Rapidly Deployable Broadband Communications for Disaster Response

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Abstract: We present the design of a rapidly deployable backbone communications system for disaster response. Although work on the system began in 2000, it is intended for disasters like those that occurred on September 11, 2001. It illuminates the disaster site with RF that supports high-capacity (100 base T or Gigabit Ethernet) links to the outside world. Operating initially at 28 GHz with a 5 GHz version now under construction, it uses non-line-of-sight (NLOS) “bounce paths” of opportunity to provide coverage at shadowed locations. Since at these frequencies most building walls and terrain features are electro magnetically rough, the radio paths are highly dispersive and require careful characterization for optimum radio performance. In order to identify such paths of opportunity and study their characteristics, we developed an impulse channel sounder based on ultra wideband technology. When perfected, it will allow our system to identify the best path and set the radio parameters for optimum quality of service. Since the channels encountered in a given disaster situation may differ significantly from those anticipated or previously experienced, our goal is to use the sounder output to drive a cognitive engine that will control the radios. We present our genetic algorithm based implementation of a cognitive radio and outline our plans for implementation and testing a cognitive version of our system in the 5 GHz band.

1 Introduction

In 2000 our group in collaboration with colleagues at SAIC began developing a broadband communications system for use in response to disasters like those that occurred on September 11, 2001. It is intended for deployment at a disaster scene where all communications infrastructure has been destroyed in an area several kilometers on a side – exactly what occurred at the World Trade Center. The system operates by using one or more hub stations on the periphery to flood the disaster scene with RF that supports high-capacity (100 base T or Gigabit Ethernet) backbone links to portable remote stations within the disaster area. See Figure 1. The remote stations in turn support a mix of individual workstations, routers, 802.11 wireless LANs, etc. The hub connects to the outside world through surviving optical or copper circuits available at the edge of the disaster area or by satellite or microwave point-to-point links to such circuits. The overall goal is to provide high-capacity Internet access to all workers on the disaster scene and to do it quickly. Fire and rescue personnel depend on this access in order to use a variety of management tools, and it provides an excellent way to link the diverse land mobile radio networks whose lack of interoperability seriously hampers response to major disasters. See [1] for full details.

At the time we began the project, broadband fixed wireless was in its infancy. IEEE 802.11 systems operated at 11 Mbps and were primarily used for office LANs. The best possibility for obtaining 100 Mbps service was to adapt satellite modem technology for use in the 28 GHz LMDS band. This approach was convenient for us, since Virginia Tech owns the LMDS spectrum in our part of Virginia. In 2000-2001, fixed wireless technology advanced rapidly and the commercial LMDS market collapsed, and 155 Mbps point-to-point operation in the unlicensed 5 GHz band became commonplace. While this paper presents data for our 28 GHz system, we are now moving forward with a 5 GHz demonstration system based on commercial radio technology modified to include significant cognitive radio functions. See [2] for a full discussion of the technological and social changes that followed 9/11/2001 and their influence on the project.

