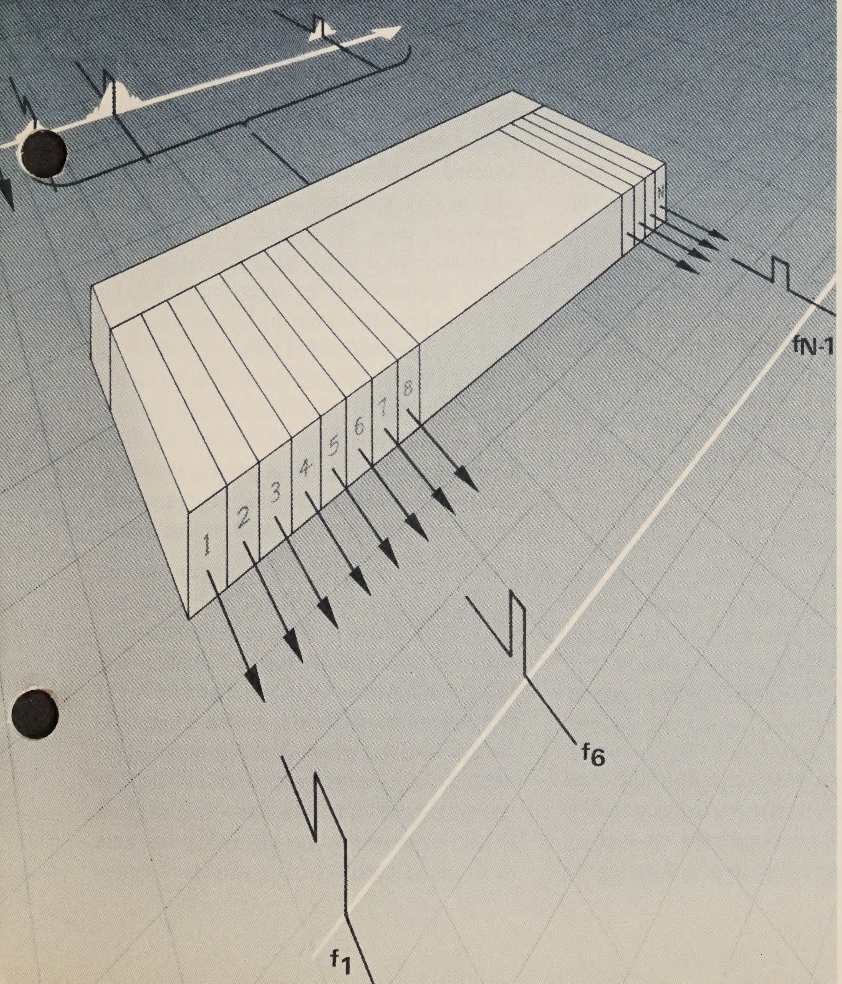
VOL 11 NO 4 JULY/AUGUST 1984

Competitive Receiver Technologies



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Tech-notes

Modern EW receivers employ a wide variety of techniques to meet highly diverse system requirements. At one end of the scale is the collection of high-fidelity information on exotic emitters, and at the other is the necessity to provide timely warning against weapons guidance systems. A diversity of challenges has led to the diversity of solutions, yet no one receiver simultaneously meets all requirements. The optimization of the receiver in its environment requires a familiarity with receiving systems in general. This article is intended to provide an overview of various technologies.

For purposes of discussion, the receivers described below accept rf input from rf distribution systems, and provide demodulated signals to a downstream signal processor. It should be stressed that choices and tradeoffs made in the rf distribution, receiver or processor all interact; therefore an analysis of the entire system is required. Nevertheless, receivers are often designed to meet specified performance criteria for sensitivity, probability-of-intercept, fidelity and physical characteristics. The ability of the receiver to extract the signal parameters of interest determines which of these characteristics deserves dominant consideration.

Each received pulse potentially provides the following information concerning the emitter:

- Frequency
- Received power
- Pulse duration
- Polarization
- Time of arrival
- Angle of arrival
- Characteristics of intrapulse modulation

If a group of pulses is intercepted from a single emitter, the pulse repetition interval may be determined, as well as possible characteristics of stagger and jitter. Again, many possible intrapulse variations may be determined, such as frequency agility, PRI agility, scan modulation, and many sorts of pulse modulations. If high-fidelity reception is required, appropriate attention must be given to the distortions generated by the tuner. The details of such distortions are beyond the scope of this article, but a discussion of fidelity parameters is given in Reference 1.

Selectivity

It is widely expected that the microwave environment will become increasingly complex as more sophisticated systems are deployed: Frequency and PRI agility will become common, as will spread-spectrum techniques and complex intrapulse modulations. In any operational environment, many radars ($>$ 100) may be operating simultaneously, as well as cw and other high-duty-factor signals. For low duty-cycle emitters (at $<<10^6$ pulses/second in-band), typically only individual short pulses are incident on the receiver (see Footnote 1). However, signals with a high duty-factor have a high probability of occurring simultaneously with any pulse of another signal. One method of receiving specific signals without interference is to select a narrow region of rf for consideration, and apply the detection and processing appropriate to the signals found within. Wide-open systems must devote considerable attention to the system response when pulse overlap occurs.

