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Link Distance Enhancement and Battery Current Savings in Wireless Systems

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RFaxis

This article describes the issues relating to power consumption, performance, cost, including the choice of semiconductor technology used in integrated wireless transceivers

Data wireless communication systems are becoming widespread on battery powered mobile and other portable platforms, and every effort is being made to reduce the power demand from these typically power hungry devices. One area of focus is the circuit that transmits and receives the RF signals because there is usually significant power drain related to this function. This article describe methods that can be employed to save on current drain, and at the same time improve system performance by increasing connection data bandwidth.

Modern digital communication technology requires a low layer link, known as the PHY (or physical) layer, to allow transmission and reception between connected devices. In most cases, an integrated transceiver cannot produce enough power to realize the full potential of the specification, typically +20 dBm. This is due to the design of the transceiver, which contains millions of CMOS gates to perform the DSP and MAC functions. These gates both take a lot of room, and dissipate a lot of power. For a fully integrated CMOS radio, fabricated on a single transceiver die, the output power seldom exceeds 0 dBm.

One approach is to include an additional die in the transceiver package to perform the radio power amplifier (PA) functions. This type of design can produce a few more dB of power output, but takes additional space on die, or results in a thicker package when the dies are stacked. The additional power dissipation can also limit performance. High power circuits can also couple to sensitive ones causing undesired interference, especially with digital modulation schemes where phase and amplitude of the modulated signals are critical.

These limitations to a fully integrated high power radio have resulted in the need for external amplifiers for systems such as 802.11 WiFi. Initially, these amplifiers were added as discrete parts—down to the transistors—requiring complex RF layouts. The industry has moved to higher levels of integration to save on space and cost, and to reduce the development time. A number of companies have developed devices that incorporate the necessary parts into one external device known as a Front End Module (FEM). These devices have now found extensive use in technology platforms such as 802.11, high powered Bluetooth, ZigBee, and other digital communication systems. These devices essentially are integrated versions of a discrete front end amplifier design, composed of a power amplifier (PA), a transmit/receive (TX/RX) switch and various optional components such as a low noise amplifier (LNA) for the receive path, baluns, filters, diplexers, power detectors, and matching components.

The FEMs in use on typical WiFi platforms, and other present day communication technologies, including ZigBee and WiMAX, have similar configurations and designs. They are typically fabricated using multiple chips, discrete components, filters, and other devices wire bonded, or connected, through traces and packaged into a single device. The integrated circuit (IC) technology used in FEMs varies by manufacturer, but generally falls into one of several types depending on the function performed. The following is a list of various RF IC

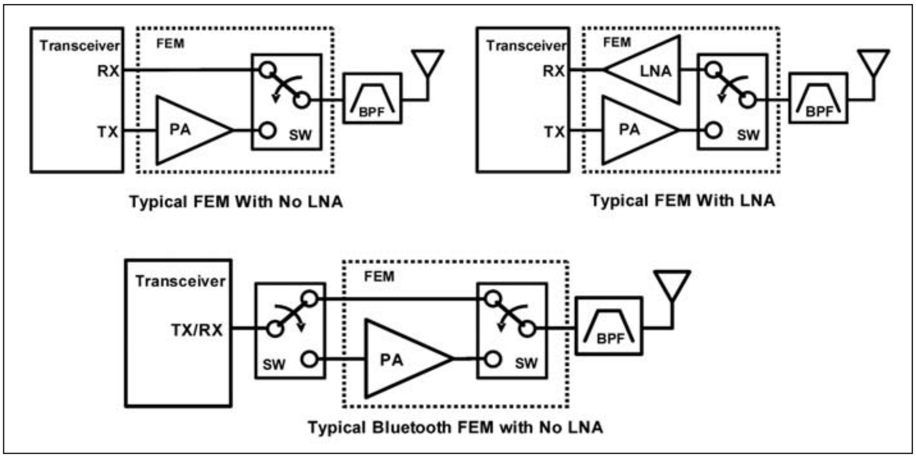

Figure 1 · Conventional FEM application circuits.

technologies and the typical functions of the devices made from them.

