System Architectures for Narrowband Reconnaissance Receivers and Beamforming Applications

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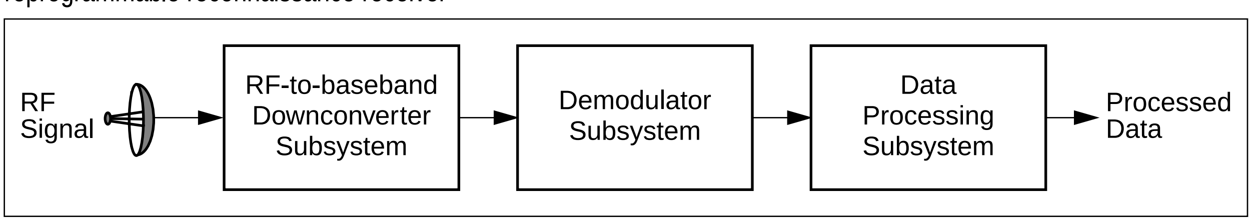
The rapid emergence and worldwide growth in single-channel-per-carrier communication systems has become a very important challenge to the reconnaissance community. New cellular, satellite, HF, VHF and UHF standards have led to high interest in flexible reconnaissance receivers that can be reprogrammed for different missions. Because of the number of different standards and variations in use around the world, mission specific hardware is no longer a practical solution to the reconnaissance problem. The complex and diverse signal environment demands that today's reconnaissance system engineer really does his homework. Development of a reprogrammable reconnaissance receiver requires a thorough examination of the processing requirements and a selection of system components that will provide the flexibility and processing power to handle the worst-case signal. Proper system architecture and selection of system components requires detailed knowledge of each signal to be processed. Each signal format generally requires unique processing because of differences in bandwidths, data rates, carrier spacing, modulation and data formats.

The advent of flexible digital tuners and programmable DSP technology provides the extensible platform on which to build reprogrammable reconnaissance receivers, but generic hardware alone is not the panacea for the country's challenging reconnaissance mission. This article provides an overview of system requirements and architecture issues for reconnaissance receiver applications including adaptive beamforming.

The requirements for a reconnaissance receiver are application specific, but often have a number of common requirements:

- Process multiple signals simultaneously: In battlefield applications, commanders are interested in monitoring many channels at the same time.
- Provide robust demodulation and data recovery: Often, the demodulation algorithms must perform better than the intended receiver since the signal may be severely distorted by multipath and low signal level caused by local terrain or distance.

Figure 1: Architecture of a flexible, reprogrammable reconnaissance receiver



Signal Parameter	Typical Range	Impact on Receiver
Number of channels to be monitored	Generally 10's–100's	Impacts the downconverter, the number of demodulators and the capacity of the data processing subsystem
Channel bandwidth	4 kHz to 2 Mbps	Impacts the bandwidth of each receiver
Channel spacing	4 kHz to 100's kHz	Determines the filter shape of the receiver
Dynamic Range	Generally >80 dB	Impacts the downconverter design
Bit rate	8 kbps to ~500 kbps	Impacts the demodulator hardware
Channel distortion	Benign to very severe multipath and co-channel interference	Impacts the complexity of the demodulator. Extensive equalization and robust demodulation algorithms may be necessary to recover the signal.
Modulation	• *Analog:* AM and FM • *Digital:* FSK, BPSK, QPSK, SQPSK, GMSK, CDMA • *Burst:* Push-to-talk, DMA/TDM and TDMA	Impacts the complexity of the demodulator
Data formatting	Every standard is different	FEC (forward error correction) decoding, descrambling, demultiplexing and message interpretation have big impact on the demodulator
Interference Rejection (beamforming)	The co-channel environment may be so severe that beamforming antennas are required to mitigate interference	Impacts the downconverter and demodulator. Requires that signals from multiple antennas be coherently downconverted and processed.
Direction Finding (DF)	Geographical location and direction finding may be part or the total goal of the mission.	Impacts the downconverter and demodulator in much the same way as beamforming. It may be necessary to demodulate the signal to determine if it is a signal of interest before DF'ing.

