The University of California Los Angeles

Wireless Communications Testbed Overview

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Executive Summary

The Narrowband Testbed is a fully configured software defined multi-antenna wireless testbed. It supports 4KHz useful bandwidth at 220MHz frequency band. Most of the radios for this testbed also cover the adjacent amateur radio band. The goals of the testbed are

1. Enable space-time modem experimentation.
2. Enable bandwidth efficient modem experimentation.
3. Enable ad hoc networking experimentation.
4. Enable an interaction of networking and physical layer research in wireless.
5. Have the testbed be a much as possible software defined so that students can use the testbed with a minimum of training.

The following is a list of building blocks of the testbed hardware.

1. 3-channel TX modem
2. Commercial Base station SEA 220MHz radio and TX/RX duplexer
3. 4-channel digital down converter with serial interface to DSP
4. Analog Devices 21xx and SHARC DSP development boards.
5. 4-channel down converter radio
6. Mobile units

With these hardware blocks, we have developed an infrastructure based wireless network (FCC compliant, linear modulation on downlink and CPM on uplink) as well as a peer-to-peer CPM modem. Various channel codecs that have been implemented include TCM, turbo-TCM, and Space-time coding. A 3x4 MIMO test system using these hardware components facilitates space-time coding and MIMO modem testing. The system has demonstrated a reliable transmission radius of 10 miles with an antenna mounted on an 8 story building and 1-2 miles of reliable transmission range in an urban mobile deployment.

220MHz Software Defined Radios	Useful Bandwidth (KHz)	Maximum Transmission Power (dBm)	AGC Capability	Duplex Mode	Frequency Band (MHz)	Number of Channels	DSP Chip
Base Station	4	46	Y	Full	220	3	ADSP2181+ADSP21160
Mobile Radio	4 (20 optional)	30	Y	Half	218-225	1	ADSP2192-12
Custom RX	2000	N/A	N	RX only	218-225	4	ADSP21160
Custom TX	2000	46	N/A	TX Only	218-225	3	ADSP2181

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Goals of the Testbed

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Advances in space-time modem designs are very dependent on actual physical channel characteristics. A goal of the narrowband wireless testbed are to easily enable space-time experiments. Experiments with up to 4 transmit and 4 receive antennas would enable important problems in multiple antenna communication systems to be investigated. We desire to support experimental research in

1. Code design (adaptive, feedforward, noncoherent).

2. Demodulator architectures (BLAST, maximum likelihood).

3. Channel estimation algorithms.

4. Channel sounding.

Having the ability to implement coded modulation and demodulation in a hardware testbed enables faster evaluation relative performance levels. A goal of the narrowband wireless testbed is to enable experiments with different coded modulations on wireless channels. We desire to support experimental research in

1. Bandwidth efficient turbo coding and decoding.

2. Constant envelope signaling.

3. Low complexity iterative decoding.

4. Algebraic interleaver design and implementation for turbo coding and low density parity check coding.

5. Soft decision decoding for algebraic codes.

Wireless networking research has been hampered by physical layer radios not being programmable. A goal of the narrowband wireless testbed is to enable experiments in networking where a parameter at the physical layer can be modified to improve network performance and throughput. This will enable some cross layer research to optimizeand wireless network performance and experimental verification. We desire to support experimental research in

1. Multiple access protocols.

2. Resource allocation in ad-hoc networks.

3. Secure communications protocols.

4. Dual capability radio nodes (narrowband and wideband).

The goal in the testbed is to put as much of the functionality as possible into software. Student communication theory researchers can capably develop software while hardware less likely to be done competently. Consequently a testbed that uses software to implement all functionality would be a desirable format. The philosophy is to have physical layer modem functions accomplished in digital signal processors (DSP) and networking layer functions accomplished in C code (either on a Linux or a Windows platform). The DSP processor family that was chosen for the testbed was manufactured by Analog Devices. There are a variety of DSPs included in the testbed depending on the hardware implementation but there is a great deal of code compatibility across the different platforms. Because of the narrowband nature of the physical layer very sophisticated algorithms can be implemented using DSP technology. Since the typical applications considered in the testbed are communicating at low rates having the networking layer implemented on a traditional operating system does not significantly impact the functional characteristics. Additionally the structure of the system will allow a quick mapping of network level simulations into actual network implementations.

Supported Test Configurations

Infrastructure Network

To accomplish interesting infrastructure network experiments we have developed two major subsystems:

1. A basestation consisting of a duplexer, radio, baseband processor, and a network processor.

2. A mobile unit (a multitude of nodes) consisting of a radio (half duplex), a baseband processor, and a network processor.

These two entities along with their complete programmability allows us to implement a wide variety of experimental system designs.

Ad-Hoc Network

Engaging in ad hoc networking research requires a mobile unit (a multitude of nodes) consisting of a radio (half duplex), a baseband processor, and a network processor. This node along with it's complete programmability allows us to implement a wide variety of experimental system designs.

