Advances in SAW technology

The latest in surface acoustic wave technology meets the demands of miniaturization, dependability and economics.

By Darrell L. Ash

In today's world, “going wireless” is associated with eliminating cumbersome wires and cables; making it possible to roam untethered anytime, anywhere, with fully operational systems.

There are three basic wireless systems in the modern market. One is represented by cellular phone systems, including systems that have a range of as long as several kilometers (such as cellular phone systems). The second is represented by two intermediate-range unlicensed systems: spread-spectrum systems and narrowband systems. Such systems have a typical range of 300 meters or more, due to higher transmitter power (up to 1 W) for spread-spectrum links, and greater receiver sensitivity (–115 to –110 dBm) for narrowband links. The third is the short-range unlicensed system that has a typical range of 1 to 100 meters.

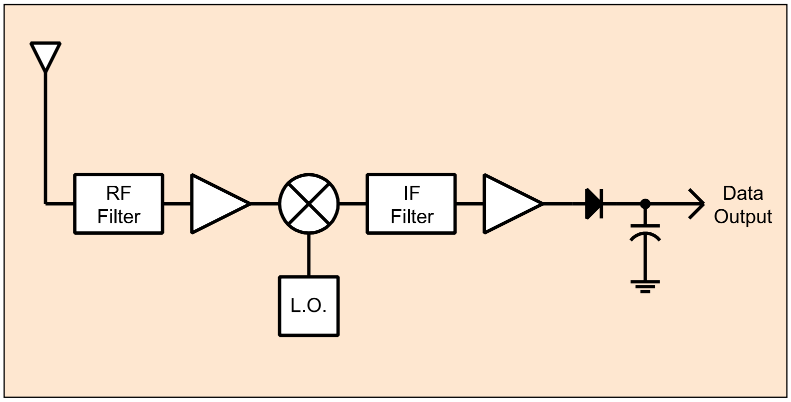

Figure 1. A diagram of a simple, single-conversion superheterodyne receiver.

The variety of applications for short-range wireless systems surpasses that of the long-and intermediate-range systems. Short-range applications include automotive keyless entry, garage door and gate openers, wireless security systems, data links, wireless barcode readers, electronic personal ID, remote meter reading, animal tagging, in-house arrest systems, wireless keyboards, wireless mice and wireless joysticks, among others.

Some desired attributes of the receivers and transmitters used in these short-range systems include low-cost, low-power consumption, miniature size, no adjustments, good frequency stability, good range, the ability to operate in a crowded frequency spectrum and ease of application by engineers with limited RF training. One of the more stringent applications requires a receiver and a transmitter to be included in a small wristwatch.

To meet these stringent TX/RX specifications, surface acoustic wave (SAW) technology has risen to the challenge.

Current TX/RX technologies

- *Transmitters*

Current low-power transmitters primarily include either SAW-stabilized oscillators or crystal-stabilized frequency synthesizers. Crystal-stabilized frequency synthesizers have greater frequency accuracy than SAW transmitters, but consume more power, have more spurious frequencies, are physically larger and cost more. The bulk crystals used as the frequency reference for such synthesizers are also fragile and frequently break when subjected to drops or impact.

SAW-based transmitters are rugged in comparison. Cost, power consumption, size and ruggedness are the most critical requirements for such step recovery diode (SRD) transmitters. The additional cost, power consumption, fragility and size of frequency synthesizers are only justified if the system uses a narrowband receiver that requires additional frequency accuracy.

- *Receivers*

The most popular current receiver technologies are the super-regenerative, superheterodyne and amplifier-sequenced hybrid (ASH) receivers. The inductor/capacitor (LC)-based super-regenerative receivers are rapidly being replaced by the other two receiver technologies. This is due to the poor frequency stability, reliability and out-of-band rejection of unwanted signals of the earlier designs. Desirable attributes of the super-regenerative receiver are low power consumption and low cost.

