The design and implementation of wireless sensor network node

J. Wu & S.F. Yuan

The Aeronautic key laboratory of smart material and structure, Nanjing Universityof Aeronautics and Astronautics, Nanjing 210016, China

ABSTRACT: The wireless sensor networks are the hotspot research of current sensor technology. These networks use small, low-power embedded devices for a wide range of applications and do not rely on any preexisting infrastructure. In this paper, a novel design method is presented for building a new architecture for the wireless sensor network node. The architecture is based on the premise that shared pools of resources should be used when possible to exploit the benefits of dynamic allocation, that buffering needs be used to decouple the general purpose data path and the radio, and that protocol flexibility is essential. Based on this design idea, the development of a wireless sensor node has been completed. It consists of a microcontroller with internal flash program memory, data SRAM and data EEPROM, connected to a set of actuator and sensor devices, including LEDs, a low-power radio transceiver, a serial port, and a small coprocessor unit and an I/O connector that allows a suite of sensors to be attached. The software platform of the designed node is based on the TinyOS platform, which is an operating system designed explicitly for the wireless sensor networks. Based on this platform, performance tests are conducted for the designed wireless sensor node, including power consumption, transmission range and data rate. The test results are satisfied, demonstrating that the presented design method can raise the efficiency for wireless sensor network node design and implementation. Additionally, with external sensor board, the nodes have been used to deploy a wireless sensor network to SHM (Structure Health Monitoring) systems. In our research, we develop it to implement the material's loading location.

1. INTRODUCTION

The concept of wireless sensor networks (WSNs) is based on a simple equation: Sensing + CPU + Radio = Thousands of potential applications. The power of wireless sensor networks lies in the ability to deploy large numbers of tiny nodes that assemble and configure themselves. Usage scenarios for these devices range from national defence and military affairs (Romer 2001), to behavior observation of animals (Mainwaring et al. 2002), to monitoring of the health of structures and materials (NIST's SHIELD Project 2002), to traffic controls (Shih 2001), to medical treatment and sanitation (Noury 2000), to monitoring of disasters (Bonnet 2000). Wireless sensor networks do not need supports of stationary networks, but monitor remote environments for low frequency data trends. The network could be incrementally extended by simply adding more devices – no rework or complex configuration. Unlike traditional wired systems, deployment costs would be minimal. Instead of thousands of feet of wire routed through protective conduit, the network just needs a small-sized node device at each sensing point.

Unlike traditional wireless devices, wireless sensor nodes do not need to communicate directly with the nearest high-power control tower or base station, but only with their local peers. Instead of relying on a pre-deployed infrastructure, each individual sensor or actuator becomes part of the overall infrastructure. Peer-to-peer networking protocols provide a mesh-like interconnect to shuttle data between the thousands of tiny embedded devices in a multi-hop fashion. The flexible mesh architectures envisioned dynamically adapt to support introduction of new nodes or expand to cover a larger geographic region. Additionally, the system can automatically adapt to compensate for node failures.

Initial research into wireless sensor networks was mainly motivated by military applications, with DARPA continuing to fund a number of prominent research projects (e.g., Smart Dust, NEST) that are commonly regarded as the cradle of sensor network research. National Science Foundation (NSF) established wireless sensor networks project in 2003, funded $34 million for basic research about WSNs. Then many academic institutions (e.g. University of California, MIT, Cornell University etc) started the research for the basic theory and key technology about WSNs. Other countries, such as Britain, Japan, Italy etc, also developed the research for WSNs and have some research outcome. However, today the research about WSNs in China just is in laboratory. Some Chinese academic institutions, such as Tsinghua University, Shenyang Institute of Automation Chinese Academy of Science and Hefei Institute of Intelligent Machines Chinese Academy of Sciences, have started on research for this line (Fengyuan et al. 2003) (Zu-chang et al. 2004).

More recently, civilian application domains of wireless sensor networks have been considered, such as environmental and structural health monitoring, in Harbin Institute of Technology and Nanjing University of Aeronautics and Astronautics (Jinpin & Hui 2004) (Xiaosong & Shenfang 2004). At the same time, civilian applications were all based on the MOTE platform, and had no own wireless sensor networks node. In this paper, a novel design method is presented for building a new architecture for the wireless sensor network node, and performance tests are conducted for the designed wireless sensor node. Then with external sensor board, the nodes have been used to deploy a wireless sensor network to SHM (Structure Health Monitoring) systems. In our research, we develop it to implement the material's loading location.