MIMO Modem Experimentation

To work on MIMO modem experimentation we have developed

1. A multichannel transmitter radio and a multiple channel baseband processing unit

2. A multichannel receiver and a multiple channel baseband processing unit.

Narrowband Infrastructure Based Testbed

Overview

The testbed uses the Narrowband Radio services band. Narrowband radio services band is a frequency band (220-222MHz) setup by the FCC for bandwidth efficient wireless communication. Communication is envisioned to be via frequency division duplexing. 200 channel pairs (downlink 220-221MHz and uplink 221-222MHz) are established with 5kHz channel spacing and 4kHz of useful spectrum. The FCC has established stringent frequency masks for this band [6]. Since 220MHz has good propagation characteristics this band was envisioned to provide wide area coverage. Our testbed is a completely FCC compliant system that achieves high bandwidth efficiency and good performance by applying the state of the art in communication theory. Transmitted power of up to 100Watts is possible, and supported ranges greater than 10 miles have been demonstrated in field tests. Fig. 1 shows the three base station radios and duplexers of our experimental system. Fig. 2 shows the transmitted signal spectrum. The combined radio and signal processing produces over 70dB of out of band suppression.

The testbed goal is to push the state of the art in wide area short packet data networking. The major goal in putting together the systems for the testbed was spectral efficiency. Modulation and coding have all been focused on providing high reliability for mobile communications at high bandwidth efficiency. This modem has implemented physical layer communication algorithms with following characteristics:

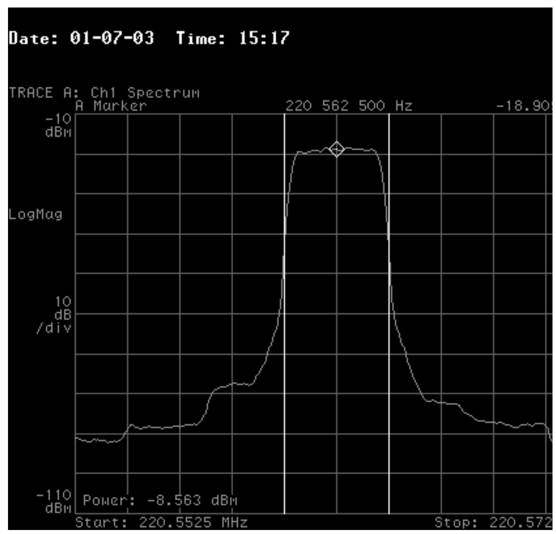

Figure 2. RF spectrum of narrowband downlink signal.

1. Spectrally efficient pulse shaping meeting stringent FCC spectral mask requirements,
2. Large QAM constellations (up to 128QAM),
3. Pilot symbol assisted demodulation,
4. Transmitter diversity modulation,
5. Turbo coded modulation,
6. Synchronization optimized for time-varying fading,
7. Soft decision decoding optimized for time-varying fading,
8. Linear high power amplifiers,
9. Bandwidth efficient CPM modulation and demodulation,
10. Short packet transmission.

In addition the networking has been optimized for short packet message delivery [1]. The forward link is a broadcast channel while the reverse link utilizes both contention and reservation modes.

The testbed implements all sophisticated communications algorithms in software. The physical layer communication processing is done with digital signal processors (DSP). The network layer functionality and the Reed Solomon codec are implemented in C on a personal computer (desktop, laptop, or palmtop). This allows the systems to be modified when new and better ways of processing the signals become available.

Basestation

The base station has been designed to provide high performance full duplex communications at 220MHz. The block diagram of the narrowband testbed base station is shown in Figure 1 for the case when three antennas are used. The components that make up the base station are the radio system, the quad receiver IF downconverter, the digital processing unit, and the multiple transmitter IF system. The transmitter IF system supports three simultaneous diversity channels. The receiver IF system can support four diversity channels. The transmit physical layer is implemented in DSP software in the transmitter IF system while the receive physical layer is implemented in the receiver digital processing unit. The network functionality is implemented in the PC.