GaAs MESFET—This was the first of the GaAs semiconductors to be demonstrated. It is a great substrate for high frequencies as the bulk GaAs substrate has a high resistivity. This allows for the design of high quality passive components and low leakage switches with high isolation between ports. Most GaAs MESFETs require a dual polarity supply, making the designs more complex. Also, the thermal resistance of GaAs is 3 times greater than the equivalent silicon material, making heat dissipation a problem.

GaAs HEMT—This class of device also includes the PHEMT and the E-PHEMT. This technology can operate at very high frequencies, above the X-band, with Noise Figures (NF) well under 1 dB. It can be utilized in a PA with very good efficiency, and can be configured as an RF switch. This technology also generally requires a dual supply; however the PHEMT devices can operate also from a single power supply. It is even more expensive to produce HEMPT than MESFET.

GaAs HBT—The transistor is a vertical structure and the optical process results in better yields and lower cost to manufacture. These devices also operate on a single power supply. The typical integrated designs for GaAs HBT include PAs and LNAs, but the process has not yielded good RF switches, and heat dissipation can be a problem as well.

CMOS—This mainstream digital process can be used to fabricate RF devices, but they generally have less desirable performance in Noise Figures and output power. Silicon on Insulator (SOI) technologies has promising RF characteristics, allowing the creation of high performance RF circuits, including RF switches, but at high manufacturing cost.

BiCMOS—This technology allows the fabrication of high performance RF parts at a very low cost. These devices are the most rugged of any of the RF devices produced today making the die packaging simple, compact, and strong. They also have excellent thermal dissipation properties improving heat transfer. These qualities make silicon the first choice for portable and mobile RF electronic devices. Additionally, BiCMOS can also implement CMOS elements, which greatly enhances the complexity. BiCMOS can fabricate PAs, LNAs and most other RF components, and can operate from a single supply.

One of the main disadvantages is the poor electrical insulating characteristics of the silicon substrate. However, this can be overcome through the use of multiple metal layers available in the process. Traditionally, the biggest limitation for a front end design in BiCMOS is the lack of an RF switch.

Front End Module (FEM) Design

In order to take advantage of the GaAs HBT process with high yields, designers of FEMs are forced to use additional die of different technology to provide the important TX/RX switch. The typical configuration might involve one PA die and one LNA die, both made from InGaP HBT, and a switch made with the GaAs HEMT process. Additionally, a bias and switch control circuit is required, which often means an additional die of some type. All these ICs are then mounted in a package and connected through bond wires and substrates. Matching and filtering components are often included in this package for the RF ports. This technology is proven and reliable, and is shipping in large quantities, but the use of multiple higher cost dies and complex packaging results in an expensive final component.

There is a number of packaging techniques used for FEMs and RF parts in general. These include QFN, LTCC, and MCMs among others. One of the most cost effective is the QFN package built using flip-chip techniques. A QFN with a lead frame can generally accommodate only one die, although it can contain multiple dies with wire bond interconnects.

RFaxis Inc., based in Irvine, California has developed a new design process that allows the fabrication of all the components needed for a front end module on a single die, including a proprietary method for switching the TX/RX RF antenna signal. This technique is being used to fabricate single die front end devices in BiCMOS, though the technology can be applied to any IC fabrication process. This new innovation is called an RF Front End Integrated Circuit (RFeIC) which allows the missing piece, the RF switch, to be included in the single die fully integrated front

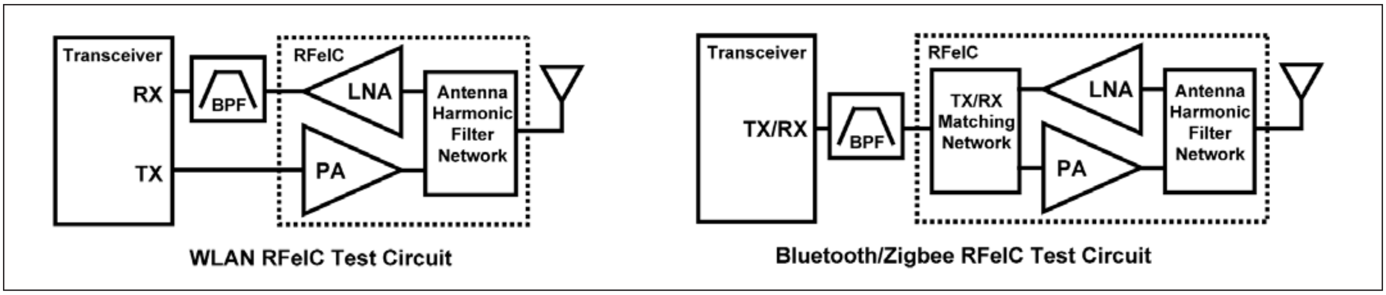

Figure 2 · RF front-end application circuits based on the RFeIC.

end device for use in modern digital communications systems.

