CRCD: Low-Power Wireless Communications for Virtual Environments

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Project Overview

This CRCD project combines research from the areas of wireless communications, low-power embedded systems, virtual environments, and human factors in an interdisciplinary program. Education in the hardware and software of virtual reality (VR) systems serves as a testbed for training engineers in a truly interdisciplinary environment. The ultimate goal of this project is to create new courses that cover real-time software and embedded systems, design of virtual environments, and design of practical wireless devices.

The research part of the proposal uses the C6, a three-dimensional, full-immersion, synthetic environment in the Virtual Reality Applications Center (VRAC) at Iowa State University (ISU). The goal is to design and implement low power wireless communications systems for wearable sensor networks in virtual environments. Figure 1 shows the C6 and a few of the wireless devices in the system. Wireless systems introduce latency issues into the design problem due to slower data rates and retransmissions. Latency is the total delay time between a user's action and the system response. Latency must be below human perceptual thresholds to create a comfortable virtual environment. Other considerations for wireless design in virtual environments are: complete coverage of the interaction space, no interference with other wireless devices, the data rates between the user and the system, and low-power requirements. The current project team includes four faculty members, three graduate students and two undergraduate students.

First Year Accomplishments

In the first year of this project, new laboratory experiments were added to existing courses in communications to enforce the concepts of hardware/software co-design and human factors issues. One example of these first experiments is a laboratory for the communications course that characterizes the complex electromagnetic environment inside a building that contains multiple types of wireless devices such as LANs and cordless phones. A second example is implementation of different methods for interference mitigation such as direct-sequence spread spectrum and adaptive antennas. Our group has studied the latency of the C6 virtual environment and the existing communications protocols for the 802.11 and Bluetooth specifications. These studies are being presented in the communications systems II class in Spring 2002.