Sensitivity

Sensitivity refers to the minimum signal strength required. The ability of a system to detect a weak signal is limited by the noise energy that occupies the same portion of the frequency spectrum as does the signal, and the necessary signal power is defined in terms of the effective noise power at the receiver input. The effective noise power is given by a thermal-noise contribution multiplied by a degradation factor called the "noise figure" (NF):

$$N\ (\text{eff}) = -114\ \text{dBm/MHz} + 10 \log_{10} \text{BW}\ (\text{eff}) + \text{NF}\ (\text{dB})$$

where the effective noise bandwidth is commonly approximated by (see also Footnote 2)

$$\text{BW}\ (\text{eff}) = \sqrt{2\ (\text{BW}_{rf})\ (\text{BW}_{video})}$$

The criteria for what is an acceptable signal level is stated in terms of the minimum discernable signal (MDS) for which the signal power is equal to the effective noise power at the input. (Equivalently, an MDS is that signal which increases the receiver's output power by a factor of two.)

S (MDS) is defined by:

$$10 \log_{10} \left\{ \frac{P_{out}\ (S_{MDS} + N)}{P_{out}\ (N\ \text{only})} \right\} = 3\ \text{dB}$$

There are two dominant requirements establishing the required signal strength for any system employing automatic detection:

1. The threshold must be high enough so that false alarms are not generated at a rate which overloads the signal processing equipment.
2. The minimum required input signal must be detected with a certain specified probability.

An attempt to threshold at MDS would produce far too many false alarms, thus a typical detection level is set 14 dB above MDS. Most parameter measurements require even more signal strength; often the accuracy of the measurement improves as the square root of the noise-to-signal ratio. Reference 3 contains an excellent discussion of detectability and false alarm rate.

Several advantages are realized by a highly sensitive system: Signals can be detected at greater range and, therefore, more signals are available for processing. Measurement accuracy is improved as the signal-to-noise ratio improves. There is the possibility of detecting an emitter through the backlobes or sidelobes of a rotating antenna and, therefore, improve the probability-of-interception (POI). With the advantages come certain disadvantages: Greater signal density imposes a greater burden on the signal processor. Extraneous multipath reflections of the primary signal can also break threshold and clog the system with undesired spurious data. Often, higher sensitivity is obtained by narrowing the system bandwidth, or narrowing the antenna beamwidth. Both of these techniques reduce the probability-of-intercept and degrade the capability to measure simultaneous or correlated signals not sharing identical frequency.

Probability-of-Intercept

Each receiving system is characterized by different limitations regarding the probability-to-intercept a signal. Systems which are wide-open in rf suffer from problems arising from pulse overlap or in-band cw signals. Systems which employ narrowband rf or narrow beamwidth require time to search for, and acquire the desired signal. There are two complementary ways to specify the problem: Either determine the time required to obtain a given probability-of-intercept, or calculate the probability-of-intercept for a given observation time. For example, for a scanning superheterodyne receiver, the intercept time (probability) will be determined by the receiver bandwidth, the receiver scan rate, the emitter bandwidth, emitter PRI, emitter pulse duration, and the number of pulses required. For receivers and transmitters associated with rotating antennas, the antenna scan rates and beamwidths must be included in the calculation as well as the receiver sensitivity. An intercept study must be used to determine the tradeoffs between antenna and receiver parameters for a certain set of targetted emitters. A simple model has recently been published which allows a straightforward calculation of the intercept time (probability) using the above considerations as input (Reference 4).

The following paragraphs describe receiver types in sequence, together with a brief discussion of their attributes. Comments of this type are subjective, and specific systems may exceed the stated parameters or avoid the obvious problems. Nevertheless, a general discussion offers an overview and a compact way of viewing a large amount of information. References are given to supplement the limited discussion.

Crystal Video Receivers

The typical wideband crystal video configuration consists of an rf bandpass filter with an optional low-noise rf

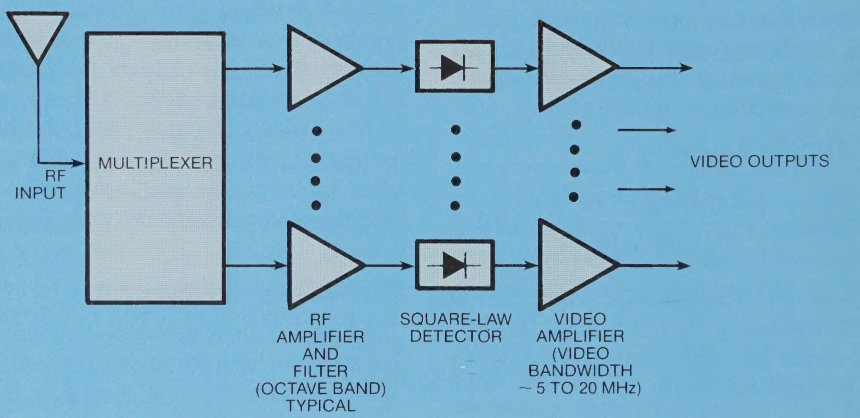

Figure 1A. Typical wideband crystal video configurations consist of an rf subdivision followed by an optional low-noise rf amplifier, a square-law video detector, and a log video amplifier.