Table 1: Features of the signals of interest and their impact on the reconnaissance receiver design

- Operate in co-channel interference environments (either intentional jamming or incidental): In many cases, it may be important to recover the signal in severe co-channel environments where, because of the mission geometry, multiple users sharing the same frequency cause mutual interference at the reconnaissance receiver. Operation in co-channel interference environments often requires the use of specialized, high performance co-channel demodulation algorithms and/or beamforming antennas to suppress interferers.
- Direction Finding: It may be important to provide direction finding (DF) to geographically locate a specific radio source and possibly many sources simultaneously.

System Requirements

A flexible, reprogrammable system architecture can be partitioned into three subsystems:

- RF-to-baseband downconverter (tuner) subsystem: downconverts the RF signal to a band that can be processed by the demodulator subsystem.
- Demodulator subsystem: Demodulates the waveform to bits or an analog voice signal.
- Data processing subsystem: handles messages and control of the processed data.

Each of these subsystems must have the flexibility to process the signals of interest and the ability to be upgraded for new signals as they become important. The requirements of a flexible reconnaissance receiver are based on the formats of the target signals and other mission constraints. All signal parameters must be considered before specifying the operational ranges of the subsystem. Key signal features that must be considered and the impact on the receiver design are shown in Table 1.

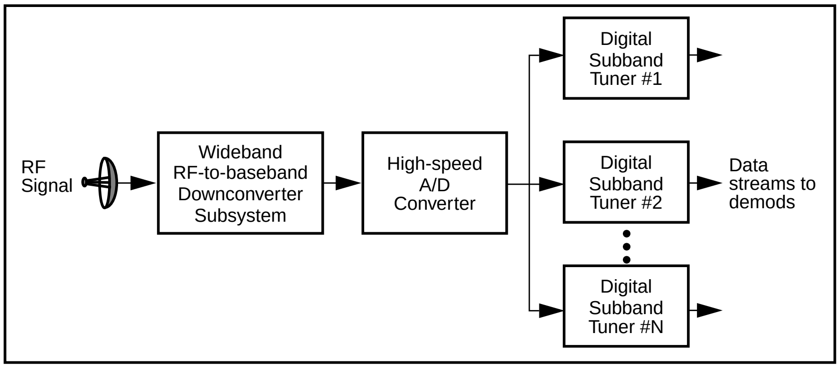


Figure 2: Block diagram of a downconverter subsystem utilizing a wideband block downconverter followed by a high-speed digitizer and bank of digital subband tuners (digital drop receivers)

System Architecture

After definition of the system requirements, the detailed subsystem architectures can be architected. The advent of high speed, wide dynamic range A/D converters and versatile digital subband tuners (drop receivers) has made the wideband block downconverter followed by narrowband subtuners very attractive architecture with regard to size, weight, power and performance. Figure 2 shows a block diagram of the RF-to-baseband downconverters used in Applied Signal Technology products. The wideband downconverter brings the entire RF band of interest to baseband. The signal is then digitized with high speed, high resolution A/D converters, e.g., 12-bit A/D converter operating at up to 65 MHz providing up to 80 dB of dynamic range. The drive to use the same architecture in commercial cellular and PCS base stations is fueling the marketplace to produce even higher performance A/Ds and subband tuners.

Digital tuner ASICs were pioneered by Applied Signal Technology in the late 1980s. They provide extremely compact subband tuning and filtering. Tuning resolution is less than 1 Hz and multiple signals can be coherently downconverted for beamforming and DF applications. Filtering is linear phase and is more than adequate to suppress adjacent channels in most scenarios. In addition, the tuned and filtered output signal is quad-downconverted and decimated to the Nyquist rate to reduce the load on the DSP processor.

The tuned, filtered and decimated signals are input to DSP-based demodulator subsystems. While a general purpose computer can be used for the demodulation, DSP processors have the computational horsepower and are architected to perform the operations needed for complex digital demodulation. DSP processors also provide smaller size, weight and power than general purpose CPUs.