2 WIRELESS SENSOR NODE ARCHITECTURE

2.1 *Key design requirements for wireless sensor nodes*

In the past, a number of early, mostly USbased research projects established a de facto definition of a wireless sensor network as a large-scale ad hoc, multihop, unpartitioned network of largely homogeneous, tiny, resource-constrained, mostly immobile sensor nodes that would be randomly deployed in the area of interest. Hence a wireless sensor network device must meet strict power consumption and size requirements. The key design requirements for wireless sensor networks nodes are cost, size, power, heterogeneity, and robustness.

2.1.1 *Cost, size, and power*

The physical size and cost of each individual sensor node has a significant and direct impact on the ease and cost of deployment. Total cost of ownership and initial deployment cost are two key factors that will drive the adoption of wireless sensor network technologies. In data collection networks, researchers will often be operating off of a fixed budget. Their primary goal will be to collect data from as many locations as possible without exceeding their fixed budget. A reduction in per-node cost will result in the ability to purchase more nodes, deploy a collection network with higher density, and collect more data.

Physical size also impacts the ease of network deployment. Smaller nodes can be placed in more locations and used in more scenarios. In the node tracking scenario, smaller, lower cost nodes will result in the ability to track more objects.

To meet the multi-year application requirements individual sensor nodes must be incredibly low power. Unlike cell phones, with average power consumption measured in hundreds of milliamps and multi-day lifetimes, the average power consumption of wireless sensor network nodes must be measured in micro amps. This ultra-low-power operation can only be achieved by combining both low-power hardware components and low duty-cycle operation techniques.

2.1.2 *Heterogeneity*

Early sensor network visions anticipated that sensor networks would typically consist of homogeneous devices that were mostly identical from a hardware and software point of view. However, each application scenario will demand a slightly different mix of lifetime, sample rate, response time and in-network processing. Additionally, for cost reasons each device will have only the hardware and software it actually needs for a given the application. The architecture must make it easy to assemble just the right set of software and hardware components. Thus, these devices require an unusual degree of hardware and software modularity while simultaneously maintaining efficiency. The degree of heterogeneity in a sensor network is an important factor since it affects the complexity of the software executed on the sensor nodes and also the management of the whole system.

2.1.3 *Robustness*

In order to support the network lifetime requirements demanded, each node must be constructed to be as robust as possible. In a typical deployment, hundreds of nodes will have to work in harmony for years. To achieve this, the system must be constructed so that it can tolerate and adapt to individual node failure. Additionally, each node must be designed to be as robust as possible.

System modularity is a powerful tool that can be used to develop a robust system. By dividing system functionality into isolated sub-pieces, each function can be fully tested in isolation prior to combining them into a complete application. To facilitate this, system components should be as independent as possible and have interfaces that are narrow, in order to prevent unexpected interactions.

In addition to increasing the system's robustness to node failure, a wireless sensor network must also be robust to external interference. As these networks will often coexist with other wireless systems, they need the ability to adapt their behavior accordingly. The robustness of wireless links to external interference can be greatly increased through the use of multi-channel and spread spectrum radios. It is common for facilities to have existing wireless devices that operate on one or more frequencies. The ability to avoid congested frequencies is essential in order to guarantee a successful deployment.

3 DESIGN AND IMPLEMENTATION OF WIRELESS SENSOR NETWORK NODE

3.1 *Wireless sensor network node architecture*

In our design, the node architecture is based on the premise that shared pools of resources should be used when possible to exploit the benefits of dynamic allocation, that buffering needs be used to decouple the general purpose data path and the radio, and that protocol flexibility is essential. It addresses performance and efficiency issues by including special-purpose hardware accelerators for handling the real-time, high-speed requirements of the radio. Accelerators provide general building blocks, not complete solutions. Figure. 1 depicts the node architecture. The core of the architecture is a central computational engine that is timeshared across application and protocol processing. Only a single computation engine is included because it allows the allocation of all processing resources to a single task when necessary. Multiple register sets can be included in the CPU so that each context switch does not require the registers to be written out to memory. Instead, the operating system simply switches to a free register set.