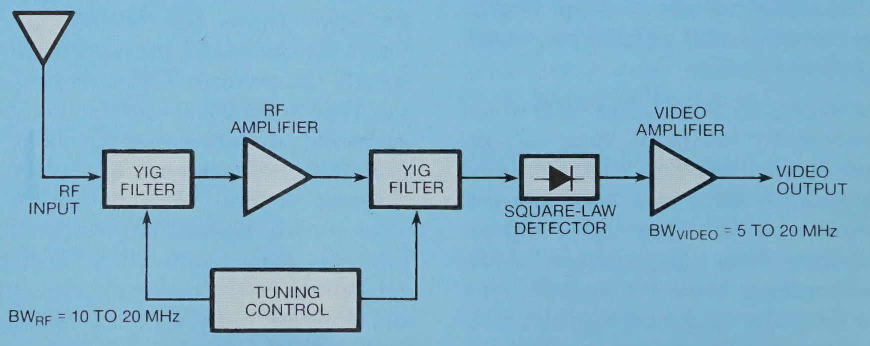

Figure 1B. Improvements in crystal video sensitivity and selectivity may be made by using a tunable rf filter to narrow the rf bandwidth.

amplifier, a square-law video detector, and a log video amplifier, as shown in Figure 1. The combination of octave rf bandwidth and 10 to 20 MHz video bandwidth results in an effective noise bandwidth on the order of 200 to 400 MHz, with the noise figure set by the rf amplifier. Without amplification the sensitivity is low (-40 to -50 dBm), but can be improved (-70 to -80 dBm) with the amplifiers. Probability-of-intercept is excellent for sufficiently strong signals, however, there is no frequency selectivity or resolution. The detection process does not preserve phase information, so that it is not possible to sort signals based on frequency or phase modulation. The lack of detailed information implies that a processor may have difficulty not only determining how many signals are present, but also in correctly identifying the signal type.

A possibility for improving the sensitivity and selectivity is to use a tunable narrowband filter with rf amplification. The type of receiver that uses this technique is called a TRF (tunable radio frequency) receiver, but is not common because a superheterodyne approach enhances performance. In this case, the sensitivity can be made much better (-80 or -90 dBm), but at the cost of degrading the probability-of-intercept. The narrow bandwidth reduces the effective density of signals. Also, there is a better probability that a measurement is valid, and the rf selectivity corresponds to the bandwidth. Such systems are only slightly more complex than the wideband version, and are often used for low-cost ESM equipment, or as a narrowband channel together with a wide-open receiver. Another possibility involves subdividing the rf band into sub-bands prior to detection. In effect, this creates a channelized receiver for which the signal density per channel is low, but the associated cost and complexity are significantly higher.

Crystal video receivers form the foundation of radar warning receiver technology, being small and simple enough to install on tactical aircraft. As threat complexity and density increase, their ability to provide adequate notification of threat signals is severely challenged, and has often resulted in combined use with other receiver types.

Superheterodyne Receivers

Superheterodyne receivers typically consist of a tunable rf bandpass filter, followed by a frequency conversion to IF, as shown in Figure 2. A narrowband IF amplifier and filter determines the processing bandwidth, and is followed by any of a variety of detectors. In a narrowband configuration, the rf bandwidth is typically 15 to 50 MHz, and, for microwave receivers, the IF bandwidth is 1 to 20 MHz. These receivers achieve the maximum sensitivity possible (-100 dBm) by a combination of the narrowest bandwidths and low-noise amplifiers. The probability-of-intercept is low, since only a small portion of the rf spectrum is viewed, however the high sensitivity frequently compensates by allowing detection of emitter antenna sidelobes. For a scanning superhet, performance is best against cw or high duty-cycle emitters, and worst against low duty-cycle emitters. The maximum instantaneous bandwidth of the receiver sets the search speed limitation, since the receiver must dwell long enough at each frequency to assure an intercept from the potential signal having the longest PRI of interest. Search time can be decreased if *a priori* information is used to avoid searching frequencies with low probabilities of activity. Furthermore, dwell time may be optimized to the signal characteristics expected within each tuner step.