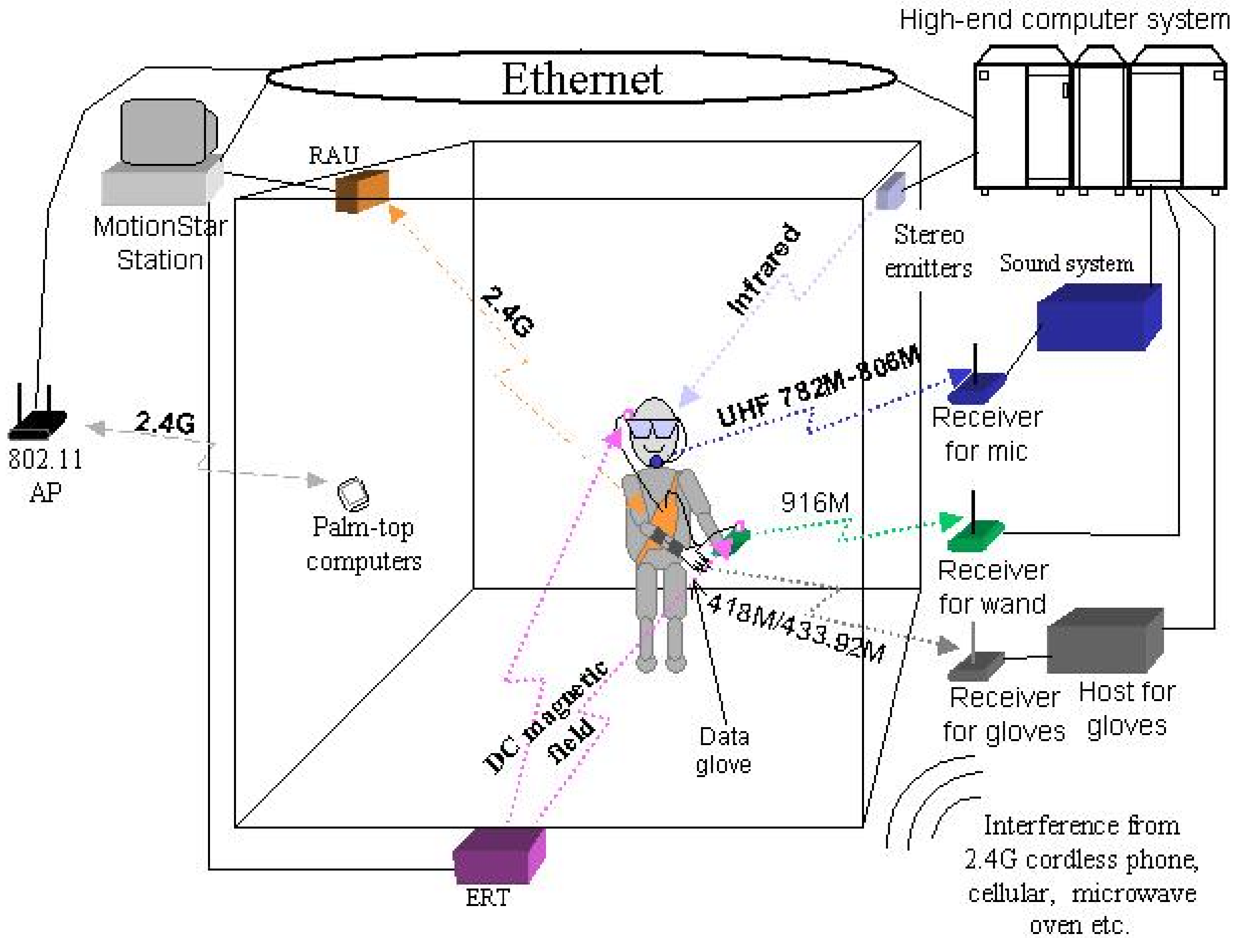

Figure 1. A user in the C6 virtual reality system communicates with his/her environment using a wireless tracking system, infrared shutter glasses, 6-D wands, and datagloves. These devices must be designed to avoid interfering with one another and other devices in the environment.

Second Year Plans

The curricular plans for the second year include offering courses in the basic functional skills needed for interdisciplinary teams:

- Offering an embedded systems course in spring 2002 that features the specification and analysis of real-time wireless systems taught by Dr. Rover.
- Introducing a communications circuits course featuring the design of practical wireless systems co-taught by Drs. Weber and Dickerson.
- Introducing a software engineering course in spring 2003 taught by Dr. Cruz-Neira.

We plan to identify current best practices and experiment with different methods of integrating the course skills between the courses. Past experience of the PI's shows that creating modules independently and dropping them into courses does not work well. We will try different approaches to integrating these skills such as co-teaching the design courses and giving guest lectures on our areas of specialization. In addition, we will explore how course learning objectives and course design might be changed to support cross-functional teaching and learning.

Curriculum Development

Table I summarizes the courses that are being developed and enhanced as part of this CRCD proposal. Enhancements to the Communications and Digital Signal Processing laboratories have already been started. The next few sections give details of the course objectives and proposed syllabi of the Embedded Systems, Real-time software engineering and communications circuit and system courses.

Title/Instructor	**Level**	**Req/ Elect**	**Freq-uency**	**Credit Hours**	**Innovation**
Electromagnetics and Wireless Communications /Weber and Dickerson	Senior/ grad	Elect	1/year	3	Interactive, integrated learning activities. Seminar based.
Design of Virtual Environments /Cruz-Neira, Weber, Dickerson	Senior/ grad	Elect	1/year	3	Hands-on advanced virtual reality hardware and software, evaluation exercises
Real-time Software Engineering for Virtual Environments/Cruz-Neira	Senior/ grad	Elect	1/year	3	Projects on current software challenges for time-critical response of multi-processed environments
Communications Systems and Laboratory/ Dickerson	Senior	Tech Elect	1/year	4	New wireless communications experiments, studies in interference
Introduction to Digital Signal Processing/ Dickerson	Senior	Tech Elect	1/year	4	Experiments in adaptive signal processing for interference nulling
Embedded Systems /Rover	Senior/ grad	Tech Elect	1/year	3	Structural and behavioral characteristics of systems and high-level design methodology for requirements, rapid prototyping and system optimization
Communication Circuits/ Weber and Dickerson	Grad	Elect	2 years		New wireless laboratory demonstrations and projects

Table I: The first three courses are new courses that will be developed as part of this CRCD effort. The other courses listed will be enhanced and updated.