- **Superheterodyne –** Figure 1 shows a block diagram of a simple, single-conversion superheterodyne receiver. This receiver achieves the stable gain necessary to achieve high sensitivity through simple frequency diversity. Because the RF and IF amplifiers are not at the same frequency, feedback from the IF amplifier output to the RF amplifier input does not cause a stability problem. Even more stable gain can be added by increasing the number of conversions or IFs. In addition, more rejection of unwanted signals is achieved by splitting the filtering between RF and IF filters, thus eliminating the crosstalk that occurs when filters are cascaded at the same frequency. As a result, this receiver architecture achieves good sensitivity and good out-of-band rejection. If the RF filter is wide enough, or is tunable, varying the local oscillator frequency can change the reception frequency of this receiver. One significant disadvantage is that frequency selectivity in the RF filter must be compromised to allow frequency agility. Other disadvantages include relatively large physical size, high power consumption, the need for a stable local oscillator, oscillator radiation, mixer spurious responses (especially the image frequency) and critical circuit-board layout.

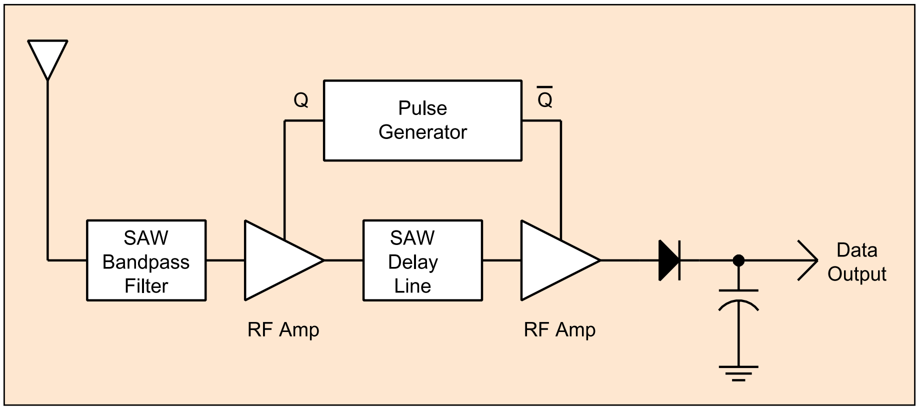

Figure 2. ASH simplified block diagram.

The relatively large physical size is due to the need for a SAW device or a crystal to stabilize the local oscillator; a SAW or other technology for an RF filter; and a SAW, ceramic or LC IF filter. The IF filter can be large because of its relatively low frequency. The high power consumption is primarily due to the need for the local oscillator to develop an RF level high enough to drive the mixer into non-linearity while minimizing intermodulation and cross-modulation distortion in the mixer.

- **Amplifier-sequenced hybrid receiver** – Figure 2 shows a simplified block diagram of this receiver's architecture. This receiver achieves the stable gain necessary to obtain high sensitivity through time diversity. The high-gain RF amplifiers, on each side of the SAW delay line, are turned on and off by a pulse generator. When one amplifier is on, the other is off and vice versa.

Because the two amplifiers are not on at the same time, feedback from one amplifier to the other does not cause the circuit to become unstable. The delay line serves as a storage element; supplying signal to the second amplifier while the first amplifier is off.

Filtering in this receiver is provided by the SAW bandpass filter and the SAW delay line. Normally, two filters at the same frequency would be limited in out-of-band rejection to much less than the resultant cascaded 100 dB by the crosstalk level that could be achieved with a particular circuit layout. However, the switching of the amplifiers effectively gates crosstalk around the delay line filter out. This provides a single-ended connection to the antenna and a differential connection to the RF amplifier, taking advantage of common-mode rejection, and, effectively eliminating crosstalk around the SAW bandpass filter. The result is a receiver with sensitivity and frequency selectivity similar to a superheterodyne receiver.

The ASH receiver architecture offers several advantages over previous architectures. All of the functions, except the two SAW devices, are included in a single custom integrated circuit. Because the SAW devices are at RF rather than a low IF, they are extremely small. This makes it possible to include the entire receiver in a small hybrid package. No adjustments are needed because the frequency of the receiver is entirely determined by the two SAW devices. No RF oscillators are needed, which eliminates concerns about LO radiation, mixer-spurious responses and the associated DC power consumption. Because the RF amplifiers consume more power than the rest of the active circuitry, the switching of these amplifiers further reduces the overall power consumption by at least 50%.

Figure 3 shows a functional block diagram of the ASH receiver, including the custom IC, SAW devices, various control resistors and baseband coupling capacitor. The diagram also displays the gain and loss values for the signal path.

