on CVC and Σ - Δ ADC. With all of these ICs, the maximum capacitance that can be measured is 17 pF. The measurement results of all of these interfaces are very sensitive to the effects of resistive leakage. All ICs have one I2C or SPI interface and can work only in the slave communication mode. The capacitance converters of AD715X Series have only 12-bit resolution.

The IC of Series MAS6510 from Micro Analog Systems is a capacitive sensor signal conditioner IC, capable to interface both single and differential capacitance sensors [41]. This 24-bit capacitance-to-digital converter, employs a delta-sigma (Δ - Σ)

conversion technique. Maximum sensor capacitance is 40 pF, and power consumption - 86 μ W. The conversion time 5.8 ms ... 86.6 ms. The IC is compatible with I2C and SPI buses.

The ZSSC3123 cLite™ from Renesas Electronics Corporation (former Integrated Device Technology) is a CMOS integrated circuit for capacitance-to-digital conversion with ± 0.25 % FSO relative error and sensor-specific correction of capacitive sensor signals [42]. The power consumption is 1.7 mW and maximum capacitance 260 pF.

The capacitance-to-digital converters of ZSSC3122 series also have a limited capacitance ranges (< 10 pF) and the same relative error [43]. The power consumption is 1.2 mW. This two ICs have two popular serial buses: I2C and SPI.

The capacitive sensor signal conditioner ZSSC3230 from the same company has the maximum target input capacitance 30 pF [44]. The power consumption is 1.3 mW. It contains the 18-bit ADC adjustable in speed and resolution. The converter has one serial I2C compatible interface.

European Sensors Systems S.A. (ESS) announces the launch of ESS113, a low power, full custom mixed-signal capacitive sensor signal conditioning IC, designed in a standard CMOS technology [45]. The capacitance range is up to 100 pF and power consumption - 1.3 mW. It also has two standard serial buses compatible with I2C and SPI.

Another capacitance-to-digital converter on the market is the 28 (12)-bit, 2 (4) - channel CDCs Series FDC2x1x from Texas Instruments [46]. The maximum input capacitance is 250 nF, and power consumption - 5.7 mW. The CDC has one serial I2C interface and is based on a resonant circuit.

The PCAP04 capacitance-to-digital converter from ams feature an integrated Digital Signal Processor (DSP) for on-chip data post-processing, and is based on the capacitance-to-time interval (between start- and stop-pulses) converter [47]. The capacitance range is from 1 pF to 100 nF, power consumption - 1.44 mW. The CDC has I2C and SPI serial buses.

The Universal Sensors and Transducers Interfacing (USTI) from F2D (former Excelera, S.L.) - an IFSA Group company, Series of IC integrated circuit can work in a capacitance-to-digital conversion mode [3, 4, 48]. The capacitance range is from 50 pF to 100 μ F and average relative error ± 0.036 %. The CDC has three popular serial interfaces: RS232, I2C and SPI. The power consumption of CDC is relatively high: 47.5 mW.

All ICs except the USTI can work only in the slave communication mode, controlled by an external microcontroller.

3. Capacitive Sensor Interface

3.1 Design Implementation

Nevertheless of some existing on the modern market integrated CDCs, the design of low-power,

accurate converter with wide capacitance range is an actual task. The very large maximum input capacitance of hundreds nF and more allows for the use of remote sensors, as well as for tracking environmental changes over time, temperature and humidity.

All this was a reason to create the low-power version of USTI - USTI MOB. The universal sensors and transducers interfacing IC Series USTI-MOB is a CMOS integrated circuit (ASIP), which can work in a capacitance-to-digital conversion mode. It is based on a three-signal measurement technique, (initially published in [49]) at which the offset, reference and measurand capacitance values are converted into three time intervals by internal capacitance-to-time converter base on the internal comparator. Similar to the USTI, the unknown capacitance should be calculated according to the following equation [3, 4]:

$$C_x = \frac{N_x - N_{off}}{N_{ref} - N_{off}} \cdot C_{ref}, \quad (1)$$

where N_x , N_{off} and N_{ref} are the numbers of reference frequency pulses counted during the measurand, offset cancelation and reference measurement stages respectively; C_{ref} is the precision reference capacitor. The direct capacitive interface needs only a few external components such as a reference capacitor C_{ref} and two resistors.

The following design consideration should be taken into account for the external components. The resistance (in Ohm) must be calculated according to the following equation:

$$R \geq \frac{0.002}{C_{ref}} \quad (2)$$

The charging time (in seconds) should be calculated by the following way:

$$T = 2200 \times C_{ref} \quad (3)$$

The charging time can be set up with the help of USTI-MOB's command "Wnn" [50]. The value of C_{ref} also should be set up with the help of appropriate USTI's command Ei.f in advance, where "i.f" is the fixed point decimal number: "I" is the integer part (1 to 12 decimal digits) and "f" is the fractional part (0 to 12 decimal digits).