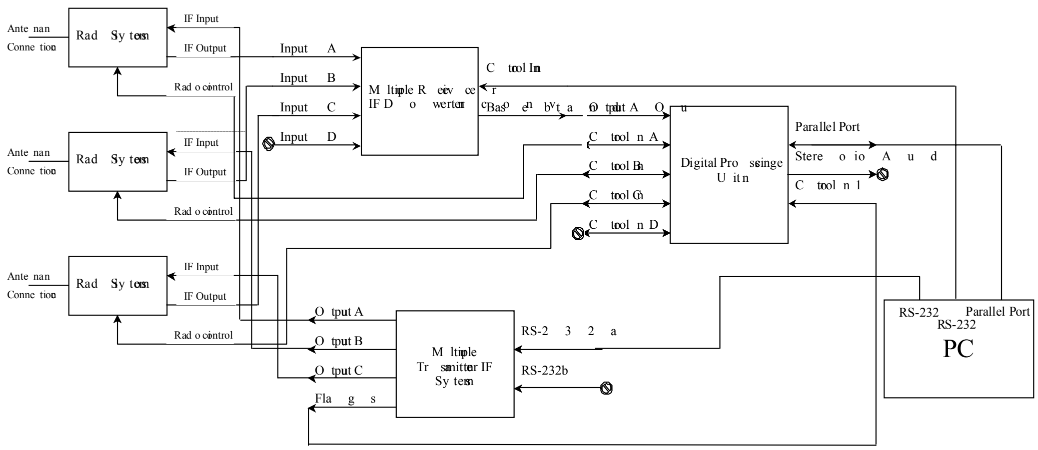

Figure 1. Narrowband base station block diagram

Mobile Unit

The mobile unit has been designed to be appropriate as a handheld radio unit. The block diagram of the narrowband testbed mobile unit is shown in Fig. 4. The mobile unit consists of two major components: a half duplex radio system and a digital signal processor (DSP) based modem. The radio system includes transmitter RF upconverter and power amplifier, receiver IF/RF downconverter and AGC amplifier. The transmit and receive physical layers are implemented in transmitter and receiver DSP units respectively. The DSP units also provide the radio flag control signals. The network functionality is implemented in mobile unit controller (MUC) hosted by the PC. The overall mobile unit for Generation 1 of the testbed is shown in Fig. 4. The Generation 1 mobile radio provides 28dBm output transmit power, 80dB of receiver dynamic range, and a receiver sensitivity below –120dBm.

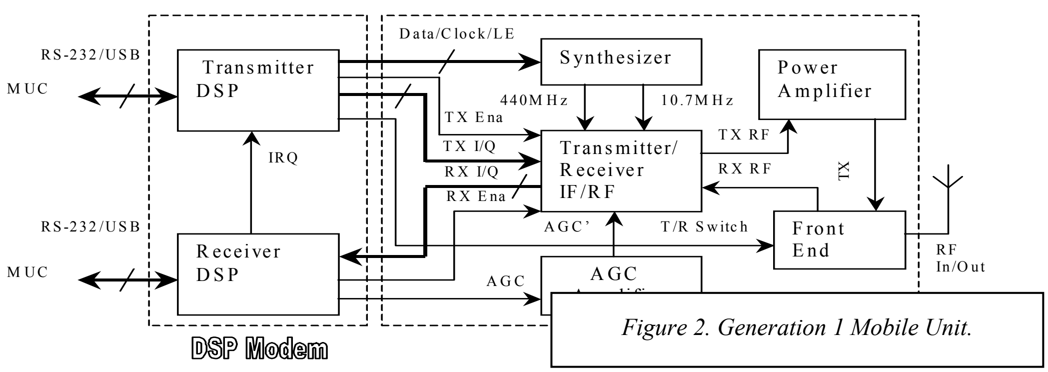

Figure 2. Generation 1 Mobile Unit.

Figure 4. Narrowband mobile unit block diagram. Generation 1.

Forward Link Physical Layer Overview

Notification Cycle Structure

The forward link uses broadcast transmissions with reservation protocol. Figure 3 shows the structure of the forward link notification cycle structure. The forward link transmits the notification cycle structure periodically. The structure allows data and a set of control packets to be transmitted. These control packets establish the reservations and control of both the forward link and the reverse link. There are two control packets distributed in the notification cycle and this is to allow the reverse link to be fully utilized, as the mobile units are half duplex radios. If a mobile unit happens to be transmitting reverse link data during the first control packet it can get its information from the second control packet (and vice versa). The control packets indicate which of the forward link data packets are intended for which of the mobile units and also supplies the reverse link transmission schedule. In order to support reasonable response time the notification cycle is set to 4 seconds. The preamble allows for quick synchronization from a sleep mode. Hence it is possible for a mobile unit to operate in an energy efficient manner in that it can sleep until a predetermined notification cycle start, wake up synchronize, and check for messages. Reliability is ensured by a concatenated coding system. An outer code (often a Reed Solomon code) optimized to prevent frame errors is concatenated with an inner coding scheme, which is optimized for the time varying land mobile channel. Packet size is set to 48 bytes. This size was deemed a good compromise between allowing for bandwidth efficient transmission of short messages and ensuring that reliable error correction and detection was possible.

Preamble	Control Packets-1	Data Packets	Control Packet-2	Data Packets

Figure 3. Forward Link Notification Cycle Structure.

Modulation and Coding Overview

A 3200 symbols per second transmission rate is used on the forward link. Since the forward link has linearized power amplifiers, the forward link modulation can be a linear modulation using quadrature amplitude modulation (QAM) and phase shift keyed (PSK) modulation without penalty. The pulse shape is chosen to be a square root spectral raised cosine (SRSRC) because the FCC spectral mask in the 220MHz band is quite stringent [6]. Pilot symbol assisted modulation is used to acquire fast frame synchronization and simple channel state estimation. Known pilot symbols are inserted with a certain pattern as illustrated in Figure 4. N consecutive pilot symbols at the beginning are inserted to facilitate fast frame and carrier synchronization and the periodic pilot symbols are inserted every N_p symbols for channel state estimation, where N and N_p are optimized for the best trade-off of error performance and bandwidth efficiency. The entire notification cycle is based on this pilot symbol frame (PSF) structure and the notification cycle consists of an integer number of PSFs. This periodic structure ensures that frame synchronization can be achieved anytime during the notification cycle. Based on the PSF structure, a variety of linear modulations and coding techniques have been implemented, namely uncoded 4PSK, trellis coded (TC) 16QAM, space-time coded 4PSK, and turbo coded 16QAM. All modulation and coding schemes target a rate of 2bits/symbol. The software radio implementation allows new physical layer modulation and coding schemes to be implemented as new schemes present themselves.