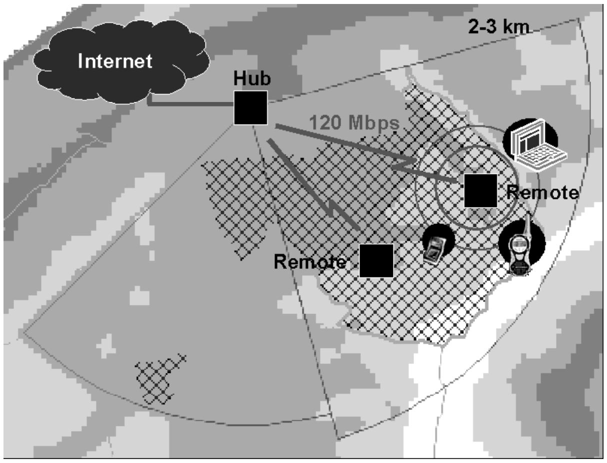

Figure 1. Disaster Communications System Concept

While 28 GHz operation normally implies point-to-point line-of-sight (LOS) operation, coverage may be extended by taking advantage of diffracted signals and particularly of “bounce paths” incorporating reflections from building walls and terrain features. The combination of short wavelengths and highly directional antennas associated with 28 GHz systems makes the propagation environment rather different from that in the 1-2 GHz spectrum well known to engineers who work with cellular telephone and IEEE 802.11 systems. Almost all reflecting surfaces appear rough at 28 GHz, and diffuse scattering (rather than specular reflection) dominates. Received signals do not consist of discrete multipath components, and signal amplitudes are not Rayleigh or Ricean distributed. In a shadowed area (one in which no clear LOS path to the transmitter exists), a receiver with a directional antenna can often find one or more good bounce paths that take advantage of scattering by building walls. Because of their rumored short lifetimes and dispersive characteristics, such “paths of opportunity” are of little commercial interest, but they may be invaluable in disaster situations. We discuss their characteristics in Section 3.

We expect diffuse scattering to be less important at 5 GHz, but at this time experimental evidence is lacking. Rough surface scattering at 28 GHz is of interest from an electromagnetics perspective, while 5 GHz effects are more important for near-term system deployment. We are investigating path characteristics in both bands.

In order to identify paths of opportunity and study their characteristics, we developed an impulse channel sounder based on ultra wideband technology. When perfected, it will allow our system to identify the best path and set the radio parameters for optimum quality of service. Since the channels encountered in a given disaster situation may differ significantly from those anticipated or previously experienced, our goal is to use the sounder output to drive a cognitive engine that will control the radios. Section 2 discusses the sounder and Section 4 presents our genetic algorithm based implementation of cognitive radio. In Section 5 we outline our plans for implementation and testing a cognitive system in the 5 GHz band.

2 The Virginia Tech Channel Sounder

One of the key attributes of the system is the integration of a novel, low-cost, broadband channel sounder developed at Virginia Tech [3]. In essence, the channel sounder takes a snapshot of the channel impulse response and passes it on to the system. This information can then be used to make intelligent estimates of possible link performance and intelligent decisions regarding system configuration. It is possible to use the digitized sounder output as input to a genetic algorithm that can determine the best system configuration for the given environment.

The channel sounder implementation is a combination of ultra-wideband technology at the transmitter and very precisely controlled sampling at the receiver. A train of short RF pulses is transmitted at a rate that is very precisely controlled by GPS clock information. The receiver samples the incoming waveform at a slightly lower rate than the transmitted pulse repetition rate. One sample is recorded for each transmitted pulse, but the effective sampling time for each successive pulse is slightly later in each transmitted pulse period. In this way, it is possible to reconstruct a single channel response based on the transmission of multiple pulses. For a more complete description of the channel sounder operation, see [1].

We have integrated the channel sounder in a pair of 28 GHz radios. Fig. 2 shows the transmitted pulse and Fig. 3 is a typical channel sounder output captured during our experiments. Note that Fig. 3 shows the effects of diffuse scattering and multipath on the received pulse.

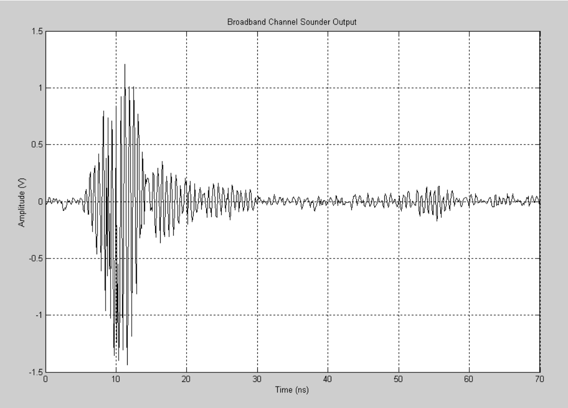

Figure 2. Pulse transmitted by the broadband channel sounder. The plot shows amplitude in volts versus time in ns.