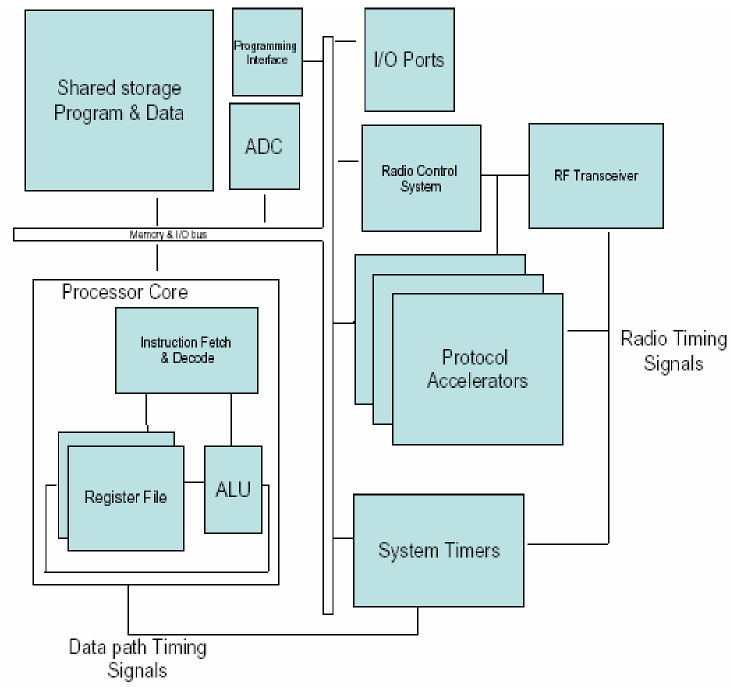

Figure. 1. WSNs node architecture.

All devices on this shared interconnect operate through a shared memory interface. Each device has control structures that are mapped into a shared address space. This allows components that were not originally intended to function together to be combined in new and interesting ways. A data encoder designed to read from memory, transform data, and write to memory many not even know that it is actually pulling data from a radio receiver block's memory interface and pushing it into a UART's portion of the communication memory. In this node architecture, the size of the shared address space dedicated to each operation can be set dynamically to meet application requirements.

The true power of this system is in the special-purpose hardware accelerators that it enables. These accelerators provide efficient implementations of low-level operations that are inefficient on a general-purpose data path. Each accelerator is designed to provide support for operations that are critical to sensor network communication. By increasing the efficiency of these operations, the overall power consumption of the system can be greatly reduced. It is important that these accelerators are communication primitives instead of complete protocol implementations so that the system can support a wide range of communication protocols simultaneously simply through software reconfiguration.

3.2 *Design of Wireless Sensor Network Node*

A WSNs node architecture has been presented that meets the key design requirements. Now, we must evaluate this architecture on real-world hardware implementations. This design serves to validate the node architecture principles we have chosen. The hardware platform, named SMART NODE, has a central microcontroller that performs all computation but it supplements the controller with hardware accelerators, as dictated by the node architecture. The accelerators we have chosen to include support to increase the transmission bit rates and timing accuracy. Existing interfaces available on commercial microcontrollers severely limit how fully the architecture can be implemented. SMART NODE using a single CPU that provides multithreading in software using the TinyOS concurrency mechanisms (Hill et al. 2000) (Tinyos.net 2004).

3.2.1 *Hardware design*

SMART NODE combines an Atmega128 processor with a RF Transceiver CC1000 (Chipcon 2002), external storage and communication acceleration. A direct connection between the application controller and transceiver provides the flexibility to meet application designs. The hardware accelerators optionally assist to increase the performance of key phases of the wireless communication.

Figure. 2 shows the block diagram of SMART NODE architecture, consisting of five major modules: processing, radio frequency (RF) communication, power management, I/O expansion, and secondary storage. The main microcontroller is an Atmel ATMEGA128 running at 8 MHz and delivering about eight million instructions per second (MIPS) (Atmel 2004). This 8-bit microcontroller has: 128-Kbyte flash program memory, 4-Kbyte static RAM, internal 8-channel 10-bit analog-to-digital converter, three hardware timers, 48 general-purpose I/O lines, one external universal asynchronous receiver transmitter (UART), and one serial peripheral interface (SPI) port. Normally, programming of these embedded microcontrollers occurs during manufacture with a firmware upload or during field maintenance. In our design, however, the embedded network can be dynamically reprogrammed during routine use. The coprocessor handling wireless reprogramming is the same controller used on Rene. Additionally, to provide each node with a unique identification, we include a Maxim DS2401 silicon serial number—a low-cost ROM device with a minimal electronic interface and no power requirements (Dallas Semiconductor 2004).