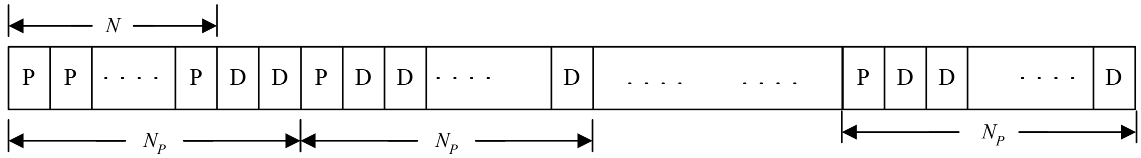

Figure 4. Pilot Symbol Frame Structure; P: Pilot Symbol; D: Data Symbol

Reed Solomon (RS) codes were used as an outer code for high reliability [8]. For example a commonly used code dimension (64,48,17) over GF(256), i.e., 64 coded symbols, 48 information symbols, minimum distance 17 symbols, and the symbol size equal to 8bits. This code can correct up to 8 random symbol errors. Berlekamp-Massey algorithm is used for decoding, which also delivers a flag for decoding failure if the code is neither decoded correctly nor gives an undetected error. A symbol size of 8bits, which accounts for 4-2 bit modulation symbols was determined to be efficient to capture burst type errors often introduced by a land mobile channel. By using a powerful outer RS code, errors are virtually eliminated during transmission. Packets are either received and correctly decoded or the decoding algorithm declares an erasure. Using this family of coding schemes implies that the packets delivered to the applications are of very high reliability even in the most demanding land mobile wireless channels.

Generation 1.0

The first system used uncoded QPSK modulation. QPSK is the optimum modulation for uncoded 2 bits/symbol linear modulation. Pilot symbols are chosen from an 8PSK constellation. This 8PSK constellation makes the pilots uniquely distinguishable from the data symbols and aids the synchronization performance. The generation 1.0 forward link is designed so that each PSF contains 150 symbols and transmit 256 information data bits (N_p=10 and N=8). Hence a (64,48,17) RS codeword comprises two PSF's.

Generation 1.5

Generation 1.5 has implemented TC-16QAM modulation as proposed in [9]. This 16QAM modulation retains an effective rate of approximately 2 bits per symbol and retains a simple complexity by using the idea of I/Q modulation. In I/Q modulation QAM codes are implemented by implementing two parallel real valued pulse amplitude modulation (PAM). Two 4-state TC-4PAM codes are applied identically and independently to the in-phase channel (I channel) and quadrature channel (Q channel), and achieve the whole 16-state trellis coded modulation. Soft-decision Viterbi decoding algorithm is used in I/Q channel separately. Decoding complexity is reduced in this way. The pilot symbol frame, preamble and notification cycle are as same as uncoded QPSK.   This coding scheme is also compatible with a frequency offset transmit diversity scheme as investigated in [14,10].   To implement this transmitter diversity scheme only the transmitter software needed to be modified and the receiver software remained unchanged. This form of transmitter diversity signaling is an effective overlay system for single antenna systems.

Generation 2.0

Several modulation formats are under development for the next generation. The first is a space-time TC scheme first proposed in [11]. In one implementation we consider two transmitter antennas and one receive antenna. For this case an 8-state concatenated space-time block code with multiple trellis coded modulation (STBC-MTCM) is used to achieve full-rate, full-diversity and substantial coding gain. MTCM has a multiplicity of 2 and 8 parallel branches. This space-time trellis code uses 4PSK constellation. Viterbi decoder is implemented at the receiver. Space-time trellis coding retains an effective rate of approximately 2 bits per symbol. Modifications of the pilot symbol architecture for the single antenna were produced based on the ideas in [12]. Here the PSAM channel estimator must produce separate channel estimates for each of the transmitter channels induced in the multiple antennas modem. This new estimator required different processing at the receiver and a different pilot symbol insertion pattern than highlighted in Fig. 6.

Another modulation format is a Turbo coded modulation using 16QAM. It is implemented via parallel concatenation of two constituent 4-state trellis coded modulation (TCM) codes. Each constituent code is a recursive TCM code with output symbols mapped to 4PAM constellations. The input to the constituent codes differ by interleaving, i.e., a pseudorandom reordering of the information sequence. The final 16QAM is obtained by independently modulating the in-phase and quadrature channels with each of the two constituent TCM codes. Iterative a posteriori probability (APP) decoding with four iterations is used for demodulation. Turbo coding retains an effective rate of approximately 2 bits per symbol.

Receive Processing Overview

The demodulation algorithms use pilot symbol assisted channel estimation and trellis based decoding optimized for time varying fading. The matched filter outputs of the uniformly spaced pilot symbols shall be used for channel estimation to aid data decoding. The interpolation filter length is chosen to be 12, where 6 pilots before and 6 pilots after the symbol of interest are used to generate the channel state estimation. The filter coefficients are set to ones for the optimum filter for Rayleigh fading with isotropic scattering and a fractional Doppler spread of 1%. This corresponds to a maximum vehicle speed of roughly 95 MPH (150KPH). Demodulation algorithm will vary as needed according to the different modulation formats in each generation. In all cases either a soft decision Viterbi decoding algorithm (optimum sequence decoding) or an optimum bit error probability decoder (e.g., BCJR [5]) is used for decoding.

