# Low Power Wireless Communication and Signal Processing Circuits for Distributed Microsensors

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*Abstract* - **Low power wireless sensor networks provide a new monitoring and control capability for civil and military applications in transportation, manufacturing, biomedical technology, environmental management, and safety and security systems. Low power integrated CMOS systems are being developed for microsensors, signal processors, microcontrollers, communication transceivers and network access control. This paper on recent advances in CMOS-based microsensor systems, low power signal processing and RF communication circuits. Communication circuits include the demonstration of a 20μA supply current, 860 MHz, low phase noise CMOS local oscillator.**

## I. Introduction

The development and deployment of distributed monitoring and control has been hindered in the past by the requirements of complex installation and communication network requirements. Conventional distributed sensors have required cable interface, and therefore, extensive modification to structures for sensor installation. The distributed, low power, wireless, integrated microsensor (LWIM) technology, reported here, provides new product opportunities and new system capabilities.

Low power systems offer a new approach for distributed MEMS based on a wireless sensor infrastructure. A wireless microsensor network may be distributed rapidly and without modification to large structures and systems. Also, wireless sensors may be applied in areas where volume and mass constraints limit the application of conventional wireline interface sensors. The wireless network architecture allows microsensor nodes to be deployed in a broad spectrum of commercial and military applications ranging from clinical medicine, precision manufacturing, and transportation to battlefield perimeter security and shoreline reconnaissance. Wireless microsensor nodes may also be applied to rotating machinery without the complex slip-ring systems that would normally be required for a conventional sensor electrical interface

The wireless microsensor network architecture described here depends on micropower nodes operating with a single base station, (supplied by conventional power sources), and numerous distributed wireless microsensors. Most information flow is from the sensor nodes to the base station with drastically less flow in the form of commands to the sensor nodes from the base station. Network architecture and communication protocols must exploit this asymmetry of distributed sensor communication.

Typical applications may be optimally serviced by sensor networks having local signal processing by sensor nodes. Thus, individual nodes may propagate measurements of battlefield environment, machine condition, or patient condition, periodically to the base station at low duty cycle. In particular, only upon an alarm condition will continuous data transmission be required. This method permits a base station to service a much larger network than would be possible for simple continuous communication with sensor node.

Typical low duty cycle, low peak data rate (1kbps) and short range (10 - 30 m) communication can permit 30 μA average current for an LWIM node operating at 3V. A conventional, (2.5 cm diameter, 0.7 cm thickness) Li coin cell provides this current and bias level for greater than three-years of unattended operating life.

The goals of low cost fabrication require that all sensor and circuit systems be implemented in commercial foundry CMOS processes. Thus, low power integrated CMOS systems are required to provide 1) microsensor analog interface, 2) reconfigurable signal processing, 3) local control, self monitoring and network interface, and 4) low power RF transceiver systems. This paper focuses on advances in low power sensor, signal processing and communication.

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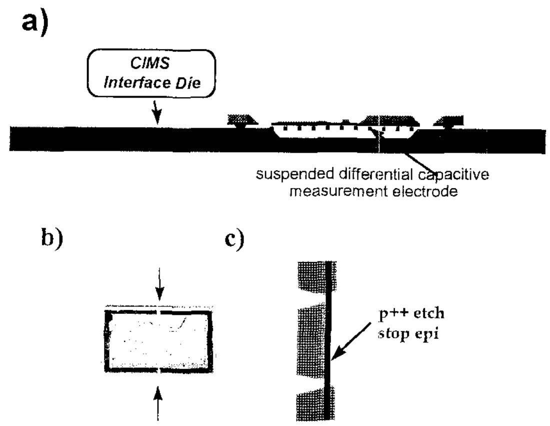


**Figure 1**. The LWIM CIMS accelerometer structure is shown in cross-section in (a). A micrograph of the bulk-micromachined, torsion suspended proof mass is shown in (b). A cross-section view of the bulk-micromachined structure is shown in (c) corresponding to the section indicated by arrows on the micrograph. The CIMS accelerometer employs capacitive sensing with a suspended measurement electrode. A micromachined cavity drastically reduces substrate parasitics that limit conventional devices. Membrane perforation provide control of squeeze film damping without requirements to perforate the proof mass.

## II. LWIM Network Sensors

Network sensor development includes both accelerometer (seismic) and infrared sensors implemented by the CMOS Integrated Microsystems (CIMS) process.[1] Seismic vibration measurement, the emphasis of this discussion, is the primary detection method for condition based maintenance and tactical remote sensing. Seismic sensors receive signal from both targets and from the uniform seismic background. For military surveillance applications, sensor sensitivity level must be at or below the seismic background level to permit operation at maximum range. In addition, it is critical that sensors be compact and densely distributed, thus permitting reliable detection.