The output of the second RF amplifier drives a square law detector, which is realized using a Gilbert cell. The IC includes a post-detection three-pole low-pass filter whose bandwidth is controlled by a single resistor: RFIL. The output of the low-pass filter is capacitively coupled to a data slicer with a fixed threshold. The output of the data slicer can drive a single CMOS gate.

SAW-based hybrid transceiver

- *Requirements*

The development of a small hybrid transceiver was driven by the market requirement for short-range wireless data links with two-way communications capability. Requirements for such systems included a smaller size than the present hybrid receiver and transmitter; a lower cost than that of using separate receiver and transmitter modules; data rates as high as 115

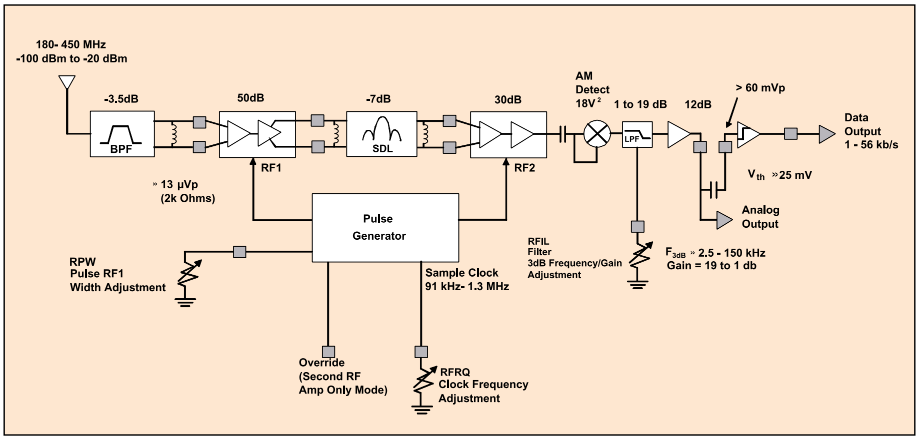

Figure 3. ASH simplified functional block diagram.

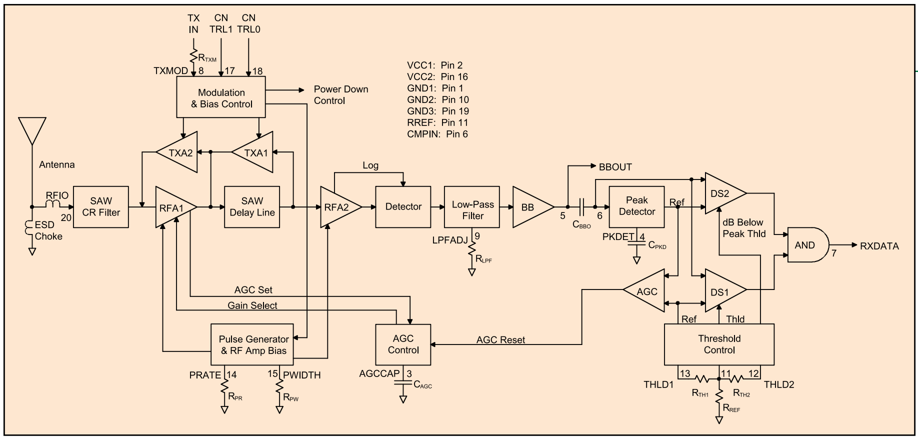

Figure 4. ASH transceiver block diagram.

kb/s; full receiver sensitivity from 300 MHz to 1.0 GHz; a much higher in-band RF saturation level than the present receiver; low current consumption; and the capability to work with on-off keying (OOK) or amplitude shift keyed (ASK) modulation. Also, the user should have access to the pulse generator, low-pass filter bandwidth, and threshold and transmitter power controls. ASH receiver architecture was used because the superheterodyne architecture did not fit the size and current requirements for the receiver. It was also considered to be more difficult to realize a superheterodyne-based transceiver using components in common with both receive and transmit functions.