Many levels of synchronization and decoding are needed to produce reliable decisions. Synchronization must be achieved all the way from the bit and carrier level on up to a synchronization to the notification cycle. These various levels of synchronization are accomplished in stages and completed before demodulation is attempted.

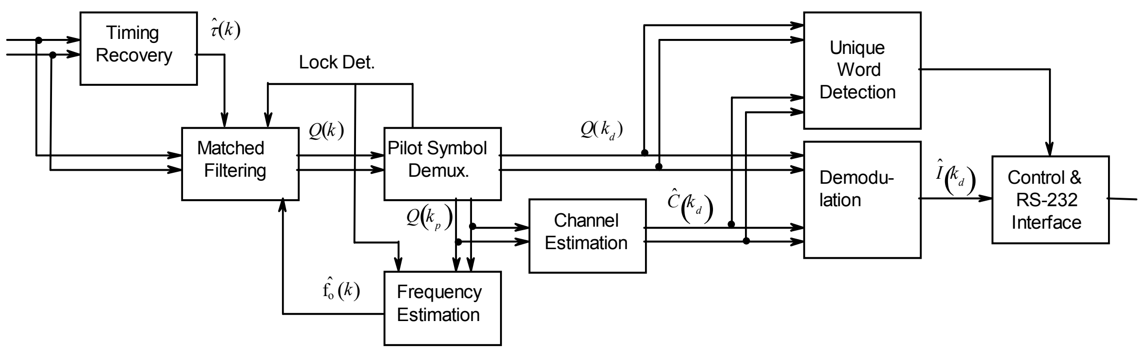

Figure 5 Demodulator functional block diagram

The first level of synchronization achieved in the processing is symbol timing. This algorithm uses the traditional square and filter architecture [16]. The nonlinear operation produces a sinusoid at the baud rate for linear modulations. A traditional ML estimator of phase [13] is used. When baud frequency offset between transmitter and receiver is significant further processing is implemented to accommodate and track this error.

The second level of synchronization accomplished is frame and carrier frequency synchronization. Pilot frame synchronization and frequency offset estimation are done jointly when demodulation is first initialized and a baud rate lock is achieved. The goal of the pilot symbol frame synchronization is to find the starting location of the PSF and the goal of the carrier frequency offset estimation is to estimate the carrier frequency offset and de-rotate the received signal. The joint synchronization is done based on maximum likelihood estimation. It turns out that a two-dimensional search, which has impractical complexity, is needed for optimal solution. Hence a sub-optimal, multi-stage reduced complexity search method was employed. The search method based largely on the work of Jerry Gansman [15] and was designed to estimate a frequency offset as large as ±375Hz. A brief overview of the processing is

1) Produce 5 channels of matched filter outputs at the baud time for channels centered at frequency offsets of 0Hz, ±150 Hz, and ±300 Hz.

2) For each channel, generate 3 sub-channels by tuning the matched filter output to a frequency offset of –50 Hz, 0 Hz, and 50 Hz. In essence, we produce a total of 15 sub-channels by employing only 5 banks of matched filter, which is computationally much cheaper than using 15 banks of matched filters, while the performance degradation is negligible.

3) For each subchannel, collect a block of observations one pilot symbol frame (150 symbols) in length and search for pilot symbol framing epoch.

4) Choose the maximum likelihood estimate of the starting pilot position among the three sub-channels for each of the 5 matched filter channels.

5) Given the estimated PSF starting location for each channel of matched filter outputs, do a fine search of frequency offset with a step of 5 Hz over the range of (-75 Hz, 75 Hz).

6) Choose the overall maximum likelihood estimates among the 5 channels.

The final level of synchronization is identifying the notification cycle start position. This frame synchronization is accomplished in a traditional search since the number of starting positions is relatively small since we already know the PSF locations and the symbol timing locations. In addition, processing is done to detect a loss of synchronization at each of the three levels of synchronization that is achieved in demodulation.

Reverse Link Physical Layer Overview

Reverse Link Frame Structure

The main goals in the reverse link design are to provide low probability of packet error and as bandwidth efficient an implementation for short packet transmission as possible. The reverse link physical layer frame structure is shown in Figure 6. Normal data packets are supported in the *Data* slots while many very short packets are supported in the *GPS* slots. An obvious application for these slots is the transmission of GPS coordinates to enable the real-time tracking of users.

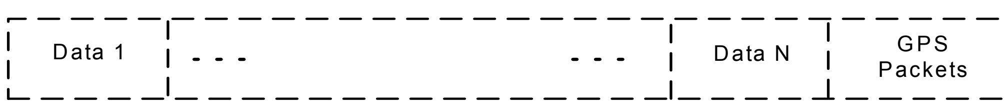

Figure 6. Reverse link physical layer frame structure

Modulation and Coding Overview

Reverse link data slot consists three parts: preamble, payload data and postamble. The preamble is included to aid synchronization of the receiver to the packet transmission. Reed Solomon codes are again used as an outer code for high reliability for the payload. Both the preamble and the payload data part use the same Pilot Symbol Frame structure as on the forward link to facilitate synchronization and channel state estimation. In addition to the pilot symbols, ±1 dotting patterns are transmitted in the preamble part to achieve good symbol timing performance. The postamble contains 51 known symbols, which are transmitted to assist the channel state estimation for payload data at the end.