The converter has three popular serial interfaces RS232, SPI and I2C for communication to PC or master microcontroller. The USTI-MOB can work in a slave communication mode with all mentioned serial interfaces and a master communication mode for RS232 communication. In the last case no any master microcontroller neither external PC should be used for IC controlling. The USTI continuously generates

converted results at its output. In the master communication mode the charging time should be set up with the help of external switches N0, N1, N2. In this mode the result at the converter's output will be presented as C_x/C_{ref} . In order to get the actual capacitance, such result must be multiplied by C_{ref} .

The USTI-MOB IC has been introduced on the market in three packages: 28-lead PDIP, 32-lead TQFP and 5×5 mm 32-pad MLF (Fig. 3). The QNF/MLF 4×4 mm package is coming soon.



Fig. 3. USTI-MOB in 28-lead PDIP, 32-lead TQFP and 5×5 mm 32-pad MLF packages.

Since every readout circuit will produce different types of output, a sensor interface that can support various types of capacitive sensors is necessary.

Taking into account that the USTI-MOB can convert also all frequency-time parameters of electrical signal shown in Fig. 2 (a, b) into a digital code, any considered before capacitance-to-frequency (period), -duty cycle, -time interval between start- and stop-pulses, -pulse width and -pulse space converters as well as converters based on the VFC can be connected directly to one of the USTI-MOB's channel. By this way a 3-channel capacitance sensor system with very wide capacitance range and high metrological performances for grounded, floating and differential capacitive sensors can be built easily (Fig. 4).

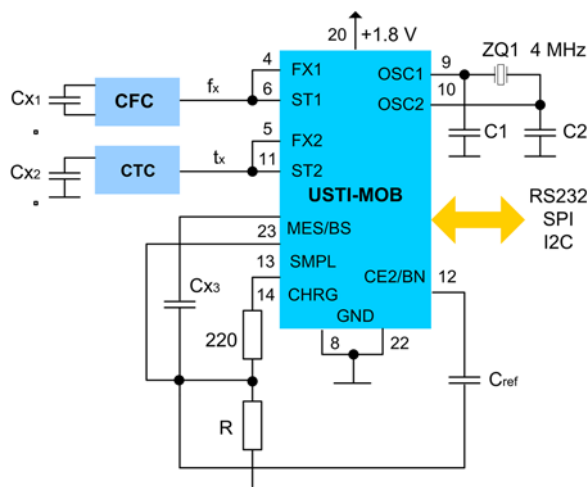


Fig. 4. Circuit diagram of CDC based on USTI-MOB (CFC – capacitance-to-frequency (period) converter; CTC – capacitance-to-time converter; C_{xn} – capacitive sensors; R – limiting resistor; $C1=C2=20$ pF).

The USTI-MOB is based on three novel patented methods for frequency-time parameters of electrical signals. So, the frequency (period) is measuring in a wide frequency range from 0.25 Hz to 1.95 MHz without prescaling and 30 MHz with prescaling, with the constant, programmable (selectable) relative error from 1% to 0.00009 % and non-redundant time of measurement, which is dependent on the error of measurement.

Taking into account the wide measuring range of USTI-MOB and advanced conversion method for frequency measurement, it will be not necessary to narrow artificially the frequency range of CFC, for example, as it was done in [32]. As the state-of-the-art review has shown, the frequency range of modern CFC is from a few Hz to some MHz. The best, reported relative error is 0.13 % [36], so, to be neglected, the frequency-to-digital conversion must be done with the relative error in one order better in comparison with the CFC' error: ± 0.013 %.