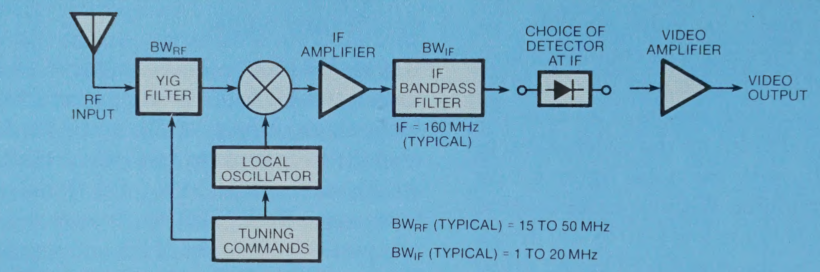

Figure 2A. Superheterodyne receivers typically consist of an rf bandpass filter, followed by a frequency downconversion to an intermediate frequency. A narrowband IF filter and amplifier set the processing bandwidth, and may be followed by a variety of detectors.

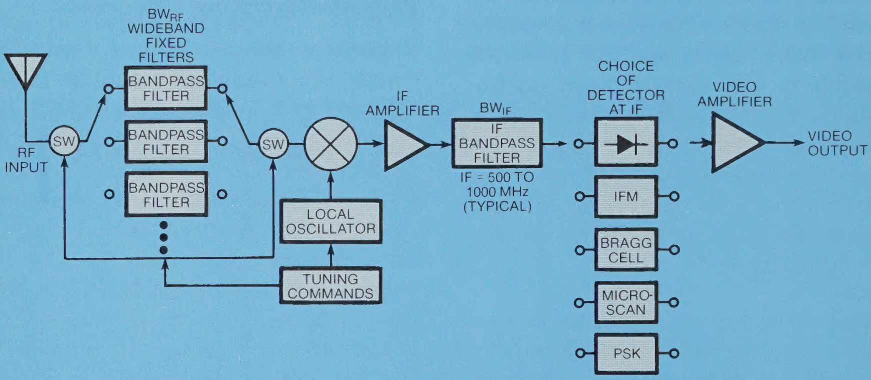

Figure 2B. Wideband superheterodyne receivers employ fixed selectable filters to perform the rf selection, and the intermediate frequency is higher to accommodate the increased bandwidth. A broad selection of processors and demodulators may be utilized. Such a receiver may be configured to detect broadband or spread spectrum transmissions, or to process many signals simultaneously.

As with sensitivity, superhets also set the standard for the available fidelity. The selectivity and resolution are excellent, limited by the IF filter and the LO step size. Phase information is preserved at IF, and a selectable IF bandwidth allows the choice of detector appropriate to the signal type. Several superhets scanning together can form an excellent high-fidelity system for ELINT purposes, to mention only one of their universal applications.

Another configuration that is becoming widely applied is the wideband superhet receiver. In this case the rf bandwidth is defined by a switched set of filters (typically having 500 to 1000 MHz bandwidth), followed by the usual frequency conversion to IF. Typical IF frequencies are higher than the narrowband case due to the increased processing bandwidth. In this configuration, all the components in the IF amplifier, filter and detector must support the increased bandwidth. In this case, some sensitivity degradation arises from the wider bandwidth; however, the probability-of-intercept is much larger (or the time to intercept smaller), and the receiver has the capability of processing frequency-agile or spread-spectrum signals.

The cost of a narrowband superhet receiver is relatively low per unit;

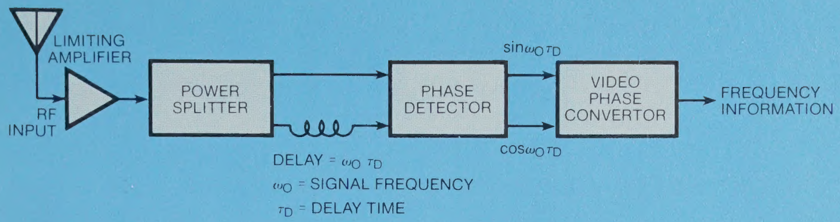

Figure 3. Instantaneous frequency measurement using a phase detector is conceptually simple: the incident signal is split into two paths, one of which is delayed by a known, frequency-dependent amount. The relative phase of the two paths is measured in a phase detector, and the output is converted to frequency information.

however, typical installations employ an entire set, so that the cost per system for narrowband tuners is comparable to the rather high cost of a single wideband tuner.

Instantaneous Frequency Measurement (IFM)

The IFM receiver employs a delay line frequency discriminator to provide an instantaneous indication of signal frequency. In this receiver, a second signal path is used to generate a signal whose phase is offset by an amount proportional to the incident signal frequency. Signal frequency is then obtained from the output of a phase detector. The inherent dynamic range of the phase detector is low, requiring a limiting amplifier at the input to compress the amplitude of the input signal, while preserving the phase information. Two broad classes of IFM exist, digital and analog. The analog devices are at least conceptually simple, as shown in Figure 3. Digital IFM devices typically consist of a group of parallel delay-line discriminators that instantaneously digitize the frequency in increasingly fine resolution, controlling the periodicity in the discriminator characteristic by changing the length of the delay line. Reference 5 contains a detailed discussion of digital IFM techniques and performance.