Generation 1.0

The initial reverse link design used uncoded QPSK modulation and heavily borrowed from the forward link Generation 1.0 design. Since the amplifiers are not linearized, the symbol rate was reduced to 2400 symbol per second and more excess bandwidth was used on the pulse shaping to reduce the sensitivity to amplifier nonlinearities. The packet structure for the Generation 1.0 design is shown in Figure 7. Clearly the bandwidth efficiency of this structure is low due to the long preamble. Using this slot format a total of 9 users could be fit in the notification cycle on the reverse link.

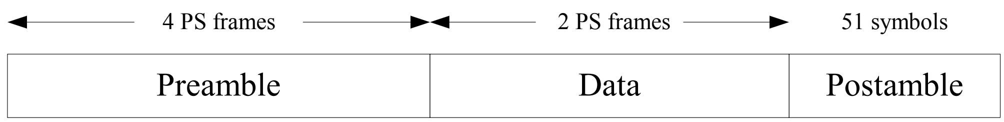

Figure 7 Uncoded QPSK data slot format

Generation 2.0

Generation 2.0 attempted to address the sensitivity to the nonlinear amplifier and the bandwidth inefficient preamble. Continuous phase modulation (CPM) was chosen since CPM is a constant envelop modulation scheme, which can provide good spectral characteristic and bit error rate (BER) performance. Since CPM has a constant envelope, high efficiency and low cost nonlinear amplifiers can be used in the place of linear amplifiers without affecting the transmitted spectrum. The packet structure of Generation 2.0 design is shown in Figure 8. Data payload is a binary 3RC (Raised cosine) signal at a symbol rate of 2800 symbol per second as this met the stringent spectral mask and provides good performance.

The preamble is much shorter than achieved in Generation 1.0 reverse link slot as it is only 52 symbols (19.5ms) in length. The transition region (19 symbols) ramps the signal (in a bandwidth efficient manner) from no signal to the desired envelope level. The remainder of the preamble was designed as a tradeoff between achieving a high level of performance in synchronization while maintaining a relatively low complexity for the algorithms. The use of minimum shift keying (MSK) signaling [2] enables a very simple closed form frequency and timing estimator [4]. However, in order to meet the stringent spectral mask the MSK symbol rate needs to be cut to one fourth. When the frequency of the MSK signal is cut to one-fourth the ability to accurately estimate timing is significantly degraded. In the end we chose to use MSK in the preamble (10 symbols at a symbol rate of 2000/3Hz) to get an initial synchronization estimate. We follow the MSK preamble with a 3RC preamble (12 symbols at a symbol rate of 8000/3Hz) and do an iterative refinement of the initial estimates based on this 3RC signal. Overall the synchronization performance is good and the bandwidth efficiency has been greatly improved. If the packet is very short we demodulate based only on the parameters estimated from the preamble but for longer packets tracking algorithms need to be implemented.

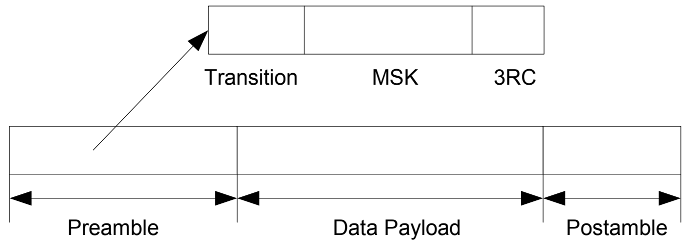

Figure 8. Generation 2.0 CPM packet structure

Receive Processing Overview

Receive processing for the Generation 1.0 reverse link is very similar to the processing on the Generation 1.0 forward link.

Generation 1.0

The first design used uncoded QPSK modulation. The demodulation and synchronization use the same techniques that are used on the generation 1.0 forward link (Also uncoded QPSK). The only difference is that here the pilot symbol frame synchronization needs to be done for each reverse link slot and no notification cycle synchronization needs to be implemented.

Generation 2.0

The Generation 2.0 uses an appropriate preamble design for fast synchronization. The packet structure is shown in Figure 8. The main purpose of synchronization is to estimate three channel parameters: packet delay, phase offset and frequency offset. For joint (Maximum Likelihood) ML estimation of these parameters, a three-dimensional search is required which results in impractical complexity. Hence, a nearly optimal but computationally simple algorithm is needed to acquire fast initial synchronization. By using 7/8 of MSK waveform, a closed form ML estimator is implemented for joint estimation of three channel parameters in Generation 2.0 [4]. A brief overview of this procedure is

1) Divide the frequency offset range into a number of bins. By searching over a range of [-300, 300] Hz with step 35.3Hz, we obtain the peak value of the frequency offset $\hat{f}_0$ among all the search points.

2) Searching over a small range [$\hat{f}_0$ - 42, $\hat{f}_0$ +42] Hz with step 5Hz, we find the more accurate peak value.

3) Given the peak value found in the second stage, we employ a quadratic polynomial fit by using its left and right bins.

4) Perform a closed form solution for initial estimates of packet delay and phase offset based on the initial estimate of frequency offset.

After the initial estimation, a one-shot Newton-Raphson iteration based on the initial estimates and the entire received preamble is employed to refine the estimates.