Embedded Systems Course

Wireless systems for virtual environments are complex hardware-software systems that must be designed to meet both functional and nonfunctional performance requirements. To design such systems, students need to understand the structural and behavioral characteristics that dictate system performance, as well as a high-level design methodology that captures system requirements and supports rapid prototyping and system optimization [12]. The Embedded Computer Systems course targets advanced undergraduate and early graduate students in computer engineering, computer science, and electrical engineering. Minimally, a background in computer architecture is expected; and operating systems, programming languages and compilers, and digital system design are relevant as well. The course covers hardware-software systems and co-design; models of computation for embedded systems; system modeling, specification, synthesis, and verification; hardware-software implementation; performance analysis and optimization; and design methodologies and tools. The course emphasizes a top-down design methodology driven by bottom-up constraints.

The course objectives state that students will:

- Learn about system-level design of embedded systems comprised of both hardware and software;
- Investigate topics ranging from system modeling to hardware-software implementation;
- Explore analysis and optimization processes in support of algorithmic and architectural design decisions; and
- Gain design experience with case studies using contemporary high-level methods and tools.

At the completion of the Embedded Computer Systems course, each student should be able to:

- Understand the concepts, issues, and process of system-level design of embedded systems, i.e., hardware-software co-design
- Model and specify an embedded system at a high level of abstraction
- Use co-simulation to validate system functionality
- Analyze the functional and nonfunctional performance of the system early in the design process to support design decisions
- Analyze hardware/software tradeoffs, algorithms, and architectures to optimize the system based on requirements and implementation constraints
- Describe architectures for control-dominated and data-dominated systems
- Understand hardware, software, and interface synthesis
- Understand issues in interface design
- Use contemporary software tools within a co-design environment
- Describe examples of applications and systems developed using a co-design approach
- Design a hardware-software system
- Appreciate issues in system-on-a-chip design associated with co-design, such as intellectual property, reuse, and verification

One of the important sections in the course deals with architecture selection, which includes both the system-level architecture and the processor-level architecture. The selection process starts with a general architecture and then specializes it in different dimensions based on system requirements and constraints, such as latency in a data-dominated system or timing deadlines in a control-oriented system. The dimensions of architecture specialization include:

- Instruction set, e.g., are there special instructions, such as for digital signal processing?
- Function unit and data path, e.g., is there specialized hardware for certain operations?
- Memory, e.g., is there a separate memory for instructions and data?
- Interconnect, e.g., what is connected to the on-chip bus?
- Control, e.g., are there coprocessors that assist the central processor?

This section is taught using an instructional technique based on Aronson's cooperative learning jigsaw technique [13]. The lesson plan is available at the course website (http://class.ee.iastate.edu/cpre588/). The class is divided into jigsaw groups having 4-5 members. Each member in a group is assigned to become the "expert" on one of the architecture specializations (e.g., control specialization). Each student is responsible for learning about the assigned specialization. "Expert groups" are then formed by having one student from each jigsaw group join other students assigned the same specialization. Expert groups review and discuss the specialization to improve their understanding about it and their ability to present it. The students return to their jigsaw groups, and each student presents his/her assigned specialization to the group. Students complete a series of worksheets as they progress through the technique, students are randomly selected to answer questions, and finally, each jigsaw group must write a paper that selects a processor and describes its specialization, co-authored by all members of the group.

In this course, students learn about the uses, capabilities, and limitations of wireless embedded systems in the C6 environment. Based on a set of requirements and preliminary specifications, students will a system-level design language and work in cross-functional groups (e.g., communications, human factors, performance, software engineering, electronics) to prototype selected hardware, software, and interfaces.

Real-time software engineering

Currently there is no course in the Computer Engineering curriculum at Iowa State University that covers software development issues for real-time (or time-critical) applications and how to design software to survive rapidly changing underlying technology. This knowledge is critical for any Computer Engineering student who plans to continue a career in the development of virtual reality applications. Since the user is the central component of a VR system, the software needs to respond to that user within very demanding time frames. The development of such an environment requires very different program design and implementation techniques than, for example, a database management environment.