By comparing the transmitted pulse in Fig 2 to the received waveform in Fig. 3, it is possible to extract the channel impulse response. The channel impulse response contains information regarding the distortion introduced by the channel. In the case of Fig 3, it is clear that the receiver first sees about 20 ns of energy that does not look like the transmitted pulse followed by a relatively undistorted pulse at around 30 ns. The initial energy seen at the receiver is a combination of multiple pulses reflected from a rough surface (diffuse scattering) while the pulse seen at around 30 ns is a specular reflection from a relatively smooth surface. Both phenomena contribute to changes in the communication link performance and both need to be characterized in order to drive the genetic algorithms necessary to control the cognitive radio process.

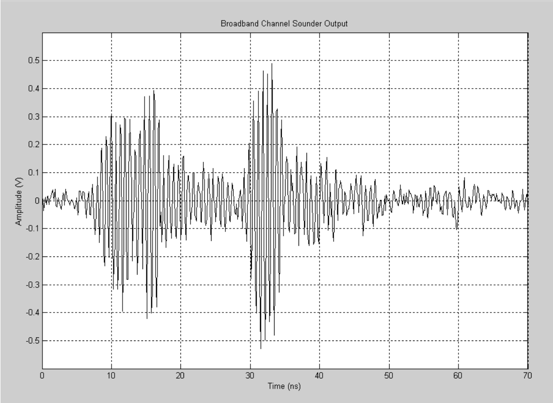

Figure 3. Typical broadband channel sounder output. The plot shows amplitude in volts versus time in nS.

3 Characteristics of Bounce Paths

For many applications at relatively low frequencies, it is generally accepted that the reflections causing multipath are primarily specular. That is, bounce paths from a single surface consist of a single reflection. The signal may be attenuated, but the energy is not spread over time. However, as the frequency increases to the level where the signal wavelength is on the order of the height of the surface irregularities, significant signal spreading may occur. Experiments conducted at Virginia Tech utilized radios operating at 28 GHz where the wavelength is approximately 1 cm. At such small wavelengths, many surfaces look rough and are therefore more likely to produce diffuse scattering.

In [4], Dillard, *et al.* showed that at 28 GHz, limestone walls exhibit significant diffuse scattering with energy arriving at the receiver as long as 75 ns after the specular reflection was received. The severity and duration of the diffuse scattering also depended on the path geometry and the transmitter and receiver placement. When the transmitter was closer to the surface than the receiver, the excess delay was larger. Both results show that the assumptions made in existing lower frequency systems (specular multipath and symmetric link performance) are not valid for rough surfaces – *i.e.*, for 28 GHz bounce paths. New methods need to be devised to characterize what the absence of these assumed conditions means to the quality of the communications link.

Very little has been published concerning the effect of diffuse scattering on communication link performance. In [5], Miniuk collected several channel impulse responses using equipment similar to [4], modeled the channel in software, and ran several Monte Carlo simulations to quantify the effect different diffuse scattering channels had on communication links. The results were interesting in that they showed that increasing the symbol rate in some channels does not necessarily decrease the performance. This suggests that the standard practice of estimating a channel's coherence bandwidth and using that value as the maximum permissible data rate may be inadequate for fixed broadband wireless communications, at least over bounce paths.

Work is continuing at Virginia Tech to determine what metric or metrics are more suitable to characterizing these channels. Early results show that amplitude and group delay variation across the band of interest could be used to better describe the quality of the link [6]. It may also be possible to calculate the actual coherence bandwidth of the channel rather than estimate it using established empirical formulas that may only be valid for other, more well-behaved channels.

4 The Genetic Algorithm Approach to Cognitive Radio

In [7], Rieser *et al.* propose a cognitive radio architecture based on genetic algorithms. Most traditional radios have their technical characteristics set at the time of manufacture. More recently radios have been built that self adapt to one of several several preprogrammed RF environments that might be encountered. Cognitive radios go beyond preprogrammed settings to operate both in known and unknown wireless channels. Most cognitive computing systems to date have been based on expert systems and neural networks. Such systems can be quite brittle in the face of unknown environments or else they require extensive training.