Similar to the crystal video receiver, the IFM has a probability-of-intercept approaching 100% within the rf passband. The sensitivity is limited by the noise produced by the processing bandwidth (-40 to -50 dBm without limiting amplifiers, -70 to -80 dBm with amplification). The major problem associated with IFMs is their susceptibility to errors produced by overlapping pulses. The response to simultaneous pulses at different rf is "somewhere in between," and is usually too complicated to sort out, since it depends (at least) on the relative amplitude of the pulses. The environment does not need very many high duty-cycle emitters before the probability of pulse overlaps become significant. The presence of a cw signal assures that every pulse will be overlapping, and the response therefore corrupted. Since accurate knowledge of the rf provides such a strong sorting parameter, much effort has gone into improving the IFM performance in dense environments.

One approach is to channelize the inputs to the IFM devices. This can be accomplished at rf by an array of bandpass filters, for example dividing the rf into 2-GHz segments. Three generic possibilities can then be used:

1. Amplify at rf (approximately 60-dB dynamic-range compression is

CHANNELIZED RF:

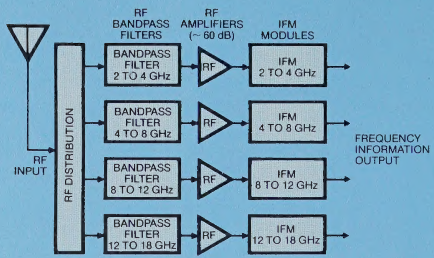

Figure 4A. Improvements to IFM performance in dense environments may be made by subdividing the rf input into bands and processing each band individually. One possibility is to amplify and perform the IFM detection at rf. This configuration requires dynamic range compression of approximately 60 dB, and employs a set of IFM modules which operate at different frequencies.

CONTIGUOUS SUPERHETS:

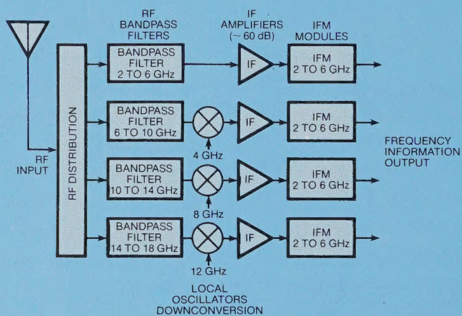

Figure 4B. A second approach is to channelize the rf and perform a frequency downconversion to IF, where the IF amplifiers and IFM modules are all identical. This configuration enhances the similarity of response between channels, but requires a local oscillator for each conversion.

BAND-FOLDED SUPERHET:

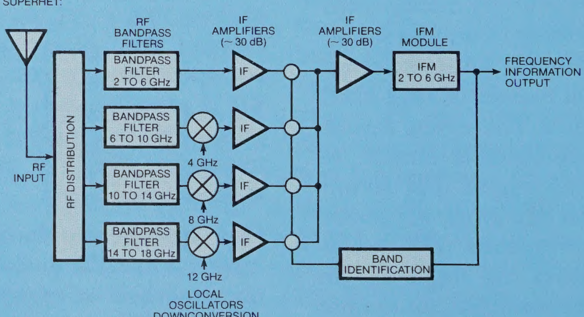

Figure 4C. A third approach is to channelize and downconvert as above, but to split the amplification into two stages. After the first stage, the occupied channel is detected and identified, and the IF signal paths are combined into one IFM module. Substantial savings in components are realized, however the IFM device sees noise generated from all channels, and the maximum sensitivity is degraded.

needed, as shown in Figure 4A). In this approach, the IFM modules are different from each other, and must work at microwave frequency.

2. Another technique is to downconvert the channelized rf to a common wideband IF, and perform the amplification at IF, as shown in Figure 4B. Not only is this cheaper, but the IF amplifiers and IFM modules are identical, and can therefore be matched in performance (at the cost of a set of local oscillators).

3. A considerable savings can be realized by band-folding the IF stage of the downconverted channels as shown in Figure 4C. In this case, the IF amplifiers can be cascaded to reduce the gain compression requirement of a single stage (about 60 dB) to a more easily realizable 30 dB per stage. In this case, the rf band is tagged, and a single IFM module performs the frequency measurement. This approach is less expensive than preserving individual channels, but suffers from two drawbacks: Noise from the entire rf bandwidth is continuously applied to the IFM module, which degrades the available sensitivity. Also, the band tagging allows one to know when two pulses are incident, but does not prevent the IFM from producing a spurious output.