In this course students will use the VR Juggler software system as the case study for a time-critical framework for virtual reality (www.vrjuggler.org). Class exercises will involve developing small projects with VR Juggler, expanding VR Juggler to add new devices or displays, and modify this framework to accommodate some user requirement not supported by the current implementation.

In some of the related virtual reality courses that we are currently teaching, it is sometimes painful to observe that some of the students are limited by the lack of a solid foundation in software engineering and the design of virtual environments. The objective of this course is to provide the students with the solid practical fundamentals of software design under demanding performance constraints and integration with diverse hardware components. We believe that this approach will provide students with a leading-edge software engineering course, which very few institutions are currently offering

The course will focus on the specifications, design, development, and evaluation of an integrated software toolkit to support a variety of virtual reality devices and configurations. The main goal of the course is to prepare students for advanced work in the area of software engineering, specifically in the areas of hardware abstraction, scalability, code portability, and time-critical computing. These four areas are critical for the successful use of virtual reality technology, which depends on the availability of flexible and efficient software to support the development of applications.

At the completion of the course, students will be skilled at:

- Techniques to abstract hardware functionality through software components.
- Approaches for the application of design patterns to provide application scalability for different levels of VR systems.
- Methods to integrate new hardware into the software system while maintaining performance and compatibility constraints.
- Software simulation of hardware devices to enable hardware-independent development.

Communications Circuit Course

The VLSI communications circuit course focuses on developing VLSI implementations of different hardware blocks such as phase-locked loops, frequency synthesizers, clock and data recovery circuits, low-noise amplifiers, mixers, power amplifiers, and transmitter and receiver architectures. As part of this CRCD proposal, this course will be re-oriented towards the design of communications circuits for practical wireless systems with an emphasis on teamwork and developing a complete system. The course will also cover the underlying communications theory for the systems studied in the class to give the students a sense of how their devices fit in with the larger picture.

The course will be based on modules that cover different aspects of the system design. The modules could be taught in the order given but they could be reordered to fit different teaching approaches. Each module would take an average of one and a half weeks. This course will be team-taught by a specialist in VLSI circuits and a faculty member in communication systems.

A. Link Power Budget
   - TX to RCV
   - RCV to TX
   - Antenna dependent and Power supply dependent

   In communication and navigation systems, there are several power level constraints relating to system design. These constraints relate to power level authorized for use, jamming levels expected, and noise figure of receiving systems. This module will provide the students with a learning experience in designing systems to accommodate these constraints. One portion of the module will require the students to propose alternatives to meeting system performance, physical constraints, and regulatory requirements. In addition to these general constraints, technology considerations such as implementation with integrated circuits, power supply limitations, and physical size constraints will govern which of several proposed systems is an optimum for any particular application.

B. Oscillator and Other Transmitter Non-linearities
   - Inter-modulation and Cross-modulation and noise up-conversion
   - Receiver Single/Double Conversions versus local oscillator choices
   - Transmitter noise modulations considerations

   All physical devices are non-linear. Whether any non-linearity affects a system depends on the system architecture. In this module, the student will consider power dissipation versus inter-modulation levels in both the transmitter and the receiver. The student will perform what is often termed in the industry as birdie analysis. This is an analysis that takes possible harmonics of the desired signal, interfering signals, and any translating frequency signals (local oscillator signals). The student will be guided through the analysis to determine what harmonic orders are important in system design. This is becoming of importance in wireless communication for networking since there will be tens or hundreds of transmitters producing signals within the same band all being received by the input stages of any receiver.

C. Power Supply Considerations

Power supply considerations occur in both battery based and land buss based systems. The conductor in land buss based systems will conduct interfering signals into the unit under consideration. Battery based systems have noise generation phenomena as a function of battery voltage. Low voltage drop out regulators produce noise filtering only at voltages above a certain difference voltage. The system designer needs to determine whether a unit fails to work at low battery or whether the unit produces interference at low battery operation. DC to DC converters produce an entire spectrum of interfering signals. The student will learn about some of these phenomena and learn how to design within these limitations.