The model in [7] is based on biologically based models of cognition inspired by child development theories of two-way associative learning through play. Our cognitive model imitates the ability of young minds to adapt rapidly to new situations. We found genetic algorithms well suited for this task because of their ability to find global solutions to changing solution spaces that are often quite irregular. Genetic algorithms are (a) able to synthesize best practices through the crossover operation and (b) enable spontaneous inspiration and creativity through the mutation operation. We devised a multi-tiered genetic algorithm architecture that allowed sensing of a wireless channel at the waveform or symbol level, on-the-fly evolution of the radio's operational parameters, and cognitive functions through use of a learning classifier, meta-genetic algorithm, short and long term memory and control. Fig. 4 shows the architecture.

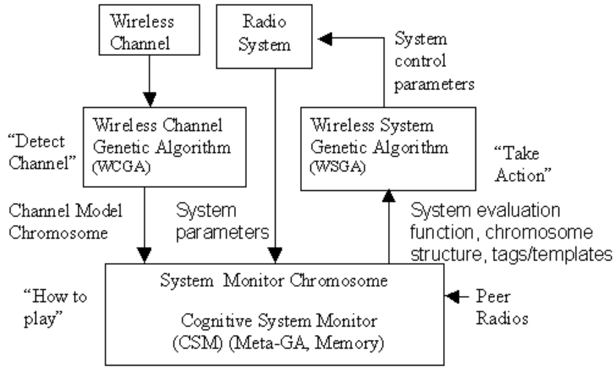

Figure 4: Biologically Inspired Framework for Cognitive Radio Based on Genetic Algorithms [7]

The Wireless Channel Genetic Algorithm (WCGA) allows modeling of any wireless channel error stream using the compact form of a Hidden Markov Model (HMM). For more discussion of HMM modeling of wireless channels please see [8].

Several chromosome structures were devised that allows the representation of wireless channels. An example of an HMM and the equivalent WCGA chromosome is shown in Figures 5 and 6 below.

The HMM of Figure 5 has N = 3 states and M = 2 possible outputs from any state.

A:

A_{11}	A_{12}	A_{13}
A_{21}	A_{22}	A_{23}
A_{31}	A_{32}	A_{33}

B:

B_{11}	B_{12}
B_{21}	B_{22}
B_{31}	B_{32}

π:

π_1	π_2	π_3

Figure 5: A Generic HMM [7]

A_{11}	A_{12}	A_{13}	A_{21}	A_{22}	A_{23}	A_{31}	A_{32}	A_{33}	B_{11}	B_{12}	B_{21}	B_{22}	B_{31}	B_{32}	π_1	π_2	π_3

Figure 6: Chromosome Structure for a HMM [7]

The WCGA algorithm works as follows:

1. Initialize population of HMM chromosomes
2. Repeat until stopping criterion
   - *Choose* parent HMM chromosomes
   - *Crossover* parent chromosomes to create new HMM chromosome
   - *Mutate* new HMM chromosomes
   - *Replace* HMM chromosomes
   - *Evaluate* statistics of output sequence produced by new HMM chromosome population
3. Choose best HMM chromosome from final generation

The genetic algorithm (GA) essentially searches for the best HMM of a given observed symbol level error stream and generates a channel model that is statistically similar to the observed wireless channel. In [8], we showed that the WCGA could produce a wireless channel model of an error stream derived from a measured channel impulse response that closely matches the actually measured bit error rate (BER) behavior of a broadband wireless channel. This experiment showed that the "sensing" portion of the cognitive radio architecture matched real world tests.

The WCGA uses are error stream for the input, which is a train of symbols representing the number of bit errors per symbol. For the WCGA to produce an accurate model, many thousands of error symbols must be collected, which would require a long training sequence, taking both time and bandwidth. A more compact and efficient approach to channel modeling is to utilize the information collected by the channel sounder.