A large component of the system design is the data processing subsystem. This subsystem handles system overhead functions including interpretation of data messages, control channels, activity detection, and data routing to store and forward subsystem and follow-on processors. Usually, a general purpose CPU is used for the data processing subsystem which also provides system command, control and the operator interface.

Beamforming Applications

While an omni-directional antenna senses the RF environment coming from all directions, beamforming antenna arrays combine the signals from multiple antennas to adjust the angular sensitivity to the RF environment. The DSP reconnaissance receiver provides an excellent platform to host advanced collection algorithms including beamforming. Beamforming has been a long-used strategy in military applications to detect or enhance the signal of interest and reduce co-channel interference.

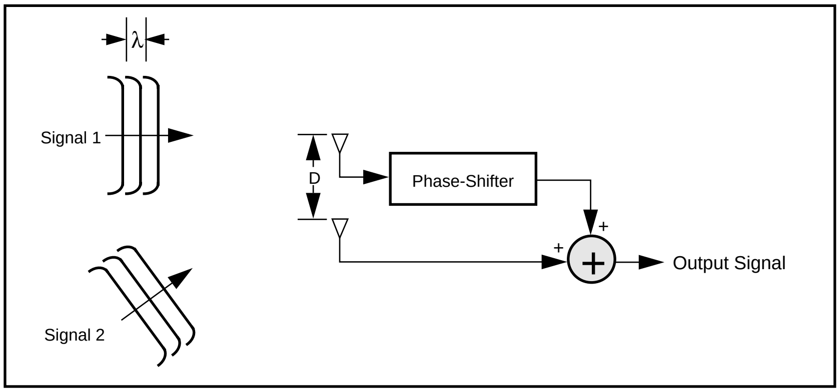


Figure 3: Illustration of the beamforming principle. The phase shifter can be adjusted to make the receiving system insensitive to either signal 1 or 2.

One of the advantages of beamforming and beamsteering antennas is the elimination of the mechanical motors and control.

Figure 3 illustrates the beamforming principle. Two signals impinge on a two-element antenna array. The antenna elements are separated by distance *D* and the signals have wavelength λ. Signal 1 impinges broadside to the array while signal 2 comes from 45 degrees off. The upper antenna output signal is phase shifted and added to the signal from the lower antenna. Signal 1 reaches both antennas at the same time while signal 2 reaches the upper antenna *D/c* seconds (*c* = speed of light) later than the lower antenna because of the additional distance traveled. If the phase-shifter shifts the phase of the signal by 180 degrees, the combiner (adder) cancels signal 1. Because it takes longer for signal 2 to reach the upper antenna, the combiner output for signal 2 is not fully attenuated. Consequently, the antenna array cancels signal 1 (i.e., puts a spatial null in the direction of signal 1) but passes signal 2. Similarly, the phase-shifter could be adjust differently to cancel signal 2 and pass signal 1 (i.e., steer a spatial null in the direction of signal 2).

Adaptive beamforming antennas are related to electronically beamsteering antennas. Electronic beamsteering antennas have a fixed beam pattern whose "look direction" can be controlled electronically. Essentially, these types of antenna arrays replace mechanically steerable narrow beam antennas. One of the advantages of beamforming and beamsteering antennas is the elimination of the mechanical motors and control. However, as with mechanically steerable narrow beam antennas, there are two major disadvantages to electronic beamsteering antennas for reconnaissance receiver applications: 1) the system is only sensitive to signals coming from the direction that the antenna is pointed, and 2) the antenna pointing angle may not be the best angle to optimize demodulator performance. For example, it may be better to point the antenna off target slightly to further suppress a strong interfering signal that is close in angle to the signal of interest. More modern beamforming antennas optimize the beam pattern to minimize the demodulated bit error rate rather than the look angle of the antenna array.