Microscan Compressive Receivers

The microscan receiver is a type of superheterodyne receiver that can simultaneously achieve a high probability-of-intercept for both cw and pulsed signals. The receiver consists of an rf bandpass filter followed by a swept-local-oscillator conversion, as shown in Figure 5. The IF is passed through a dispersive filter which maps the IF frequency into a time delay. During the duration of a single pulse, the LO must be swept through the entire region of interest. The IF during the pulse will then change linearly, proportional to the frequency difference between the primary rf and the changing LO. This changing frequency signal then encounters a frequency-dependent delay which is arranged so that all the energy emerges from the filter output at one time, producing a sharp pulse whose onset time (measured

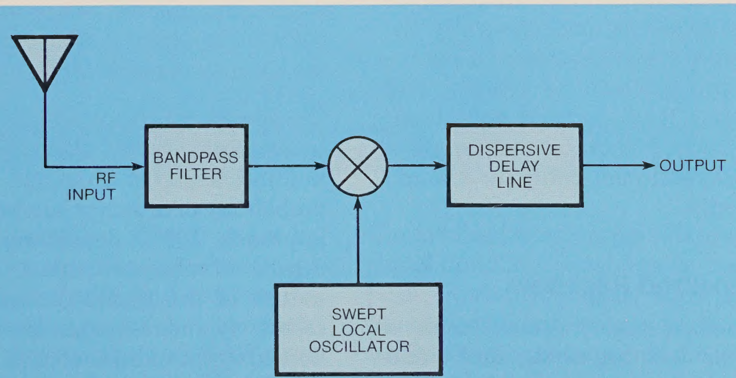

Figure 5. Microscan compressive receivers operate by sweeping a local oscillator to produce a time-varying IF during the signal pulse. A dispersive filter maps the IF frequency into a time delay, such that the signal energy appears as a very short pulse at the filter output. The time offset at the filter output is proportional to the rf frequency of the signal.

from the LO sweep start time) is proportional to the rf frequency.

High POI is achieved by sweeping the LO in a period shorter than the duration of the shortest pulses of interest. Herein lies the difficulty: A wide region of rf containing short pulses implies that the LO must sweep at an extremely high rate, and the processor which measures the output time must be able to keep up with the output during the duration of the shortest pulse. For ELINT purposes, where many trains of short pulses abound, the data rate from the filter places severe demands on the digitization and pulse processor. These receivers typically perform better in COMINT applications, where longer pulse durations ease the difficulties.

The sensitivity of a microscan receiver is similar to a comparable bandwidth superhet, and the probability-of-intercept can be made very high for limited regions of rf. The pulse shape at the output is completely altered by the compression, and the phase and frequency modulation characteristics of the signal are highly distorted. The selectivity and resolution are good (limited by the ability to resolve the leading edge of the output pulse), and the system can process simultaneous cw and pulsed signals. Generally, the receivers are relatively low cost, but the associated processor is complex and expensive. Typical applications occur where the high probability-of-intercept and high resolution justify the cost and complexity.

Channelized Receivers

Channelized receivers subdivide the rf spectrum into segments, and simultaneously downconvert each channel to a common IF. The rf breakdown is accomplished by banks of contiguous filters, each mixed with a fixed frequency local oscillator. Each channel becomes, in effect, a fixed-tune superhet receiver, and preserves the high sensitivity and fidelity associated with a superhet receiver. The brute force approach is to place a processor on every channel, but this leads to high cost and volume, so that successful implementation depends on allocating processing power to fewer channels, time shared or multiplexed to bring down the number of components. The basic architecture and operation is shown in Figure 6.

One straightforward approach is to channelize fairly coarsely (say in 500-MHz increments), and use the presence of a hit in a coarse channel to tune a local oscillator such that the active channel undergoes a second conversion to an IF, where a set of specialized detection processors can analyze the signal. For instance, an acousto-optical processor, microscan receiver, or IFM could make precision measurements on the contents of the selected channel.

The channelization schemes fall into the same basic categories as were mentioned in the IFM section: Brute force (detectors for every channel), band-folding (where the channels are tagged and the set of IF signals are summed), or time-multiplexed (where the downstream processor is time-switched to the channel of interest).