While the channel sounder response can provide an immediate understanding of the channel, the data received from the sounder is large and bulky. By using the channel sounder response, a model of the channel is derivable by simulating the channel as a filter with an impulse response derived form the channel sounder. A random bit sequence passed through the simulated channel will produce an error sequence. The WCGA can now receive an error sequence without the required overhead of a training sequence.

Because we are interested in a statistical model of the channel, we can use the simulated channel instead of the true error sequence. The Hidden Markov Model of the channel developed by either a true error sequence or a simulated error sequence is still a statistical representation of the channel. However, this representation is very small compared to the channel sounder data and is capable of representing the channel equally well.

Fig. 7 shows how well-matched the simulated channel is to a theoretical AWGN channel. The WCGA was then used with the simulated error stream to develop a channel model with the statistics represented in Fig. 8, which shows a histogram of the number of errors of a certain burst length over the channel. Fig. 9 then shows how well matched the HMM representation of the channel is compared to the simulated channel, and therefore, how well matched the HMM representation is compared to the actual channel (via Fig. 7).

Figs. 7, 8, and 9 are the subject of a paper we submitted to the Microwave Theory and Technique Society's 2004 International Microwave Symposium that has not yet been published [8]

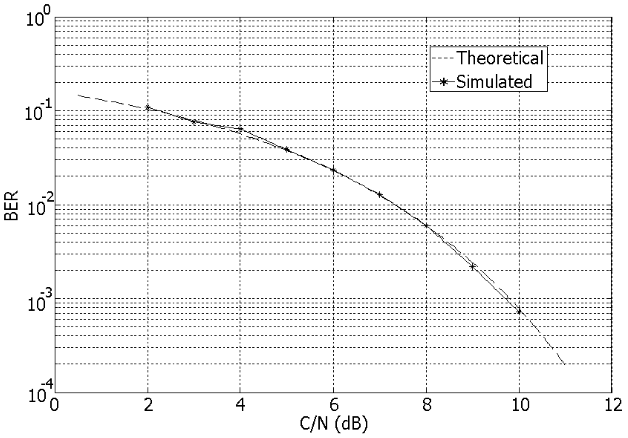

Fig. 7. A simulated model of an AWGN wireless channel versus the theoretical channel.

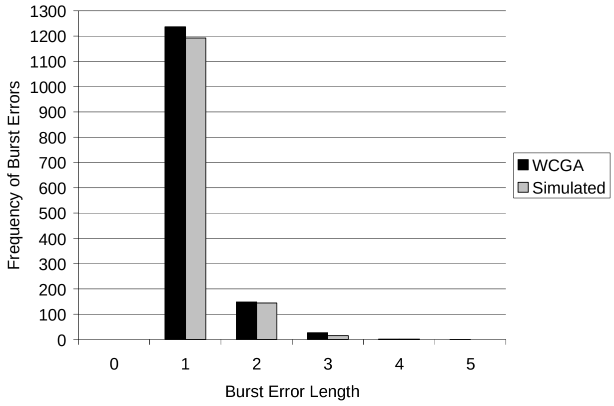

Fig. 8. Burst error statistics of the simulated channel versus the HMM channel. [7]

The Wireless System Genetic Algorithm (WSGA) operates in a similar manner as the WCGA in that it uses a chromosome structure that represents the parameters of the radio under test. The WSGA is given a fitness function, or set of goals, by the Cognitive System Monitor (CSM) module and continuously adapts the radio based on these goals. Example goals could be providing a desired balance of BER, power, frequency, modulation, and data rate behavior for a given Quality of Service and wireless spectrum band.