- *Transceiver realization*

Figure 4 displays the block diagram of the resultant transceiver. The same two SAW devices used in the ASH receiver were used for the transmitter function. This was accomplished by adding a pair of amplifiers to the custom IC, TXA1 and TXA2, that are turned on in the transmit mode. TXA1 and the SAW delay line used in the receiver form the transmitter oscillator. TXA2 is the transmitter output amplifier. The receiver's input SAW-coupled resonator bandpass filter acts as the harmonic filter on the transmitter output. The RF amplifiers in the receiver, RFA1 and RFA2, are disabled in the transmit mode. The Q of the delay line allows the new transmitter to be OOK modulated as high as 38 kb/s with a typical rise time of 7 to 8 µs (for higher data rates, ASK modulation is used).

This result is realized by leaving the oscillator amplifier (TXA1) on while modulating TXA2. The typical rise time for the modulated transmitter output, in the ASK mode, is less than 1 υσ.

The transmitter modulation input was designed to allow quasi-linear modulation of the transmitter amplitude. Thus, shaping the data input to the modulator can control the modulation sidebands of the transmitter's RF output. This allows fitting the modulated transmitter into a restricted bandwidth. By the same means, the power output of the transmitter can be controlled by the value of the user-accessible resistor, R_{txm}, in series with the modulation input port.

Thus, the ASH receiver architecture was easy to convert to a transceiver by reusing the same two SAW devices used in the receiver to stabilize the center frequency and provide harmonic filtering in the transmitter. Because the same IC provides the transmit and receive functions, and both functions share the same SAW devices, the size and cost of the new transceiver have been minimized.

The RF amplifiers in the new custom IC were designed to have a 3 dB bandwidth exceeding 1.0 GHz, making it possible to have full receiver sensitivity from 300 MHz to 1.0 GHz. To increase the RF saturation level of the receiver component in the new transceiver, it was necessary to make three changes to the original ASH receiver.

Referring to Figures 3 and 4, the first change was in the detector. The first receiver uses a single square law detector following the second RF amplifier. This detector saturates at a receiver input level of –80 dBm. This problem was addressed in the transceiver by using distributed detection along the entire second amplifier, simulating a logarithmic detector. A modified Gilbert cell detector was also used at the output of the last amplifier. The outputs of all of these detectors were then summed together and fed into a three-pole gyrator low-pass filter. Thus, as each of the detectors reach saturation level, the outputs of the previous detectors still function. Figure 5 is a plot of the RF input level at the input to RFA1 versus the detected level at the

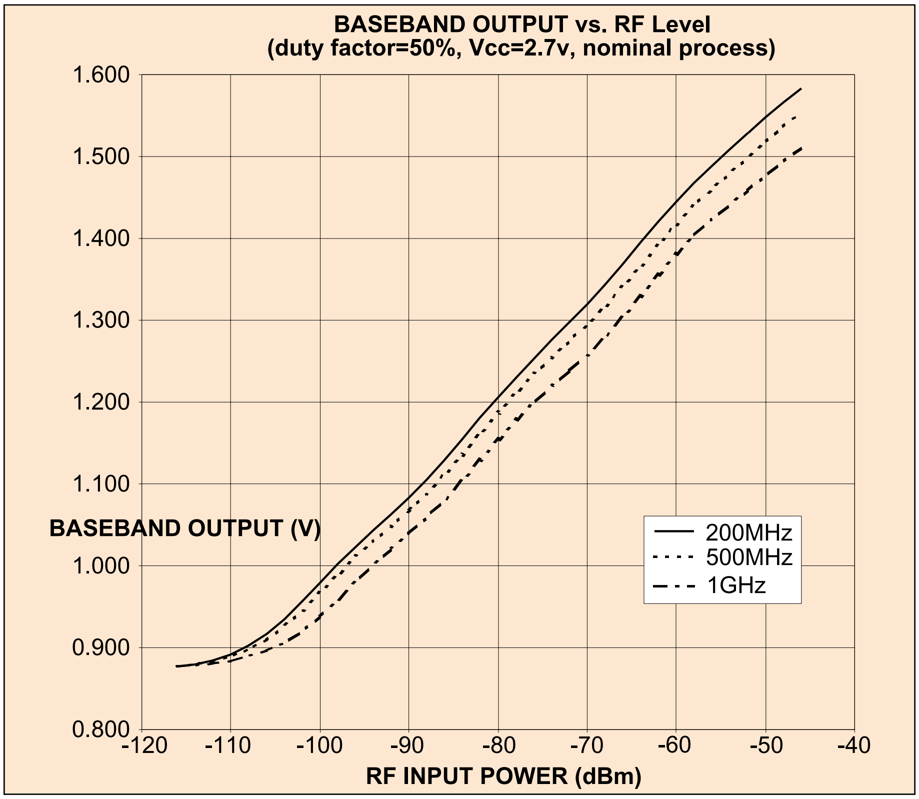

Figure 5. Transceiver RF input vs. detected output.