An example of USTI-MOB's commands for the direct capacitance-to-digital conversion ($C_{x3}=108.3$ nF), frequency (C_{x1}) and duty-cycle (C_{x2}) measurements for RS232 serial interface, slave mode, is shown in Fig. 5.

```
> M11 ; Capacitance measurement mode selection
> E0.000000112 ; Reference set up  $C_{ref}=112$  nF
> W01 ; Set up the charging time (200  $\mu$ s)
> S ; Start Measurement
> C ; Check the measurement status: 'r'-ready, 'b'-busy
> R ; Get the result in F:
0.000000108422

> M00 ; Frequency measurement mode in the 1st channel
> A06 ; Set up the measuring error 0.01 %
> S ; Start Measurement
> C ; Check the measurement status: 'r'-ready, 'b'-busy
> R ; Get the result in Hz:
45005.1250876

> M14 ; Duty-cycle measurement mode in the 2nd channel
> S ; Start Measurement
> C ; Check the measurement status: 'r'-ready, 'b'-busy
> R ; Get the result in %:
30.005799
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Fig. 5. USTI-MOB commands for capacitance, frequency and duty-cycle measurements (RS232 interface).

3.2 Experimental Setup

The USTI-MOB was tested in the laboratory at the 24.0-27.5 °C temperature range and 20-40 % RH to check the metrological performance at capacitive measurements. The IC together with all external components was assembled on the USTI-MOB development board prototype.

The supply voltage of the development board was +14 V dc, provided by the programmable power supply FA-851 Promax. The digital storage

oscilloscope OD-591 *Promax* was used for the signal's shape monitoring on the USTI-MOB's SMPL pin (13). The experimental setup is shown in Fig. 6.

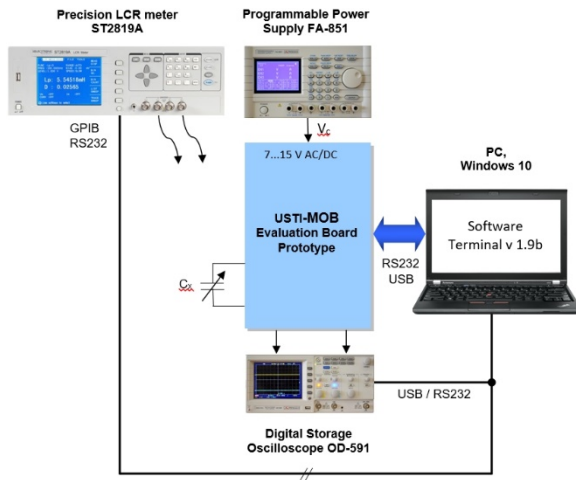


Fig. 6. Experimental Setup.

The USTI-MOB was applied to the measurement of capacitance in a wide range: from 50 pF to 0.1 μ F. Preliminary, 15 points were selected for the experiment from the mentioned range. Each capacitor was measured 100 times ($n=100$), and appropriate statistic have been calculated. The nominals for external components R , C_{ref} and charging time T values were calculated for each of point. The C_x , C_{ref} and R were measured with the precision LCR meter ST2819A, whose basic accuracy is better than ± 0.05 %.

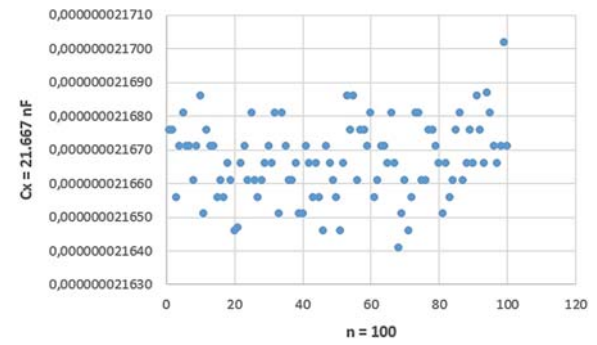
Preliminarily, the USTI-MOB was calibrated at the laboratory temperature range in order to eliminate an additional systematic error due to the quartz crystal oscillator trimming inaccuracy (calibration tolerance) and a short term temperature instability. The USTI-MOB development board was connected to a PC working under the MS Windows 10 operation system, where terminal software Terminal v1.9b was running. The USTI-MOB was running in the slave communication mode with the RS232/USB interface.

3.3. Experimental Results

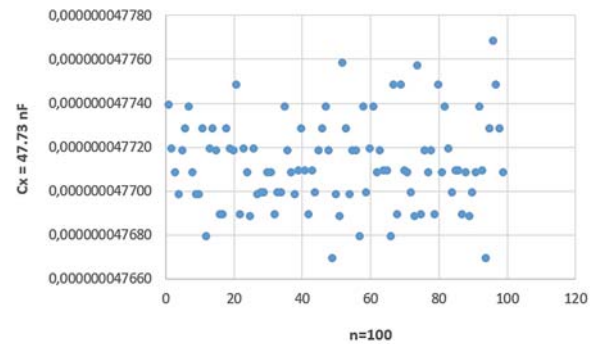
The USTI-MOB based CDC directly measures the value of floating capacitors in wide capacitance range from 50 pF to 0.1 μ F with the average relative error ± 0.3 %. It has power consumption 1.5 mW at +1.8 V supply voltage.

The measurement results for various values of C_x are shown in Fig. 7 (a)-(c). As it is visible from the experimental results, the relative error is changed from ± 1.00 to ± 0.04 % dependent on the specified capacitive range. The best accuracy is achieved in the nF capacitance range. The accuracy can be improved

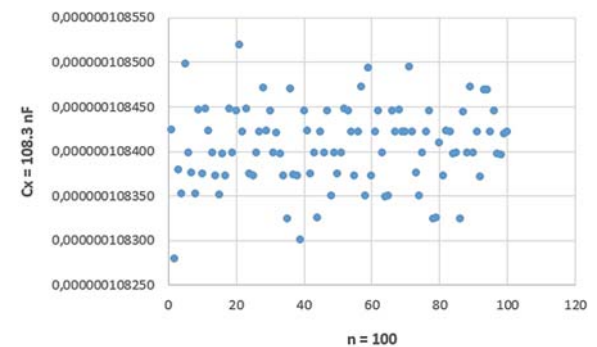
by the usage more precision external components such as C_{ref} , and R .



(a)



(b)



(c)