RFaxis has designed multiple configurations of these devices to support highly integrated solutions for WLAN, Bluetooth, ZigBee, WiMAX, MIMO, WAVE, and other systems that require two way communications between RF connected platforms.

Application Circuit Descriptions

Figure 1 illustrates two circuit configurations, which are implementations of existing FEM products used in WLAN designs, and to a lesser extent Bluetooth class-1 and ZigBee systems, for extended communication link range applications. The first module is composed of an RF switch and a PA. The second implementation has also incorporated an LNA. The switch allows the module to operate in either transmit or receive mode, and is almost always fabricated in GaAs based technology. In addition, the PA and LNA are typically separate chips inside the module assembled together. Implementation of these circuits requires either multi-die modules, or expensive single-die technologies such as ED-pHEMT.

The circuits with no LNA architecture shown in Figure 1 adversely impact system Noise Figures because of the insertion loss of the switch, usually 0.5 dB or more. Additionally, the insertion loss of the band pass filter (BPF), in the range of 1.5 dB to 2.5 dB, will further degrade the system noise.

Figure 2 details the implementation of the RFaxis, Inc. circuit design using the RFeIC. The integrated harmonic filter allows for the placement of the band-pass filter between the transceiver and the LNA, minimizing the degradation of the system NF. Additionally, the low NF of the LNA provides additional improvement to the noise performance of the entire system. At the same time removing BPF loss at antenna side results in implementation of a PA with lower current drain from battery.

The typical system Noise Figure in a WLAN, Bluetooth, or ZigBee integrated transceiver is 7 dB to 9 dB, and is often even higher. Figure 3 demonstrates the improvement to system NF with the addition of LNA gain at the front end. Figure 4 graphically displays the improvement to link distance that results from this same LNA gain, and it is notable that an improvement of 200% can be easily achieved.

The communication link range enhancement is proportional to the square root of the relative sensitivity, which is impacted by the overall NF improvement. By utilizing the LNA to improve the system NF, the RFeIC application circuits detailed above can reduce transmit power and associated current consumption while increasing available network bandwidth.

Test Results and Examples

The Bluetooth design in RFeIC application circuit was tested with the following conditions:

- The transmit chain in this test contains only a final stage PA and a single-stage LNA.
- A basic rate GFSK modulated signal has been used.
- The Bluetooth chip itself was operated without forward error correction and with the onboard band-pass filter.

This resulted in a receiver sensitivity of –84.5 dBm with a BER of 0.1% as shown in Figure 5.

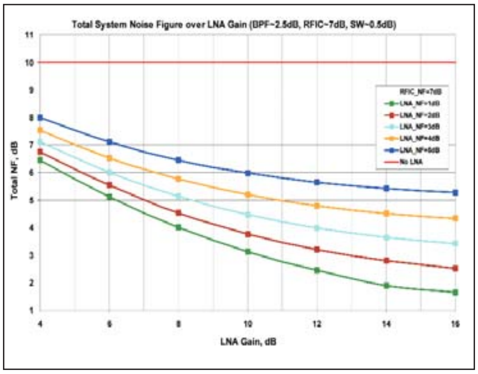

Figure 3 · LNA Noise Figure impact on system NF.

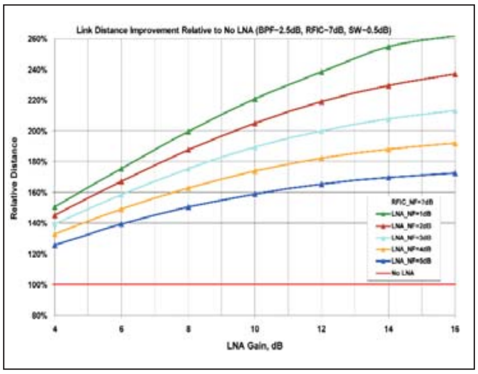

Figure 4 · Link distance enhancement due to the addition of an LNA.