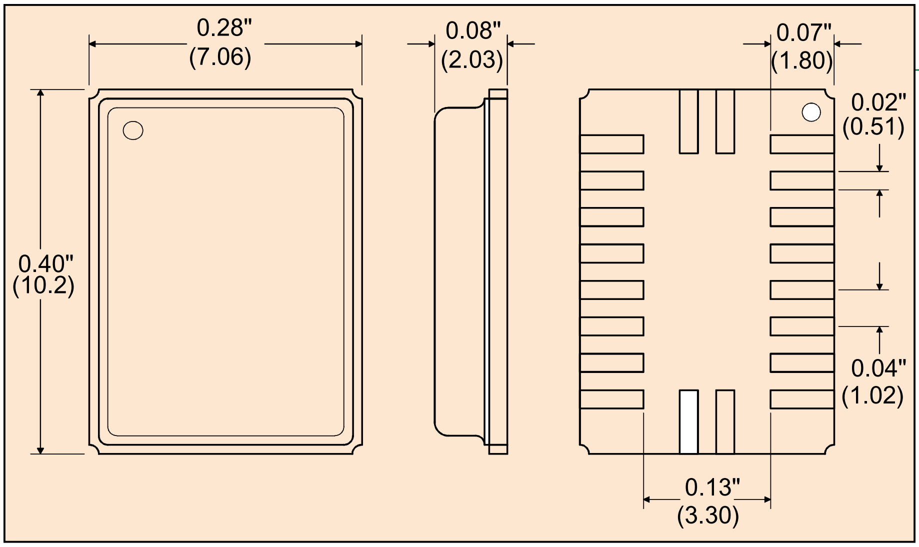

Figure 6. Transceiver footprint.

baseband output.The horizontal axis is in dBm while the vertical axis is linear, so the plot indicates a close approximation to a logarithmic detector.

The second change was in the receiver's gain distribution. The gain in the first RF amplifier, RFA1, was decreased from 50 dB in the original receiver to 35 dB, and the gain in the second amplifier, RFA2, was increased from 30 dB to 50 dB. This change improved the receiver in two areas. The gain increase of 20 dB in RFA2 increased the log detector range by 20 dB over what could be obtained with a 30 dB gain block, and the gain decrease of 15 dB in RFA1 increased the RF input level that could be handled without saturation by 15 dB at the delay line input.

The third change was to include an optional automatic gain control (AGC) system in the new transceiver. The user can choose to either enable or disable the AGC function. Again, referring to Figure 4, a simple stepped AGC was included. When the output level of the final stage of RFA1 is 1 to 2 dB into compression, it sets a flip-flop in the AGC control circuit that changes the gain of RFA1 from 35 dB to 5 dB. This increases the RF input level required to saturate the receiver from –45 dBm to –15 dBm. The AGC circuit resets RFA1 back to full gain when the detected signal level multiplied by 0.8 in the baseband circuit drops below the threshold reference for the “fixed” reference data comparator.

The ability of the new transceiver to work with ASK modulation can be used to greatly reduce the adverse effects of a high-level, amplitude-modulated, in-band interfering signal. The modulation from such an interfering signal appears during the “carrier off” condition with OOK modulation, but is masked when using ASK, because the desired RF carrier is present for all data conditions.

At higher data rates there is also distortion in an ASK signal. This is due to frequency band-limiting by either the filters in the receiver or in the transmitter. It is important that it does not prevent slicing the detected signal at the correct level to get good data reproduction at the output of the data comparator. The logarithmic detector can make band-limiting distortion even worse.