D. Technology vs. Architecture

As systems progress further toward integration, filtering mechanisms will change. Analog filtering may be optimal for discrete device based circuits such as printed circuit board assemblies. When integration is necessary, filters are more difficult to implement both with digital and analog techniques. Architecture changes can produce designs that limit the amount of filtering necessary.

E. Technology Difficulties in Wireless Systems

Noise Figure. One limitation in integrated circuit design is getting very low noise figures at low impedance levels with low power dissipation devices. As devices shrink, other types of noise will become important such as quantization noise. This module is designed to allow the student to investigate what may be important in wireless receiver systems of the future.

Transmitter Efficiency. Battery power systems produce a constraint on the efficiency of power generation. There are physical limitations on power conversion efficiency in the microwave frequencies. The student will learn what those constraints are in order to develop an intelligent system design. These modules are not meant to substitute for coursework where the student learns to do the circuit design but to learn the limitations of circuit design in order to design systems that can actually be built with real hardware and real processes.

Communication Systems Sequence and Laboratory

The communication systems sequence at Iowa State University consists of two lecture classes and a hands-on laboratory. The sequence prepares undergraduate students to effectively work in the communications industry. A student who finishes this sequence will have the mathematical background and understanding to be able to analyze and design basic analog and digital communication systems. Designing a communication system requires the student to:

- Analyze Communication Channels
- Evaluate and compare different modulation schemes
- Evaluate different detector/discriminator methods
- Select channel encoding methods
- Determine bit error rates

The Communication Systems II course covers the following topics:

- Pulse modulation systems
- Noise analysis
- Quantization and pulse-code modulation
- Time division multiplex
- Information theory, coding
- Data transmission
  - Spectral shaping
  - Transmission impairments
  - Error rates
- Comparison and evaluation of modulation schemes for data transmission.

Communications Systems Laboratory

The Communication System Laboratory covers the practical aspects of modern communications. A theoretical model may provide excellent performance in a simulator, but the real-world model may not provide the same level of performance. Students also learn how to perform in real-world work environments by solving problems in groups. These topics are designed to cover the basic areas of communications. When a student finishes these courses they will have the ability to work on developing a practical real-world communication system in a realistic setting.

We have updated our existing experiments in an attempt to provide problems similar to real-world situations. The students are typically required to solve a problem with some unknown factors. For example one of the experiments the students are given six sealed boxes that has only an input and output. These boxes represent a channel[a]. The students are required to determine the characteristics of each box. Then use these results to decide which modulation schemes could effectively communicate over each channel.

[a] A channel is the medium, which the transmitted signal travels through to reach the receiver. The medium can be a copper cable, fiber optic cable, or air.

Another experiment introduces students to antennas in a practical environment. This experiment is not intended to replace antenna courses, but to show students how different types of reflectors and different frequencies will affect the performs of an antenna in a communications system. This experiment also covers some of the issues of interference. One, interference may come from many different sources, such as microwave ovens, power lines, or even being to close to the transmitter of a radio station. Two, interference can make a good communication system perform poorly.

Research

This project has two goals: develop a real-time wireless system and improve education. We will be presenting our experiences working with the existing wireless systems in the C6 immersive virtual environment at the Immersive Projection Technology Symposium[1]. Wireless systems intensify the need to incorporate human factors issues into the immersive environment design problem. Human factors characterize human responses to man-made systems. For virtual environments, human factors include information on visual, auditory, and force feedback responses of the system. We are particularly concerned with the latency that may be introduced by the use of wireless communications. Latency is the total delay time between a user's action and the system response. To create a comfortable virtual environment, latency must be below perceivable thresholds. Too much latency can lead to user irritation and cybersickness. Wireless communication systems can introduce additional system delays due to limited bandwidths and retransmissions, therefore these latencies need to be characterized and factored into the system design. A new approach to wireless system design is needed to close the gap between human factors requirements and current wireless system specifications.

Wireless systems must provide a high quality of service in virtual reality to avoid missing data, and introducing latencies and noise. This leads to the following wireless system requirements:

- Provide complete volume coverage, with limited radio frequency (RF) power of the virtual environment.
- Provide sufficient bandwidth for user communication with the system.
- Minimize interference with other wireless devices.
- Low power requirements so that the system can be lightweight and not require frequent recharging or new batteries. These should be at least 120 minutes of battery life.
- Provide for multiple users within the environment.
- Produce low latency.
- The system is scalable to include easy installation of new devices.
- The system must be easy to use.