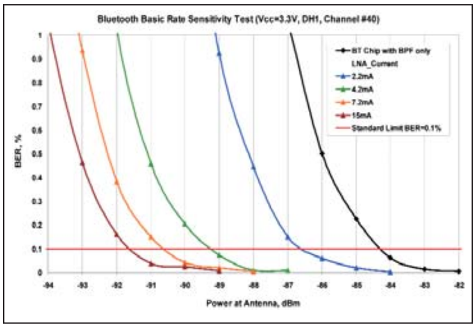

Figure 5 · Bluetooth sensitivity test results for varied LNA current.

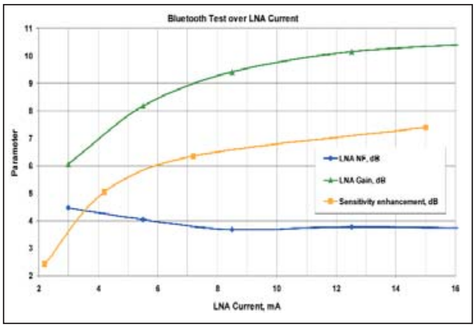

Figure 6 · RF front-end receive NF, gain, and sensitivity plotted over LNA current.

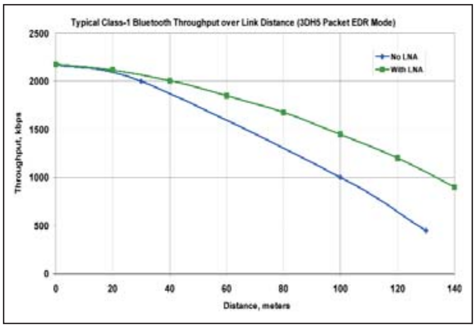

Figure 7 · Typical Bluetooth throughput over link distance.

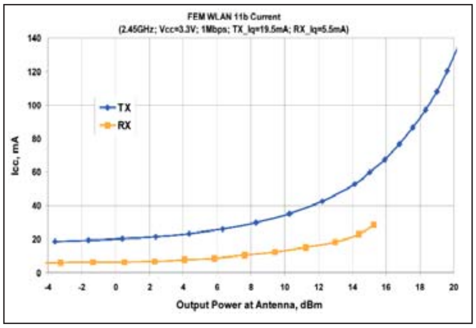

Figure 8 · Example of measured TX and RX current for the RF front-end versus power output at the antenna.

The LNA gain of this circuit was varied by controlling the current applied to the amplifier, and Figure 6 illustrates how the change in gain results in a sensitivity enhancement of between 2 dB to 7 dB. This graph presents the gain and NF of the LNA, and by plotting the data it is shown that an LNA with a gain of 8.5 dB and NF = 4 dB results in 6 dB of total system NF enhancement, which doubles the link range for the RFeIC application circuit.

To better understand the relationship of data throughput versus distance, refer to Figure 7. By using a transmit power of +16 dBm, the blue line shows the data throughput versus the distance for Bluetooth communication link based on the typical FEM circuit with no LNA. As the link distance increases, the data throughput decreases dramatically, and at 130 meters, the data rate has dropped to less than 500 kbps. The green line represents the performance of the LNA RFeIC Bluetooth circuit, and with 6 dB of LNA gain, where the system sensitivity will increase by almost 3 dB. As shown in the chart, the data throughput at 130 meters will be greater than 1000 kbps, which is more than double the throughput of the typical no-LNA circuit.

In order to increase a given link distance by 2 (or 6 dB of sensitivity improvement), the LNA amplifier may require as much as 7 mA of additional battery current. Instead of just increasing the link range, an option for some applications may be to save a substantial amount of current by implementing increased sensitivity on both ends of the link, and reducing transmit power. Consider the case for 802.11b operation as shown in Figure 8 where the transmitter PA is operating at +16 dBm with a current consumption of 70 mA. If the transmitter output power is reduced by 6 dB to +10 dBm, the current supply will be reduced to 35 mA. By implementing the LNA in the front end to make up for the 6 dB reduction in the PA, there will be a net savings of 28 mA of current.