Referring to Figure 4, this type of distortion is handled well in the new receiver with the addition of data slicer, DS2, whose threshold is positioned about 6 dB below the peak of the detected pulse. This is accomplished by using a peak detector to find the top of the pulse and offsetting the thres-hold by 6 dB, using the slope of the logarithmic detector to determine the correct DC offset from the peak. The output of DS2 and the output of the fixed reference comparator, DS1, drive the input to an AND gate. Both comparator outputs must be high before the gate outputs a high. This prevents noise spikes from either of the comparators from appearing at the receiver output unless both comparators see them. Once again, the user can either enable or disable the peak detector-referenced comparator.

Finally, to address the issue of low current consumption, the sequencing of the RF amplifiers in the ASH receiver architecture reduces the current consumption by at least 50%. At low data rates, reducing the duty cycle of the RF amplifiers below 50% can reduce the current consumption even further. This is accomplished by decreasing the pulse rate in the pulse generator while maintaining

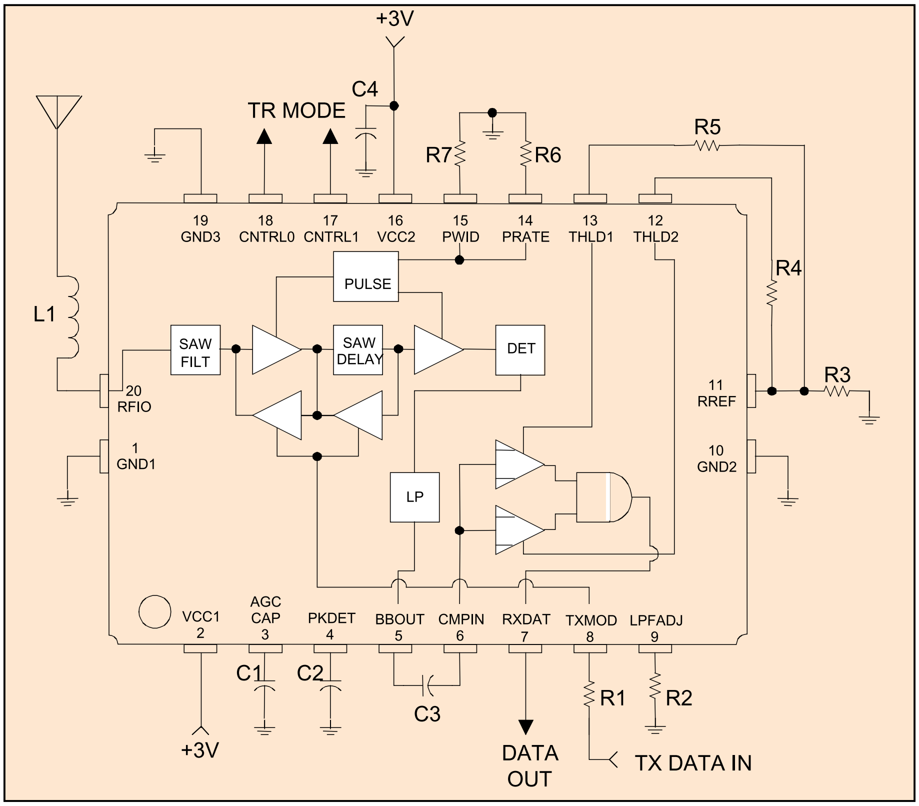

Figure 7. ASH transceiver electrical connections.

RECEIVER	
Data rate	2.4 kp/s
sensitivity	–102 dBm (50% sampling)
Sensitivity	–97 dBm (12.5% sampling)
Out-of-band rejection	100 dB
RF bandwidth	500 kHz (minimum)
Maximum signal	0 dBm
Detector saturation	–45 dBm
Detector saturation w/AGC	–15 dBm
DC voltage	2.4 to 3.5 VDC
DC current	3.0 mA (50% sampling)
DC current	1.6 mA (12.5% sampling)
TRANSMITTER	
Power output	0 dBm
DC voltage	2.4 to 3.5 VDC
DC current	10 mA peak
operating temperature	–40 to +85° C

Table 1. ASH transceiver performance example.

the same pulse width. Second, the new transceiver was designed to have a "power down" mode that is invoked by pulling the CNTRL1 and CNTRL0 ports to a complementary metal-oxide semiconductor (CMOS) low. (See Figure 4). If this mode is used, the receiver can be periodically turned on to see if a recognizable wake-up code is being transmitted.