Fig. 7. Measurement results for 21.667 pF (relative error 0.04 %), 47.73 pF (relative error 0.05 %) and 108.3 pF (relative error 0.099 %) values.

The measurement results for frequency-time parameters of electrical signals were reported early in [5, 51, 52].

The comparative performance summary of USTI-MOB and other commercially available CDCs are adduced in Table 1.

4. The Future Research and Developments

Taking into account that the most effective approach for the modern CDC design for standard 40-nm (and less) CMOS processes is the usage of CFC

(oscillator- or VFC-based) followed by a FDC on the basis of novel methods for frequency (period) measurements, it will be expediently to integrate such components together in a single chip. Such solution will be highly digital in its nature. It will have low power consumption, small chip area, wide input capacitance range, excellent noise immunity and high

accuracy. In addition, such solution will be more efficient trade-off between conversion time, consumed power and resolution compared with the other CDCs because of many disadvantages of the existing ADCs- and TDCs- based CDCs will be eliminated, and cheap integrated multichannel ICs for various capacitive sensors applications will be manufactured.

Table 1. Performance summary of USTI-MOB IC and commercially available CDCs.

IC	Performance	Capacitance Input Range	Supply Voltage (V)	Power Consumption (mW)	Number of Channels	Digital Interface
<i>Analog Devices</i>						
AD7745/7746/7747/7748		Up to 17 pF	2.7	1.9	1/2	I2C
AD7150/7151		0 - 14 pF	2.7	0.3	2	I2C
<i>Texas Instruments</i>						
FDC2112/2114		Up to 250 nF	2.7	5.7	2/4	I2C
<i>Renesas Electronics Corporation (former Integrated Device Technology)</i>						
ZSSC3123		Up to 260 pF	2.3	1.7	1	I2C, SPI
ZSSC3122		Up to 10 pF	1.8	1.2	1	I2C, SPI
ZSSC3230		0- 30 pF	1.68	1.3	1	I2C
<i>ams</i>						
PCAP04		1 pF – 100 nF	3.0	1.44	3/6	I2C, SPI
<i>Micro Analog Systems</i>						
MAS6510		Up to 40 pF	1.8	0.086	2	I2C, SPI
<i>European Sensor Systems</i>						
ESS113		Up to 100 pF	3.3	1.3	1	I2C, SPI
<i>F2D (former Excelera)</i>						
USTI-MOB [This article]		50 pF – 0.1 μ F	1.8	1.5	1/3	I2C, SPI, RS232

5. Conclusions

Experimental investigation of USTI-MOB IC working in the capacitance measuring mode has confirmed its high metrological performance, suitable for low power consumed applications such as sensor systems for IoT, wearable and mobile devices. This new robust and energy-efficient IC can be used for both types of capacitive sensor interfaces: direct sensor interface and quasi-digital capacitive sensor interface.

The capacitance range of the USTI-MOB is from 50 pF to 0.1 μ F. The average relative error is ± 0.3 %, and power consumption – 1.5 mW at +1.8 supply voltage, suitable for battery operations.

The obtained results are achieved due to the application of three-signal measurement technique for direct capacitance interfacing, and novel, patented conversion methods for frequency, period and duty-cycle for capacitance-to-digital converters with a preliminary conversion of a capacitance into the frequency (period) or duty-cycle of square wave pulse signals.

The USTI-MOB IC has been introduced on the market by the IFSA Group's company – *F2D, Ltd.*, Ireland. In comparison with the early designed USTI IC, the energy-efficient USTI-MOB - based

capacitance-to-digital converter has a lower metrological performances but significantly lower power consumption and supply voltage.

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