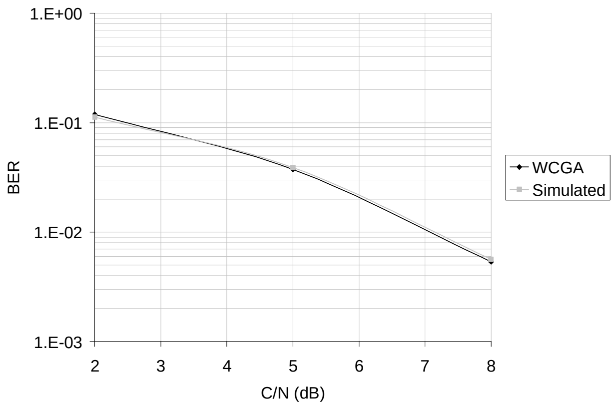

Fig. 9. BER curves of simulated channel versus the HMM channel. [8]

The CSM genetic algorithm consists of a learning classifier function that classifies the observed channel model received from the WCGA or broadband channel sounder and a meta-genetic algorithm that determines the appropriate fitness function, chromosome structure, and tags and templates using the crossover operator based on knowledge from its short and long term memory as well as the creative new solutions generated from its mutation functions.

The GA approach to adapting a wireless radio provides many benefits. First, it is a chaotic search with controllable boundaries that allow it to seek out and discover unique solutions efficiently. In unknown channels, chaotic behavior could produce a solution that is absolutely correct but counter-intuitive. By being able to control the search space by limiting the number of generations, crossover rates, mutation rates, fitness evaluations, etc., the cognitive system can ensure legal and regulatory compliance as well as efficient searches.

Another major benefit of the GA approach is the versatility of the cognitive process to any radio. While a software radio is an ideal host system for a cognitive processor, any legacy radio with the smallest amount of adaptability can benefit from our cognitive processes. The cognitive system defines the radio by a chromosome, where each gene represents a radio parameter such as transmit power, frequency, modulation, etc. The adaptation process of the WSGA is performed on the chromosomes to develop new values for each gene, which is then used to adapt the radio settings. If a radio cannot adjust a particular parameter, then the adaptation process will ignore the gene representing that parameter. Also, if there are certain parameters unique to a particular adaptable radio, we have left a few genes unused so as to be used for such proprietary purposes.

Because each radio will have a unique method of adapting the radio parameters and each parameter will mean something different, a small hardware interface module is required to connect the WSGA to the radio. The interface module will take the chromosome from the WSGA and use the gene values to properly update the radio. The interface is a small piece of software required for each radio while the cognitive processing engine remains system-independent.

While the independence of the WSGA and cognitive processor to the radio allows any radio to become a cognitive radio, it should be clear that the more adaptable a radio is, the more powerful the cognition becomes.

5 Plans for Implementation and Testing

We are implementing the WSGA and CSM for a set of 5 GHz Proxim *Tsunam*i radios. The WSGA module of the cognitive radio test bed will enable the radios to change a number of their operating parameters based on the sensed behavior of the wireless channel. These parameters include power, modulation index, forward error correction (FEC), and TDD mode. We have written a hardware interface module that provides a uniform interface between the WSGA and the Proxim radio. We plan several tests of the CSM and WSGA algorithms in which the cognitive radio test bed algorithms are supplied with different stored error streams representing several known and unknown wireless channels and the algorithms are run to show their performance in these channels on the fly. This experiment will validate the WSGA's ability to evolve the radios based on changing wireless channel conditions and spectrum availability as well as the CSM's cognitive ability to discern how best to direct the radios to operate in the given wireless spectrum environment. Future tests will enable live measurement of the wireless channel using impulse responses captured by the broadband channel sounder or symbol level error streams recorded by the receiver.

As the project matures, we envision the use of the cognitive processes on a more adaptable software defined radio, which would enable us to show the increased power of the GA based cognitive radio.

6 Conclusions

Our work represents early steps in using an impulse sounder to characterize a wireless channel and pass appropriate information along to the genetic algorithms that will allow them to effectively configure a broadband disaster communication system and realize a functioning cognitive radio.

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