An example would be turning the receiver on for 10 ms every second. This would reduce the receiver's average current consumption by a factor of 100. The new receiver typically consumes 1.6 mA of current when set up for a 2.4 kb/s data rate; thus, a reduction by a factor of 100 would reduce the average current to 15 µA. This makes the transceiver useable in watch or ID card applications using lithium coin cell batteries.

Transceiver performance

The performance of the resulting transceiver with a data rate of 2.4 kb/s is included in Table I. The surface-mount package dimensions for a complete 868 MHz transceiver are 10.2 X 7.06 X 2.03 mm. The case outline drawings for the new hermetic package are shown in Figure 6. Figure 7 includes a package outline, simplified block diagram, required external components and external electrical connections for the hybrid transceiver. The components and connections of Figure 7 use every available option. The small size and current consumption of the device make it suitable for applications such as the watch example given.

CR filter	+1 MHz, 19 dB	+2 MHz, 33 dB	+5 MHz, 18 dB	+10 MHz, 29 dB
CR filter	–1 MHz, 30 dB	–2 MHz, 38 dB	–5 MHz, 23 dB	–10 MHz, 38 dB
ETSI Specification	30 dB	35 dB	50 dB	60dB

Table 2. Original SAW-coupled resonator rejection vs. proposed Class II blocking ratio.

TETRA/ETSI requirements

The spectrum is becoming more and more crowded, as evidenced by the recent problems caused by introducing the new Trans-European trunked radio (TETRA) service in the United Kingdom. The problem in the U.K. was compounded by the presence of a narrow 418 MHz low-power band, located between the TETRA mobile frequencies and the TETRA base station frequencies, that is primarily used for automotive keyless entry. The manufacturers of the receivers used in this low-power application did not anticipate the introduction of such a service, so the receivers were ill-equipped to deal with the interference potential of the TETRA system. Many were LC-stabilized super-regenerative receivers with their inherent poor frequency selectivity.

Earlier this year, superheterodyne receivers equipped with SAW-coupled resonator RF front-end filters demonstrated more than acceptable performance in the presence of simulated TETRA signals when shown to the Radiocommunications Agency.

• *Proposed ETSI requirements*

The new 868 to 870 MHz SRD band has been a topic of much discussion in light of the TETRA interference problems encountered in the 400 MHz band. ETSI, in conjunction with industry, is rewriting EN 300 220-1 to include more stringent specifications on SRD transmitters and receivers. For example, the present draft includes a transmitter maximum-frequency drift specification of ±100 ppm under the extreme voltage and temperature conditions of that document. This can be met with SAW-based equipment, including the new transceiver.

In the area of SRD receivers, a blocking or desensitization specification has been added. For Class 1 equipment, whose low performance or failure would result in physical risk to people, the blocking ratio between the desired in-band signal and an interfering out-of-band signal is specified to be 84 dB, starting at a 1 MHz frequency offset. For Class 2 equipment, whose low performance would result in an inconvenience that cannot be overcome by other means, the blocking ratio is specified to be 30 dB at 1 MHz, 35 dB at 2 MHz, 50 dB at 5 MHz and 60 dB at 10 MHz frequency offset. For Class 3 equipment, whose low performance would result in an inconvenience to persons and which can simply be overcome by other means, no blocking performance is specified.

• *Present transceiver*

The present 868 MHz transceiver uses a SAW-coupled resonator for the front-end RF bandpass filter whose frequency response is shown in Figure 8. This filter is a two-pole structure with a bandwidth of about 700 kHz and a center frequency of 868.35 MHz. The filter ultimately reaches >60 dB of rejection, but, as can be seen in Figure 8, the

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ETSI Specification	30 dB	35 dB	50 dB	60dB

Table 3. SAW-coupled resonator rejection vs. proposed Class II blocking ratio.

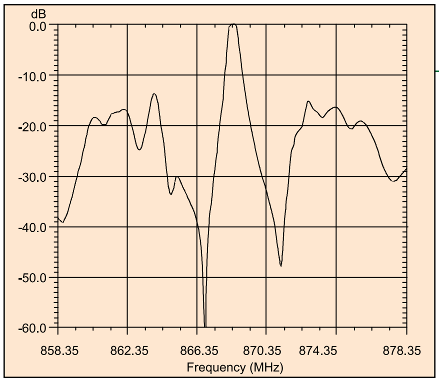

Figure 8. Present SAW-coupled resonator filter response.

device has close-in spurious responses that affect the receiver's blocking performance at the frequency offsets of 2, 5 and 10 MHz. The rejection of the coupled resonator at the ±1 MHz points is limited by the 12 dB/octave roll-off rate, characteristic of a two-pole filter.