The sensitivity of channelized receivers is excellent, since they consist of multiple superhet channels, and the probability-of-intercept can be made to approach 100%, depending on the degree of channelization, and the nature of the signal processor. The selectivity and resolution are excellent, limited by the number of channels, and the fidelity is again similar to a superhet. Obviously, in a dense environment, a channelized receiver can produce a staggering data rate, and sophisticated processing techniques

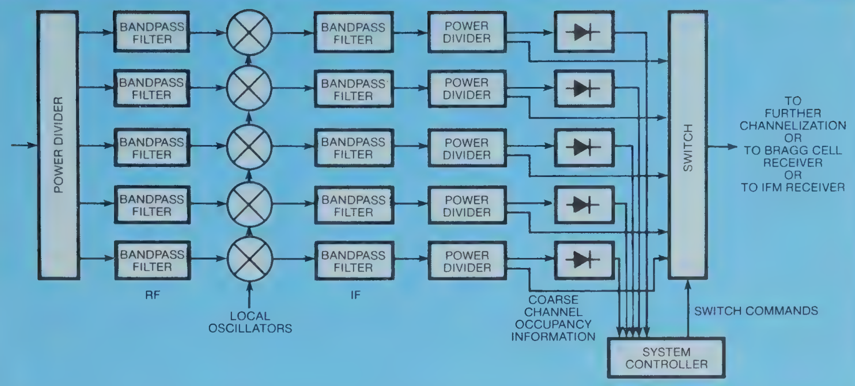

Figure 6A. A channelized receiver subdivides the rf spectrum and performs individual frequency conversions on each channel. Typically, detectors will be placed on each coarse channel to determine occupancy, and the coarsly channelized signals will be processed further by switching the occupied channel into a precision measurement device such as a Bragg cell receiver or frequency discriminator.

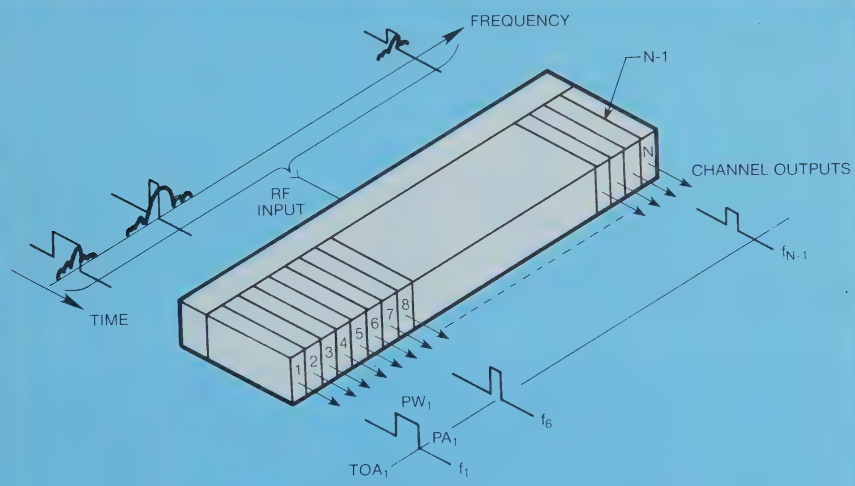

Figure 6B. The operation of a channelized receiver allows simultaneous signals to be processed through individual signal paths.

(such as adaptive filters) may be required to sort for the signals of interest. Complexity and cost can be high, depending on the sophistication; however, developments in SAW-filter technology have dramatically lowered the cost for moderate systems. A more detailed discussion of channelizer design and SAW technology is found in References 6-8.

Channelized receivers provide multiple signal-handling capability to remove pulse overlap problems, while maintaining sensitivity over a wide bandwidth. The amount of signal processing can be arbitrarily large, encompassing IFM technology, acousto-optical processing, or whatever demodulation is necessary. The problem with channelizers is not so much limitations in

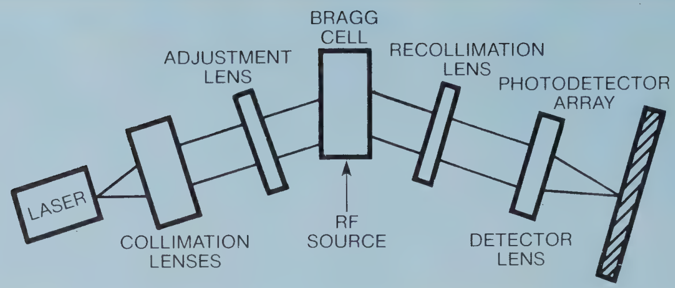

Figure 7A. A Bragg cell receiver consists of a laser source passing through a crystal material which is acoustically excited by an rf signal.

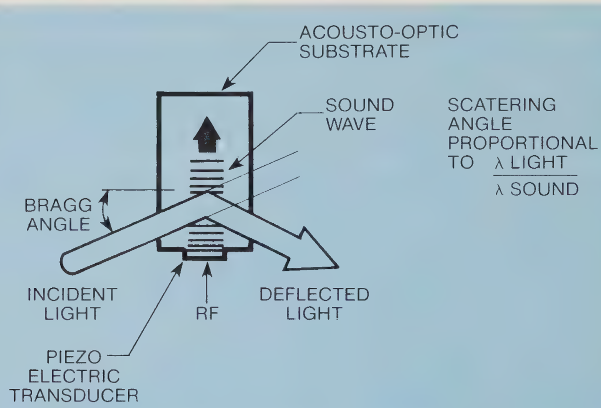

Figure 7B. The laser light is scattered through an angle proportional to the ratio of the wavelengths of light and source in the crystal. The scattered light is collected onto a photosensitive array, which is read out electronically.

capability, but how to extract the maximum performance within a fixed volume, power or cost budget. These receivers are often used in large systems where high probability-of-intercept, and high fidelity justify the investment.