These issues are specific to the type of system used to transfer the data. The data rates include both the uplink and downlink directions. The uplink is transmission of data from the user to the system, and the downlink is the transmission of data from the system to the user. Crucial components of a communication system's design are communication protocols (data transfer methods), antenna type and placement, and the needs of the users.

There are currently two competing wireless specifications, Bluetooth and IEEE 802.11, available in off-the-shelf hardware. We are investigating both of these communications protocols to determine their capabilities in virtual environments. Bluetooth originally was developed to replace the cables used by portable computers, such as the printer cable, network cable, and scanner cable, but has evolved into a personal wireless network. A personal wireless network is similar to a wireless local access network, but with a coverage area in the general vicinity of the user. IEEE 802.11 is a specification for a wireless local access network. Neither system provides all of the functionality for a wireless virtual reality.

Latency

To make a virtual environment feasible for "real-world" applications, its performance has to satisfy certain requirement related to human-machine interface characteristics, known as human factors. Human factors cover a wide area of characteristics, but this paper is only concerned with timing requirements, also known as latency.

The latency of a virtual reality (VR) system is defined as the total time period between a user action and the system response [2]. Researchers have noticed that the overall system latency is crucial for a user to be immersed within the virtual environment. High system latency will degrade or even totally compromise the virtual environment [3, 4]. High latency has been known to contribute to vertigo, also called Cyber Sickness, and in extreme cases, physical sickness has occurred [5].

A commonly cited figure of acceptable latency is a response time of less than 0.1 second [6]. However, research on human factors has shown that for different applications, different devices, and different virtual object sizes, there is no specifically defined threshold [7]. As VR applications become increasingly complex it is becoming increasingly difficult to maintain acceptable levels of immersion in the virtual environment. We need to improve our understanding of latency to improve system and application designs to ensure a seamless VR environment.

Wloka presents a list of possible latency sources in VR applications. This list includes: User input devices, Applications-dependent processing, Rendering, Synchronization, and Frame-rate-induced lag [3]. The conversion from wired systems to wireless systems is considered part of User input devices. Wireless systems produce higher latency as compared to a wired system. This occurs for several reasons: increased amount of data processing and retransmission of data due to errors.

Experimentally specifications of latency must be determined with respect to the virtual environment. These specifications must be used as part of the design specifications for future wireless systems.

Bluetooth

Bluetooth named after a 10th century Scandinavian king who united several Danish kingdoms, is a proposed set of specifications for short-range use within the home or office and is fairly inexpensive to implement. Its modulation scheme is frequency hopping spread spectrum in 2.4

GHz Industrial, Scientific, and Medical band with a data rate up to 2 mega bit per second (Mbps). Bluetooth is still in its infancy and the standard is continuously being modified to satisfy higher data rates. Bluetooth provides easy integration of a device into the wireless network for use in low-power applications. However, due to the communication method that Bluetooth devices use, latency increases and bandwidth decreases as new devices are added to the network. If the number of devices used is below 20, then latency and bandwidth requirements can be met. In addition, Bluetooth claims to have a range of up to 10 meters, but this fact has not yet been established in real-world settings. We are not currently pursuing Bluetooth as a viable option for VR [8].

The specifications of Bluetooth are separated into two categories: core and profiles. Core is the technical details of the protocol stack, whereas the profiles define parameter settings and procedures [9].

Bluetooth is a frequency hopping spread spectrum radio that operates in the 2.4 GHz ISM band. Each channel is spaced 1 MHz apart with 1600 hops per second (in the US, Europe has 79 channels. Spain, France, and Japan have 23 channels). The modulation method is Gausian Frequency Shift Keying (GFSK), which provides a link speed of 1 Mbps. This is usually implemented on a single IC chip [10].