Bluetooth typically operates in a burst mode with different packet widths and duty cycles. Figure 9 and Figure 10 show the power savings that can be realized by using the transmitter output power reduction strategy mentioned above. When the output power is reduced by 6 dB and sensitivity improvements of 6 dB are added to the receiver to make up for the smaller signal, the power saving are shown side by side for each packet type in Figure 9, and the percent power savings are summed up in Figure 10.

Wireless LAN and Current Consumption

The WLAN market is growing fast with new applications becoming available every day. The rise of Internet services and low-cost Voice over Internet Protocol (VoIP) phone calls has become a key driver for WLAN chips in mobile phones. WLAN systems have a time domain duplex architecture conveying information through data packet transmissions. Mobile phones with WLAN chipsets are typically the client devices, which are connected to an access point (AP) that manages the data traffic.

The 802.11 standard operates by using burst transmission techniques, which are more complicated than in a Bluetooth link and the communications occur without fixed time intervals. The burst length can lie between several tens of microseconds to several milliseconds, and depends on the data rate of the link, the data packet size being transmitted, the number of clients in a network and their activity, the distance to the AP, the priority of each link, and so forth. A figure of

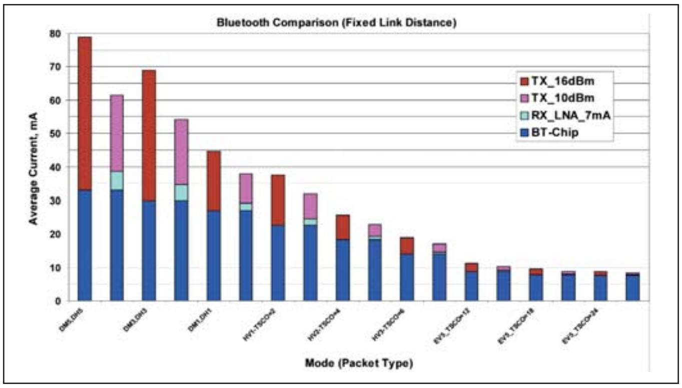

Figure 9 · Total Bluetooth system current with and without an LNA, for various tranmission modes.

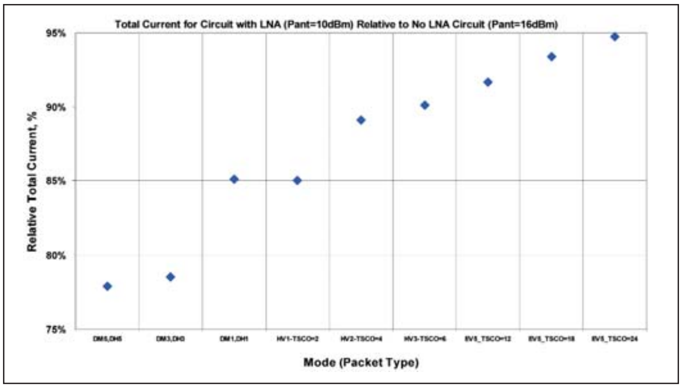

Figure 10 · Total battery current savings for a Bluetooth system with an LNA.

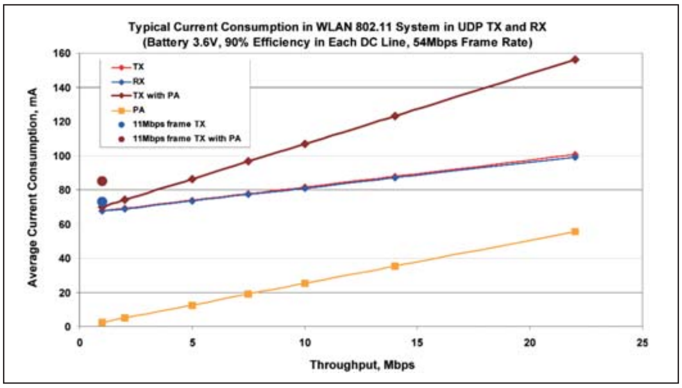

Figure 11 · Typical current consumption for a WLAN system versus throughput.