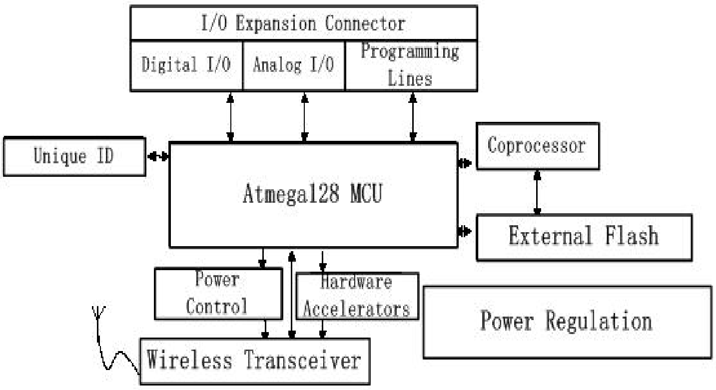

Figure. 2. Block diagram of SMART NODE architecture.

The radio module consists of an RF Monolithic CC1000 transceiver. CC1000 is a true single-chip UHF transceiver designed for very low power and very low voltage wireless applications, mainly intended for the ISM (Industrial, Scientific and Medical) and SRD (Short Range Device) frequency bands at 315, 433, 868 and 915 MHz, but can easily be programmed for operation at other frequencies in the 300-1000 MHz range. The main operating parameters of CC1000 can be programmed via an easy-to-interface serial bus, thus making CC1000 a very flexible and easy to use transceiver. A typical application circuit is shown in Figure. 3. A 4-Mbit Atmel AT45DB041B serial flash chip provides persistent data storage (Atmel 2004). We chose this chip because of its interface and small footprint, 8-pin small-outline integrated circuit. We designed the power subsystem to regulate the system's supply voltage: a Maxim1678 DC-DC converter provides a constant 3.3-V supply. The converter takes input voltage as low as 1.1 V (Maxim 2004).

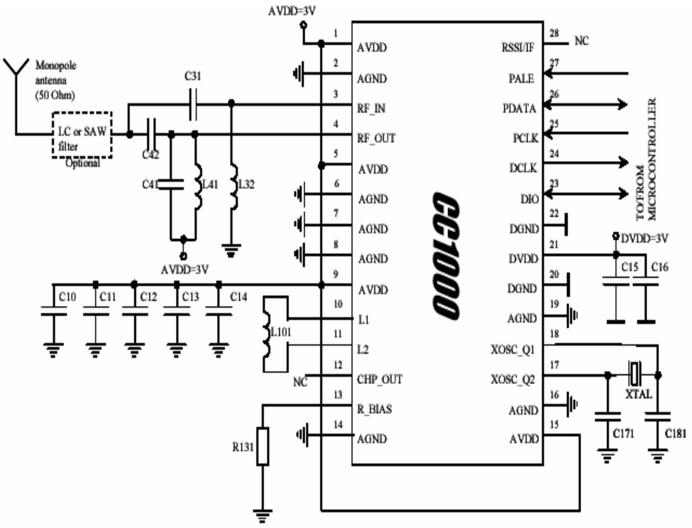

Figure. 3. Typical CC1000 application circuit

The I/O subsystem interface consists of a 51-pin expansion connector that we designed to interface with a variety of sensing and programming boards. We divided the connector into the following sections: eight analog lines, eight power control lines, three pulse width modulated lines, two analog compare lines, four external interrupt lines, an I2C-bus from Philips Semiconductor, an SPI bus, a serial port, and, a collection of lines dedicated to programming the microcontrollers. The expansion connector can also be used to program the device and to communicate with other devices, such as a PC serving as a gateway node. Additionally, it contains a standard UART interface to control or provide data to any RS-232 protocol-based device. Many sensor boards with a variety of sensors can be developed that use this expansion connector.