The Generation 2.0 data packet is demodulated using soft output processing on the trellis that defines the CPM signaling scheme. The BCJR algorithm can provide optimum soft-output in the form of symbol-by-symbol a posterior probability (APP) based on the observations of entire transmitted sequence [5]. After the whole sequence is received, BCJR algorithm will perform both forward and backward recursions for making the decision. By using a Gaussian Markov phase model, phase estimates can be obtained in the forward recursion [4]. Since a small phase and frequency offset will cause bit error rate (BER) performance degradation, a joint phase tracking adaptive BCJR algorithm (which is termed as ABCJR algorithm) is developed for a preamble-based burst mode communication system, which already has initial synchronization. It simplified form, the Max-Log-ABCJR algorithm, reduces the system complexity and achieves a good BER performance.

Since the small frequency offset estimation error will cause a significant phase rotation at the end of data packet, the Max-log-ABCJR algorithm only works for short CPM packets. Also, in the fading environment, pilot symbol assisted modulation (PSAM) is implemented for channel state estimation. Because of the memory characteristics of CPM signals, the PSAM structure for linear modulation cannot be directly applied into CPM signals. At the end of each frame, the phase trellis is terminated to a known phase and then that known phase is transmitted during one symbol period. The PSAM structure for CPM signals is shown in Figure 9, where N_d is the number of information symbols per frame and N_p is the number of symbols per frame.

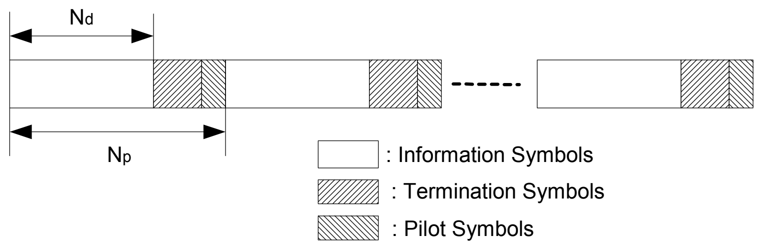

Figure 9: PSAM structure for CPM signals

Network Layer Overview

Design Goal

The narrowband infrastructure based network aims to provide both non-time-critical data services such as E-mails and real-time short message services such as bus location tracking. Two modes of operation are supported by the physical and MAC layer protocols. Standard packet switching wireless architectures can be supported by the system. In addition on the reverse link where bandwidth is scarcer due to the resource contention issues and the constraints on the power amplifier there is the ability to send short packets providing real-time information but no quality of service guarantees. This resource could provide real-time mobile unit tracking if the mobile unit sent GPS coordinates in these packets.

Configuration

The entire network is designed such that the infrastructure needs as little resources as possible. Figure 10 shows the hardware configuration of the network. Except for the wireless modems, only cheap networked computers are needed for the infrastructure. The portable computing devices on the MU side could be either laptop computers or handheld devices such as Pocket PCs.

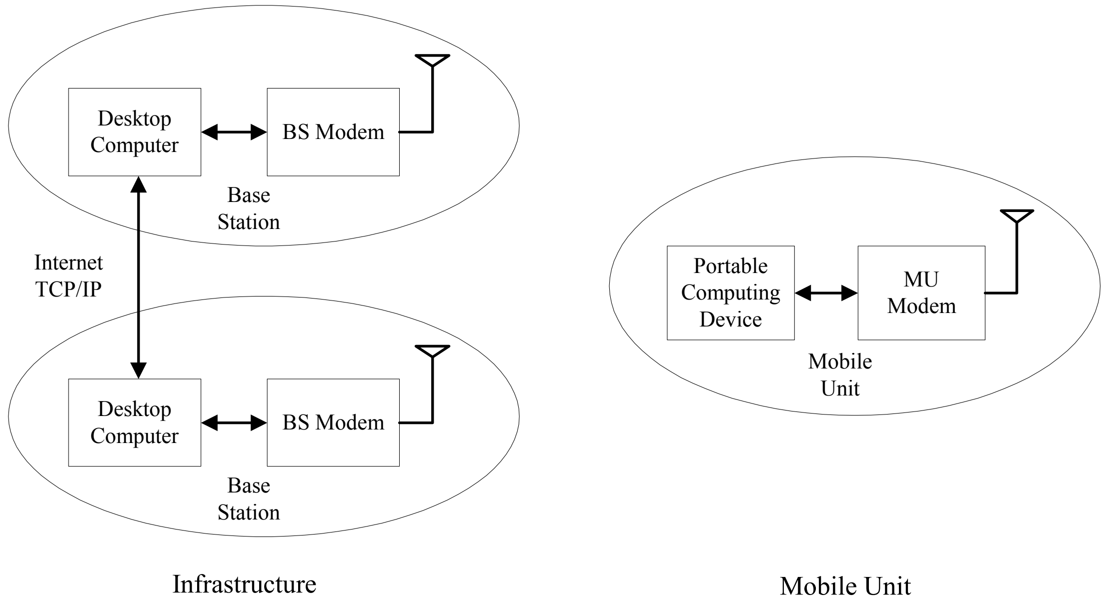

Figure 10. Hardware Configuration of the infrastructure based network

The network layer software is implemented in C/C++ and runs on the computers at both the BS and MU side. It interfaces with the physical layer through standard computer interfaces such as RS232, Parallel, and/or USB port depending on what physical hardware it interfaces with. This configuration allows easy implementation and upgrading while not sacrificing real-time performance significantly given the information rate that the Narrowband network typically supports. Another benefit of implementing network layer software on a personal computer is that inter-BS communications can be easily realized through Internet. This greatly saves the cost of implementing inter-cell hand-off both hardware-wise and software-wise.