An example antenna beam patterns of an 8-element antenna beamforming system is shown in Figure 4. There are six co-channel signals. The signal of interest (SOI) arrives from 68 degrees. The signal to interference ratio (SINR) = –24 dB and the SOI is 34 dB weaker than the strongest signal. The contours show the relative sensitivity of the receiving system to signals from different directions. The beam pattern can be configured to make the system insensitive to signals arriving from specific directions, such as in the direction of interferers. In more modern beamforming and interference applications, the beamforming pattern is formed to minimize the bit error rate of the demodulated signal that adapts as the signal sources or the receiving platform moves. The beam pattern shown in Figure 4 was adapted from an omni-directional pattern after only 300 samples. After beamforming, the SOI SINR was about 17 dB.

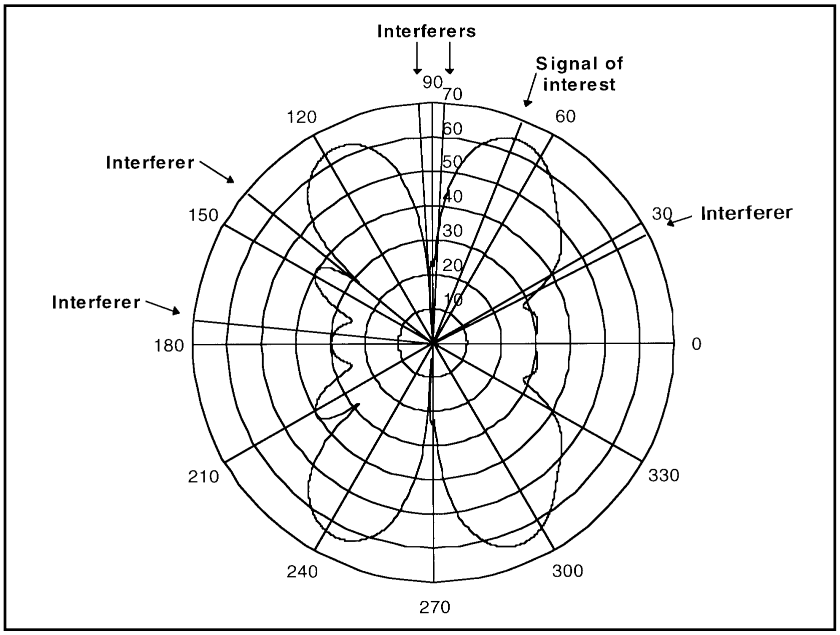


Figure 4: Examples of antenna beam patterns for an 8 element antenna array. Concentric circles represent signal sensitivity as a function of receive angle. Notice that the antenna system is insensitive to the interfering signals while relatively sensitive to signal of interest coming from 68 degrees.

In reconnaissance applications, the co-channel interference signal may come from another signal of interest. A major advantage of the adaptive beamformer over beamsteering antennas is that if antenna signals are available to more than one beamformer, more than one signal can be recovered simultaneously.

Adaptive beamforming can be performed on the signal at RF, IF or baseband. At baseband, the phase can be adjusted in DSP demodulator engines to perform the combining required to apply beamformer algorithms. This allows multiple signals to be recovered with the same antenna array.

System Components

Applied Signal Technology is one manufacturer of integrated reconnaissance systems as well as PC and VME card level components for processing a wide range of signal formats. One example of a DSP-based reconnaissance system is shown in Figures 5 and 6. The Model 1239 can be used for multiple mobile radio standards as well as supporting beamforming and DF algorithms. The Model 1239 is a high performance COTS VME-based processing system that integrates real-time, adaptive beamforming and interference cancellation with demodulation and signal processing functions. The system is able to mitigate co-channel interference in dense signal environments and dynamically track target signals. It uses an 8-channel, phase-coherent, tunable UHF downconverter. Preselection filters isolate the RF band of interest and additional bandpass filters provide the band-specific selection.

Figure 5: Block diagram of the Applied Signal Technology Model 1239.