The bandwidth of the SAW delay line second filter in the receiver is 1.5 MHz, and the filter response is close to that of a six-pole linear phase Bessel filter. As a result, the coupled resonator filter must provide the majority of the receiver selectivity needed to meet the blocking requirement. The rejection of the coupled resonator filter, derived from the plot of Figure 8, is shown in Table II for each of the specified frequency offsets versus the Class 2 proposed blocking ratio specifications. This filter does not meet the proposed blocking requirements for a Class 2 system. Thus, the present receiver would be suitable for Class 3 equipment, but not Class 2 with the proposed blocking requirement.

- *Proposed new transceiver filter*

A new 868 MHz SAW-coupled resonator filter is being designed for the transceiver that would meet the proposed blocking requirements for Class 2 equipment. The form factor for the upgraded transceiver would be the same as for the present device. The frequency response of the new filter is shown in Figure 9. The new coupled resonator filter is a four-pole device with a typical bandwidth of 620 kHz and a center frequency of 868.35 MHz.

This bandwidth accounts for the temperature variations of the transmitter and receiver, as well as the data-modulation side bands. The ultimate rejection is about 70 dB, and the close-in spurious responses of the present filter have been eliminated. The rejection of the new filter, derived from the plot of Figure 9, is shown in Table III for each of the Class 2 frequency offset points. The filter provides the needed selectivity to meet the proposed blocking ratios. The ultimate out-of-band rejection of the entire transceiver (>100 dB) will be about the same as that obtained using the present filter, but the close-in spurious responses will be eliminated by the new filter.

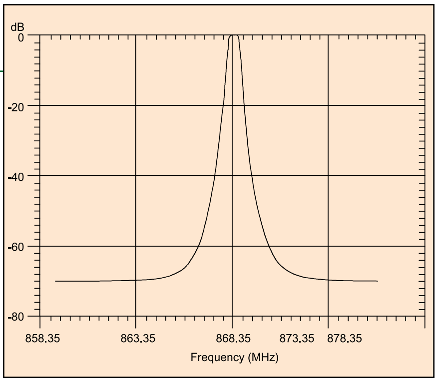

Figure 9. New SAW-coupled resonator filter response.

The final analysis

A new transceiver design has been developed around the capability of

SAW devices. The delay of a SAW delay line was used as a storage element to create a time diversity receiver while using its amplitude characteristics to perform a filtering function. The same delay line's phase characteristics were then used to create the transmitter oscillator. On the antenna port, a SAW-coupled resonator filter was used as a preselector filter on the receiver input, and it was used to filter out harmonics on the output of the transmitter. The use of the same two SAW devices in both the receiver and the transmitter, in conjunction with a custom IC for the active functions, made it possible to include the entire transceiver in a 10.2 X 7.06 X 2.03 mm surface-mount package. This small size, in combination with low power consumption, low cost and excellent radio data link performance, make the new transceiver suitable for wireless SRD applications involving watches, ID cards, hand-held apparatus, computers, computer peripherals, tags and many more applications.

RF

About the author

Darrell Ash is senior vice president and CTO of RF Monolithics. He received his BSEE from the University of Evansville and then was awarded a National Science Foundation Fellowship to attend Brigham Young University where he received his MSEE, magna cum laude. Ash co-founded RF Monolithics where he served as vice president of engineering until 1995. Since that time, he has served as Sr. VP and chief technical officer working on new technologies, including the new miniature RF transceiver. Ash has 32 years of experience in the design of radio frequency filters, circuits, RF hybrids and systems. He has had 12 patents issued in his name on the application of SAW devices to circuits and systems. He has presented numerous technical papers on his work and is presently a senior member of the IEEE. He can be reached at 972/789-3845. The author would like to thank Darren Ash for his invaluable assistance in putting this paper together. *This paper first presented at the Low Power Radio Association's Radio Solutions conference in Birmingham, England in 1999.*