3.2.2 *Performance tests*

Figure. 4. shows the picture of SMART NODE wireless sensor network platform. The form factor (7.5×4.0 centimeter) is a similar size as a pair of AA batteries. Here sensor boards are not shown in the picture. Currently our sensor boards include support for monitoring thermal temperature, light, strain, and piezoelectric stress. In the performance tests, the function generator simulates the sensor signal. Test items for SMART NODE are power consumption, transmission range, sample rate and bit rate.

Figure. 4. Picture of SMART NODE wireless sensor network platform.

3.2.2.1 *Power consumption*

First, we tested the power consumption for SMART NODE. We use a pair of AA batteries to supply the platform. In four nodes, we install CntToLedsAndRfm component of TinyOS (One TOS data package is transmitted per second, meanwhile LEDs flash). Frequency band is 915 MHz. Transmission strength is 0 dBm, while the work current is from 10 mA to 15 mA. Table. 1. shows the different lifetime to corresponding AA batteries. Batteries are generally rated in milliamp-hours (mAh). If the node is always in sleep mode, when the current is lower than 200 uA, its lifetime can extend to more than one year. It is significant for some application.

3.2.2.2 *Transmission range*

Next to lifetime, transmission range is the key test item for wireless sensor network platforms. However, The transmission range of a wireless system is controlled by some factors. The most intuitive factor is that of transmission power. The more energy put into a signal, the farther it should travel. The relationship between power output and distance traveled is a polynomial with an exponent of between 3 and 4 (non-line of sight propagation) (McLarnon 1997). Table. 2. shows the different transmission range to corresponding transmission power. All tests are performed in the laboratory.

Batteries（mAh）	Lifetime（h）
1000	98
1700	170
3000	291

Table. 1. Different lifetime to corresponding AA batteries.

Power（dBm）	－20	－10	0	5
Range（m）	7.5	11	27.5	33

Table. 2. Different transmission range to corresponding transmission power.

3.2.2.3 *Sample rate and bit rate*

The communication bit rate also has a significant performance item, decided by the wireless transceiver. While sample rate is controlled by the analog to digital converter. Higher communication rates translate into the ability to achieve higher effective sampling rates and lower network power consumption. The communication bit rate for the wireless transceiver is 38.4 Kbaud. The sample rate is up to 15 kSPS at maximum resolution. In the test, the function generator simulates the sensor sine wave signal, 250 mA for the peak value. Figure. 5. and Figure. 6. show the received signal by PC when the sine wave frequency is 1 KHz and 2 KHz. From the two figures, we can find that the received data cannot give mass information for the input signal when the frequency is up to 2 KHz.

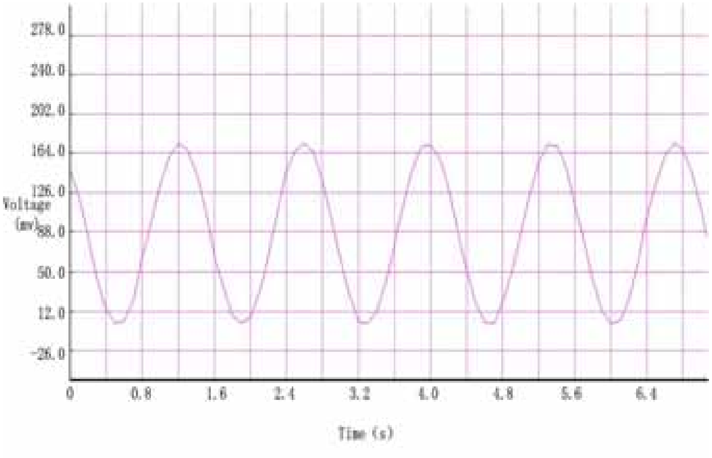

Figure. 5. The received signal by PC when the sine wave frequency is 1 KHz.

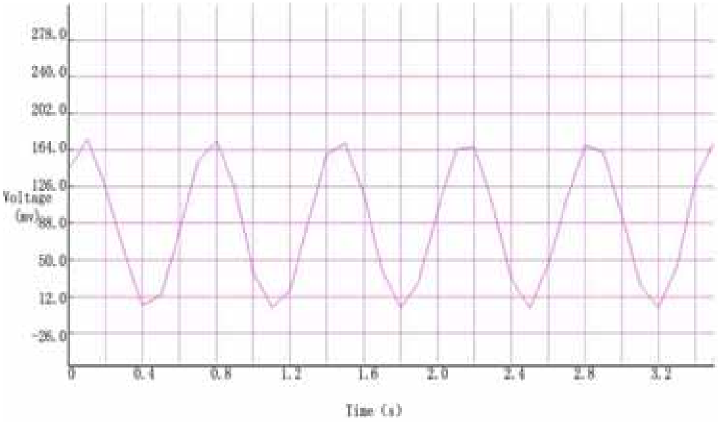

Figure. 6. The received signal by PC when the sine wave frequency is 2 KHz.