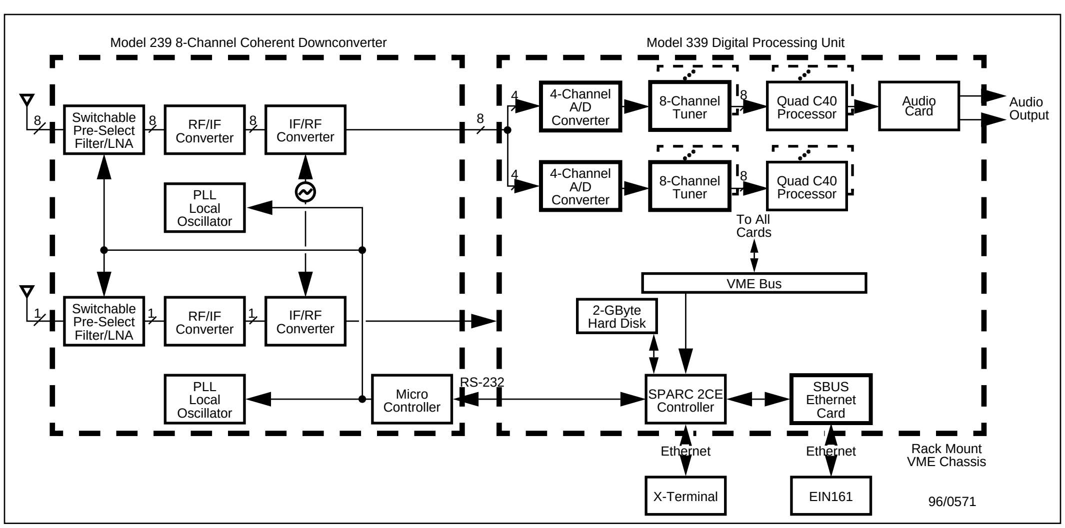


Figure 6: The Applied Signal Technology Model 1239 is capable of processing a wide range of signal formats. It also supports co-channel interference rejection.

Careful system analysis and application of advanced signal processing techniques are enabling the reconnaissance design engineers to utilize COTS boards and subsystems to meet the growing challenges of mission requirements.

The phase-coherent outputs of the down-converter drive the inputs to the COTS VME-based Digital Processing Unit. The IF signals are coherently digitized using the Applied Signal Technology B108D wideband digitizer cards with 12-bit A/D converters operating at 33.5 MHz. The digitized data are routed to Applied Signal Technology B108T sub-band tuner cards for specific channel tuning. Coherent baseband signals from the B108T tuners are passed to quad DSP boards for beamforming, demodulation, and control processing.

The beamforming is performed in the DSP engines at baseband. This allows multiple beamformers to operate in parallel. The eight channel beamformer can steer seven nulls in the direction of interferers while optimizing the beam pattern to receive the signal of interest. In addition, using special co-channel interference mitigation techniques, the Model 1239 system can extract up to four signals coming from the same direction.

Control and command processing is handled via an embedded SPARC processor. The user interface also operates on the SPARC and displayed either remotely or via keyboard and display connected directly to the Model 1239. Dynamic resource assignments maximize available resource usage.

The flexibility of the Model 1239 through software programmability, high dynamic range of the B108D digitizer card, fine resolution tuning of the B108T Digital Tuner card and efficient DSP boards make the Model 1239 an excellent example of an architecture programmable for a variety of applications. It has been programmed for operation against a number of signal formats including beamforming applications.

Conclusion

Reconnaissance receivers require flexible, reprogrammable equipment to meet the needs for processing current signals, including variants, as well as emerging signal formats of interest. Advances in commercial A/D, subband tuner, and DSP technology are providing a new generation of flexible, programmable hardware that is being utilized in reconnaissance receiving systems to monitor a wide range of signal formats. In addition, beamforming applications for interference rejection and direction finding are becoming more cost effective as they optimize beam patterns to minimize the bit-error-rate of the recovered signal. Careful system analysis and application of advanced signal processing techniques are enabling the reconnaissance design engineers to utilize COTS boards and subsystems to meet the growing challenges of mission requirements.

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