Acousto-Optical Processors

Acousto-optical processors make use of the interaction between a sound wave and light propagating through a crystal to provide spectral analysis of the signal. Certain crystals support acoustic waves in the GHz range, and when a laser source is shined through the crystal, the light beam is scattered through an angle proportional to the ratio of the wavelengths of light to sound. The scattering angle (Bragg angle) corresponds to constructive interference in the reflection of light from successive wavefronts of the sonic wave. The coherent, monochromatic light is supplied at a fixed wavelength by a laser, and the sound wave is supplied by the rf stimulating the crystal through a piezoelectric transducer. The acoustic wave affects the index of refraction, such that the Bragg angle is modulated by the rf. After passing through the crystal, the light is collected by a photosensitive array, and read out electrically, as depicted in Figure 7. The electrical analog to the system would consist of a bank of

1-MHz filters simultaneously feeding a capacitor-diode readout chain, readout by a commutating switch.

The Bragg-cell receiving system usually consists of a tuner or channelized front-end supplying a Bragg cell IF processor. The output at the photodiodes is proportional to the frequency spectrum of the applied IF, leading to the term "Instantaneous Fourier Transform receiver." This system has the capacity to process a large number of signals simultaneously, including concurrent cw and pulsed signals with frequency agility. The major problem is that the readout is difficult to arrange, and rather slow. In the case of integrating photoarrays, pulse width information is lost. Sensitivity limitations and frequency resolution are primarily limited by the state-of-the-art in photodetecting arrays. Current performance is roughly 1-MHz frequency resolution per 1-GHz rf bandwidth.

The primary attraction of the Bragg cell processor is that it allows a wide portion of the rf (or IF) to be analyzed instantaneously, while obtaining good resolution at the output. Thus, there is a good deal of recent activity in this field: To improve the photosensitive readout, to integrate the laser with the Bragg cell, and to improve properties of the crystal. A discussion of a current system is found in Reference 9. Receivers of this type are currently in use as IF processors, and due to rapid advances in performance are likely to find further applications in the near future.

Conclusion

The major conclusion of this overview is that there is no "free lunch." Almost any of the receiver performance factors can be optimized, with corresponding cost or complexity. The optimization will involve tradeoffs involving not only the receiver, but also the rf distribution and signal processor. Generally, a careful analysis must determine whether the system in question can perform its job in the environment where it must operate. A summary of the discussion is given in Table 1.

	Wideband Crystal Video	Narrowband Crystal Video	Narrowband Superhet	Wideband Superhet	Wideband IFM	Narrowband IFM	Microscan	Channelized	Acousto-Optic Bragg Cell
Sensitivity	Poor/Fair	Good	Excellent	Good	Poor	Excellent	Excellent	Excellent	Good
Probability of Intercept	100% Inband[1]	Poor	Fair	Better	100%[2]	Fair to Good	Excellent	Excellent	Excellent
Resolution/ Selectivity	None	Fair	Excellent	Excellent	None	Good	Good	Excellent	Excellent
Fidelity	Poor	Better	Excellent	Good	Good	Good	Poor	Excellent	Poor
Physical	Cheap/ Simple Small	Only slightly worse than wideband	Low per unit moderate per system	Moderate per unit	Moderate	Moderate	Complex expensive	Moderate to high cost — can be very complex	Variable (state-of-the-art) can be used as processor in channelized system

NOTES:
1. Corrupted by pulse overlaps, does not work in dense environment.
2. CW in band causes errors — works well in low density environment.

Table 1. Overview of receiver performance factors.

Footnotes

1. The pulse overlap probability can be calculated by assuming the probability that a pulse will arrive within a specified interval follows a Poisson distribution. Assuming a pulse density of 5×10^6 pulses per second, with an average pulse width of 0.5 μseconds produces the estimate that the probability that two or more pulses will overlap in a given interval is 71%, and that 4 of the 5 million pulses will be overlapped.

2. A more accurate representation of effective noise bandwidth can be derived from Reference 2:

   For Square Law Detectors:

$$BW_{eff} = BW_{video} \left\{ 1 + \left[\frac{2\, BW_{rf}}{6.3\, BW_{video}} \left(1 - \frac{BW_{video}}{2\, BW_{rf}} \right) \right]^{1/2} \right\}$$

   For Linear Detectors:

$$BW_{eff} = \frac{BW_{video}}{2} \left\{ 1 + \left[1 + \frac{8\, BW_{rf}}{6.3\, BW_{video}} \right]^{1/2} \right\}$$

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 Printed in U.S.A.