LWIM, therefore, requires a low power, sub-μg sensitivity vibration sensor (permitting detection at the background limit). A capacitive measurement system for accelerometer mass motion detection is selected for this application since it permits the highest sensitivity of available, manufacturable detection methods.[2] Capacitive measurement resolution is limited by the amplitude of capacitance sensing drive signals and the broad band input noise of the preamplifier.

The CIMS acceleration sensor is shown in Figure 1. The CMOS interface die supports low parasitic capacitance measurement and data conversion circuits. The CIMS accelerometer relies on a single crystal flexure supporting a proof mass with a resonance frequency that may be adjusted (by design) from less than 50Hz to 10kHz.

## III. Low Power Sensor Signal Processing

Distributed MEMS devices must continuously monitor multiple sensor systems, process sensor signals, and adapt to changing environments and user requirements, while completing decisions on measured signals.

Low power sensor signal processing must be provided for continuous monitoring operation of remote, autonomous sensors. Optimal, low power system operation can be obtained by operating only the essential sensor and signal processor systems while maintaining the microcontroller and all other components in a sleep state. Spectral analysis for LWIM nodes employs parallel, low clock rate, low bias voltage, dedicated datapath signal processors. This method accommodates the limited power available to a remote, wireless node.

The signal processor datapath elements compute power spectral density (PSD) values for selected bands identified adaptively by the user and base station systems. PSD outputs are compared with spectral weights also provided by the user. A decision is made, therefore, on the average of many data records and on the spectral character of this record. Parallel operation provides high throughput, while low clock rate minimizes power. It is important to note that this system permits the node to incorporate a high power dissipation microcontroller that operates at a low duty cycle. In particular, the data path and threshold comparator operate continuously at low power, waking the processor from a sleep state only when a suspected threshold excursion is observed.

Low power data path elements, have been designed in 0.8μ HPCMOS technology. At the word rate of 200Hz (required for the seismic sensor), it is estimated that with eight parallel channels, total current drain will be less than 5μA for the 8-bit resolution signal processor.

## IV. LWIM Low Power Transceiver

The LWIM network is expected to operate in an environment of densely distributed nodes and interference sources. In addition, wireless microsensor nodes must recover low power transmissions with electrically small loop antennae. Wireless microsensor system design must exploit, therefore, the low duty cycle (0.01 - 1 percent), low data rate (1 kbps) and short transmission range (30 m) requirements for sensor networks. In addition, spread spectrum signaling with low power frequency hopped implementations must be provided for security and interference rejection capability.

The requirements for wireless microsensors include low average operating power, low peak current (due to compact storage cell limitations), and compact geometry. Compact storage cell capacity is degraded by current values in excess of 1 mA - thus defining a peak current requirement. RF system design for wireless microsensors is based on CMOS RF components integrated directly with sensing and control systems. The requirements of low power operation motivates the development of new methods for obtaining low power and high performance RF communication in a multi-user environment.

The LWIM network requires spread spectrum signaling to provide simultaneous transmission of low bit rate data by many nodes in a cluster of sensor nodes. Spectrum spreading by frequency hopping requires drastically lower power than spreading by direct sequence methods, due to the high bit rate requirements inherent to direct sequence methods. Multipath fading and interference expected for low data rate LWIM systems are sufficiently suppressed by slow hopping at a small fraction of the data rate (many data bits transmitted between hops). RF system power is determined, therefore, by the properties of receiver and transmitter systems operating at a single frequency within the 902-928 MHz ISM band.

LWIM low power transceiver design has focused on the primary components that determine both power and performance. First, transmitter operation focuses on efficiency in output power amplifiers, operating at 1 - 10 mW RF power, and low duty cycle operation. Receiver design, in contrast, adds the requirements of low noise and high selectivity operation. Also, for some protocols, the wireless sensor receiver must operate at high duty cycle to enable each sensor node to capture randomly arriving signals characteristic of the sensing environment. This development has been directed to the demonstration of the first microampere supply current level, MOSFET weak inversion oscillators for the 900MHz band.

Low power oscillator systems, fundamental to transceiver operation, are limited both by the requirements for oscillator loop gain and phase noise. First, it is noted that fundamental oscillators relying on inductive feedback elements (for example, Colpitts, Pierce, Hartley, and Clapp-Gouriet circuits) display a familiar constraint on minimum feedback loop gain. Now, loop gain is proportional to the quality-factor, Q, of the inductive, resonant feedback network and transconductance. Specifically, the condition for oscillation sets a constraint on the maximum value of the ratio of inductor resistive loss to transistor transconductance. Alternatively, the product of Q and transconductance must be greater than a minimum value. Thus, for a fixed transistor geometry, with transconductance scaling with drain current, $I_D$, the condition for oscillation forces a scaling between inductor Q and minimum transconductance value, $g_m(\min)$,

$$(1)\quad g_m(\min) \propto \sqrt{I_D} \propto \frac{1}{Q} \quad \text{(for strong inversion)}$$

$$(2)\quad g_m(\min) \propto I_D \propto \frac{1}{Q} \quad \text{(for weak inversion)}$$