Bluetooth is organized into two types of networks: piconet and scatternet. A piconet is a group of devices using the same timing or hoping pattern. The piconet has one master and the rest are slaves. Only a master and slave can communicate with each other; for two slaves to communicate they have to either route data through the master or make another piconet. One master can handle up to seven devices actively. If there are more than seven slaves that want to communicate on the same piconet, the master will instruct active slaves to switch to park mode and then instructing other parked devices to become active. The master will continue switching between all of the slaves to ensure everyone communicates. When there are more than eight devices on a piconet then the bandwidth available to all of the devices is reduced. A scatternet is the interconnection of multiple piconets. A bridge node forms the interconnection. A bridge node can be either a master or slave device. Data is exchanged between piconets in the following manner:

1. Starting on piconet A, the bridge node will systematically interrogate each device for data to be transferred to piconet B. The bridge node holds all data until it switches to piconet B.
2. The bridge node switches to piconet B and passes along any data to the appropriate devices.
3. The bridge node starts the process over, except it will interrogate the devices on piconet B instead of A [10].

Issues with Bluetooth

To establish piconets there must be a method for devices to identify and communicate with each other. Since this is a frequency hopping system, devices must be able to find each other, this is referred to as inquiry and paging. Inquiry is a protocol to find other devices and paging is how to connect them together. Bluetooth defines a specific hopping sequence for use in inquiring and paging between devices. When this is occurring no other communication can occur with the other devices on a piconet. This is a serious drawback to the system, because it reduces capacity and will affect time sensitive data. Bluetooth does not define exactly how to balance between data transmission and adding devices to a piconet. In fact this is a serious research issue that must be addressed [9].

Current implementations of Bluetooth devices produce significant amounts of interference, even when the device is in stand by mode. This interference is enough to degrade and/or halt other LANs, such as Wi/Fi and IEEE 802.11. This problem appears to come from the implementation details of the chip. This problem may not be avoidable unless the specification design is changed or more expensive materials are used to produce chips[9].

Because of these interference issues, Microsoft has withdrawn software support for Bluetooth. The long-term affect of this is yet to be known, but many feel that this will significantly hinder Bluetooth's growth.

For Bluetooth to be used as the standard for real-time systems, the capacity and real-time issues must be addressed. At this time it does not appear that this will happen, therefore other specifications are being investigated.

IEEE 802.11

The IEEE 802.11 specification provides a wider range of coverage than Bluetooth. It allows data rates of either 1 Mbps or 2 Mbps in 2.4 GHz Industrial, Scientific, and Medical band with either direct sequence spread spectrum or frequency hopping spread spectrum modulation schemes. It has two high-data-rate extensions: IEEE 802.11 (a) and IEEE 802.11 (b)[11]. IEEE 802.11 (b) allows data rates up to 11 Mbps in 2.4 GHz frequency band, while IEEE 802.11 (a) permits a data rate from 6 to 54 Mbps operating in 5 GHz unlicensed national information infrastructure frequency band. The current data exchange protocols cannot guarantee acceptable latency thresholds. A solution to guarantee latency thresholds have been proposed based on Token Ring concepts for the data transfer protocols. There is a configuration that can provide normal real-time capabilities, but the bandwidth is limited and the ability to combine multiple users is significantly reduced. Wireless equipment that conforms to the IEEE 802.11 specification cannot be used as plug-n-play and intermediate equipment is required to interface with virtual reality devices. Even with these drawbacks, the IEEE 802.11 specification is currently the only viable off-the-self option for use in virtual reality.

Low Power Transceivers

As portability becomes an important feature of electronic systems, the efficient use of energy becomes absolutely essential for wireless communication interface. The development of wireless communication has been emphasizing very low power consumption to increase mobile computing capacity and to extend the operating life of the battery in mobile systems. In wireless system, the transceiver subsystem consumes a fair amount of power as compared to the following stages. In the past, most wireless designs have been optimized for either high performance or energy-efficiency. As more advanced semiconductor technologies become available, many researchers have been focused on high-performance low-power transceivers using several leading-edge semiconductor technologies.

Conclusions

As immersive virtual reality systems have evolved the communication links between the user and the system have also evolved from wired systems to wireless systems. The wireless systems increase mobility and safety, but add to system latency. We are continuing to evolve courses and hands-on laboratory experiments that will help the students learn to attack multi-disciplinary engineering problems.

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