4 CONCLUSION

We have presented a generalized architecture that addresses key issues that arise when building a wireless sensor network device that must meet strict power consumption and size requirements. To validate the node architecture we first presented the SMART NODE. Composed from off-the- shelf components, it only approximated the architecture. It included specialized hardware accelerators that help decouple the RF and data path speed. In the performance tests of this platform we test its power consumption, transmission range, sample rate and bit rate. The SMART NODE platform has proven itself both in theory and through deployment in long-term, battery operated application scenarios. We argue that the platform could improve the design efficiency for wireless sensor networks.

ACKNOWLEDGEMENT

Financial supports for this study provided by grant from National Natural Science Foundation of China, International Cooperation Project（50420120133）is gratefully acknowledged.

REFERENCES

Kay Romer, 2001. "Time Synchronization in Ad Hoc Networks", Mobihoc

A. Mainwaring, J. Polastre, R. Szewczyk & D. Culler,2002. Wireless Sensor Networks for Habitat Monitoring, Intel Research, IRB-TR-02-006.

NIST's SHIELD Project - http://jazz.nist.gov/atpcf/prjbriefs/prjbrief.cfm? Project-Number=00-00-5306

Shih E, Cho S, Ickes N, Min R, Sinha A, Wang A, Chandrakasan A, 2001. Physical layer driven protocol and algorithm design for energy-efficient wireless sensor networks. In: Proceedings of the ACM MobiCom 2001. Rome: ACM Press, pp 272－286.

Noury N, Herve T, Rialle V, Virone G, Mercier E, 2000. Monitoring behavior in home using a smart fall sensor. In: Proceedings of the IEEE-EMBS Special Topic Conference on Micro technologies in Medicine and Biology. Lyon: IEEE Computer Society, pp607－610.

Bonnet P, Gehrke J, Seshadri P, 2000. Querying the Physical World. IEEE Personal Communication, Vol. 7, No. 5, pp. 10-15.

REN Feng -Yuan, et al. 2003. Wireless Sensor Networks, Journal of Software, Vol. 14, No. 7, pp. 1282－1291.

MA Zu-chang, et al. 2004. Survey on wireless sensors network, Journal of China Institute of Communications, Vol. 25, No. 4, pp. 114-124.

Jinpin OU, Hui Li (2004), Recent advance of structural health monitoring in mainland China, http://mceer.buffalo.edu/outreach/intActivity/ANCER/Activities/2004/li_h_edpmrc.pdf

Lai Xiaosong, Yuan Shenfang, 2003. The Research of the Material's Loading Location Based on Ad hoc Wireless Sensor Network, Measurement & Control Technology, Vol. 23, No. 12, pp. 8～10.

Hill, J., et al.2000. System architecture directions for networked sensors. in ASPLOS 2000.

http://www.tinyos.net/

Chipcon Corporation, CC1000 Datasheet, Chipcon Corporation: http://www.chipcon.com/files/CC1000_Data_Sheet_2_2.pdf

Atmel Corporation, Atmega128 Datasheet, Atmel Corporation: http://www.atmel.com/atmel/acrobat/doc0945.pdf

Dallas Semiconductor, DS2401 Silicon Serial Number: http://pdfserv.maxim-ic.com/arpdf/DS2401.pdf

Atmel Corporation, AT45DB041B Datasheet, Atmel Corporation: http://www.atmel.com/dyn/resources/prod_documents/doc3443.pdf

Maxim, Maxim 1-Cell to 2-Cell, Low-Noise, High-Efficiency, Step-Up DC-DC Converter, MAXIM1678. 1998:http://pdfserv.maxim-ic.com/arpdf/MAX1678.pdf

McLarnon, B., VHF/UHF/Microwave Radio Propagation: A Primer for Digital Experimenters: http://www.tapr.org/tapr/html/ve3jf.dcc97/ve3jf.dcc97.html.