Layered Structure

The designed network protocol has a clear-layered structure and functional separation for intra-cell operations and inter-cell operations. Figure 11 illustrates the overall network system. It has four basic components protocol-wise, i.e., home agents (HA), foreign agents (FA), mobile units (MU) and outside network. HA's and FA's are both at the base station side. The outside network could be Internet which typically serves as a service provider such as emails and do not need any customized development.

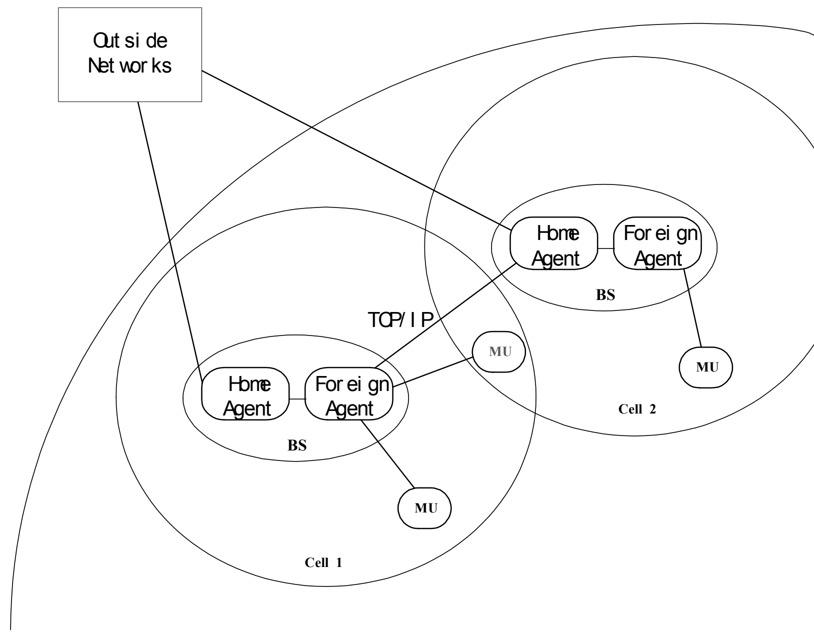

Figure 11. A two-cell narrowband wireless network

- Home Agent:
  The home agent has two different roles in this system. It serves as an application server which could be just a simple agent interacting with outside network or a real server providing services to the network. It is also responsible for forwarding application data to the appropriate foreign agent or collecting data from the foreign agent for a roaming mobile user. An HA communicates with the outside network or an FA at a different BS using the standard TCP/IP.

- Foreign Agent:
  The foreign agent mainly is a relay station between the home agent and mobile unit. From the HA's point of view, the FA provides reliable connections to it.

- Mobile Unit:
  A mobile unit communicates directly with the FA in the current Cell.

Figure 12 describes the structure of the network layer software. The network software is clearly divided into different modules and layers for different functions.

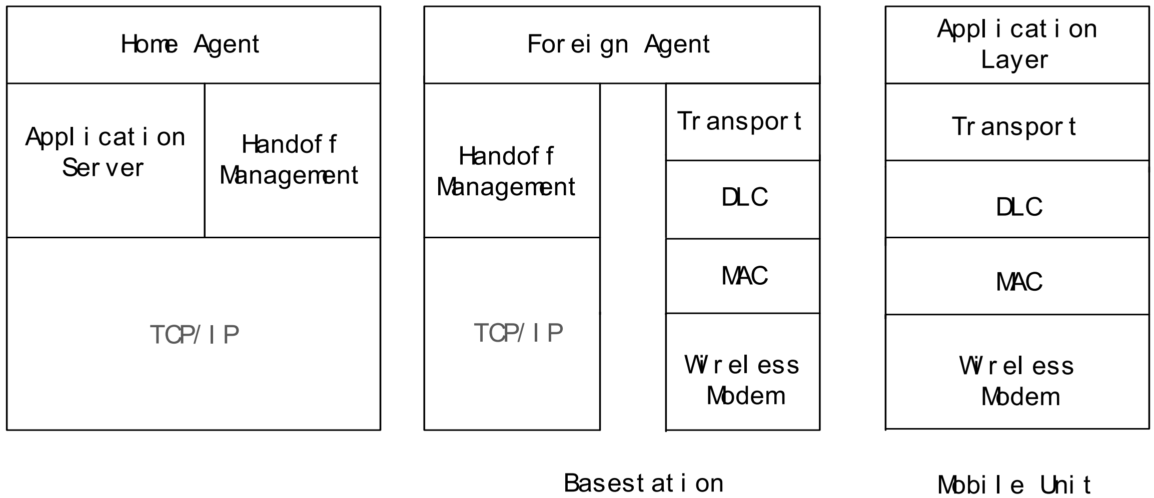

Figure 12 Layered Structure of The Network Software

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