Second, receiver selectivity is determined by the stability of each local oscillator required for frequency translation (down conversion) of RF signals. Oscillator phase noise power also scales with Q. In addition, Oscillator phase noise power (for frequency, f, near the center carrier frequency, $f_C$) scales with "1/f" or "flicker" noise power. Thus, for an MOS with gate area, WL, flicker noise coefficient, $K_{FLICKER}$, oscillator phase noise power, $S_\phi$, is

$$(2)\quad S_\phi \propto \frac{K_{FLICKER}}{Q^2 (WL)(f - f_C)^3}$$

Equation (1) demonstrates that required drain current for oscillator operation scales inversely with $Q^2$. Similarly, Equation (2) demonstrates that to obtain a fixed phase noise level, transistor area requirements scale inversely with $Q^2$.

Low power oscillator operation and performance is, therefore, highly sensitive to and is enhanced by increasing inductor Q. In addition, transistor area requirements scale favorably with increasing Q. The reduction of receiver operating power, without reduction in performance, requires new methods for high Q inductor integration. Inductors implemented with the Al conductors of conventional CMOS technology provide Q-values in the range of 3-5 for frequencies near 1GHz. These Q-values are limited by both series resistance loss and loss in supporting substrates. However, compact wire and thick-film inductors display Q-values of 20-100. The low power wireless sensor systems may, therefore, rely on high-Q inductors packaged with the CMOS transceiver die by the MEMS flip-chip methods described above.

A demonstration of the weak inversion RF method has been provided by a low power Colpitts oscillator implemented in 0.8μ HPCMOS using an off-chip, 40 nH, loop inductor. The Colpitts oscillator, shown in Figure 2a, was supplied with an on-chip buffer amplifier for coupling to 50-ohm measurement systems. Selection of the source resistance in this circuit set drain current. A varactor tuning diode was implemented with a source-substrate junction capacitor shown in Figure 2b. Oscillation at 860 MHz was obtained at a drain current of 20 micro-A and supply bias of 3V. Tuning over a range of 4MHz with 3V control voltage swing was obtained.

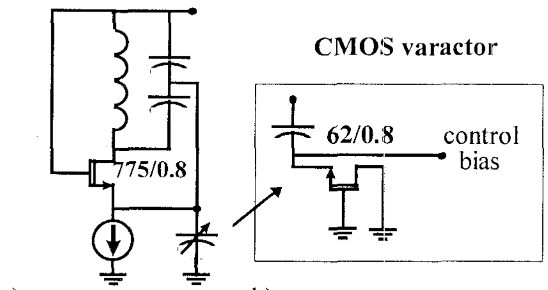


**Figure 2:** The Colpitts VCO implemented in 0.8μ HPCMOS is shown in (a). Frequency control is obtained by a varactor implemented with a source-substrate junction capacitance, shown in (b). Operation of this oscillator was demonstrated at 860MHz with 20micro-A drain current at 3V supply bias. The high-Q inductor is implemented with an off-chip loop.

The critical output phase noise of this oscillator has been measured using a Hewlett-Packard 3048A Phase Noise Analyzer system. Phase noise at an offset frequency of 100kHz was measured to be less than - 90dBc. This phase noise is comparable to that of conventional CMOS oscillators operating at high power, but, with lower circuit Q values. For comparison, low phase noise is obtained in conventional, commercial bipolar oscillators (- 114 dBc at 100kHz offset) at supply bias of 12V and supply currents of 22mA for a power dissipation of over 260 mW,[3] orders of magnitude larger power dissipation than that of the micropower CMOS oscillator reported here.

## V. LWIM Network Access

Communication network access architecture is critical for determining wireless node power and network capability. Distributed MEMS devices will evolve towards intelligent systems that cooperatively identify signal sources through use of array signal processing. Distributed MEMS networks must identify and incorporate new nodes into an operating network without interfering with operations. Thus, distributed MEMS requires an optimized medium access control (MAC) protocol operating at orders of magnitude lower power and data rate than that developed for conventional applications. Self-organizing network protocols, LWIM-MAC are under development for low power wireless sensor networks.

## VI. Conclusion

Distributed microsensor applications address large systems and diverse measurement capability. Many distributed measurement applications require spatially dense networks of wireless sensors. Wireless autonomous sensors must operate from low energy, low voltage, low peak current capability batteries. The requirements for low power operation are met with the combination of microsensor design, signal processing architecture, low power RF circuit methods, and network medium access protocols. The CMOS Integrated Microsystems (CIMS) process may provide high performance, integrated sensors with novel structures and materials combined with foundry CMOS. Microsensor system design must address the constraints of low power analog interface circuits. Low power digital VLSI and weak inversion operation RF circuits will provide signal processing and communication capability.

## VII. Acknowledgments

This work was supported by the Defense Advanced Research Projects Agency, (DARPA) / Electronics Technology Office.

## VIII. References

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