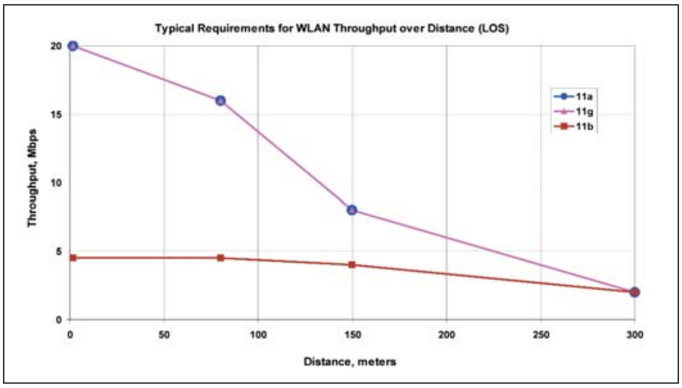

Figure 12 · Typical throughput capability for WLAN systems versus link distance.

merit of a communication link is throughput, which is the amount of useful data transferred between two network nodes.

There are two primary power management modes supported by the 802.11 standard also known as the "active" mode and "power save" mode. The purpose of the power save mode is to allow a client to turn off its radio for some period of time while the AP buffers packets for later transmission, thus saving power.

The high data rate of traffic used in WLAN systems along with the +16 dBm to +20 dBm power required at the antenna results in a large current drain from a battery for both transmit and receive mode on a mobile platform, and a number of power saving strategies have been developed to address this problem. Figure 11 details the current drain of a typical WLAN 802.11b/g chipset fabricated on conventional semiconductor technology. The graphs are average battery current consumption with operation at 2.4 GHz using the UDP protocol for transmitting and receiving data. The transceiver and RF radio circuits are powered up only during the time required to transmit/receive and process the data. As different parts of WLAN chipset require different voltages, for convenience a 3.6 V common battery was used with 90% efficiency for the power conversion.

As higher throughput is needed for a WLAN link, larger average current consumption is required by the transceiver and front end circuits. The red and blue lines are the current drain for receive and transmit operation with the maximum of 54 Mbps data rate without the PA current included, and these two modes are usually close due to similar circuitry used for those functions. The brown line presents the average current versus the UDP throughput in transmit mode with the PA current included. A 2 Mbps throughput typically used for low bandwidth applications such as MPEG3 download or JPG image upload results in 75 mA of battery current consumption and there is a little impact from the PA on the overall current. In more demanding applications requiring higher bandwidth such as video streaming, or faster processing of low bandwidth applications, the PA current contribution to the total current drain from the battery can rise significantly up to 50% of the transceiver current, which can as much as 150 mA for the throughput levels above 20 Mbps.

The data rate and packet duty

cycle can have a big impact on the current drain of the system. The data presented in Figure 11 shows that a throughput of 2 Mbps requires a current drain of 75 mA, and the current drain for 20 Mbps is 150 mA. This result shows a factor of two increase in current drain, but the throughput has increased by a factor of 10. Significant power saving is achieved by passing data at the highest rate possible, and thereby utilizing the packet duty cycle to go into the power save mode as much as possible.

The data in Figure 11 is based on full power applied through the PA. Many factors can influence the RF power requirements of a WLAN system, and additional current drain savings can be realized by using power control on the PA, and when the system Noise Figure is low, as is the case with the RFeIC designs.

Even WLAN VoIP applications that require a relatively low bandwidth in the sub-100 kbps range can reduce current drain if connected at a very high data rate and the burst transmissions are interleaved with the power save mode.

Figure 12 presents typical throughput capability for a WLAN system versus link distance. Many factors can influence throughput including interference, environment, and communication system quality. The RFeIC designed by RFaxis can improve system quality by assuring an excellent system Noise Figure and utilizing a high quality PA, which will further extend the range and bandwidth, especially when an RFeIC is present on both ends of the communication link.

Conclusion

As operation of wireless data communication systems become more common on battery operated mobile platforms, it is crucial that these systems minimize their impact on battery current drain. The information presented in this article details how WLAN and Bluetooth systems will realize the lowest current drain from the system battery when data throughput is operated at the highest clean data rate possible while maximizing the duty cycle of the low power standby mode of operation. By improving system Noise Figure through the use of an LNA, and transmitting with a clean efficient PA, range and throughput can also be increased, and additional power savings can be realized by reducing the PA output power.

The integrated single die front end device (RFeIC) developed by RFaxis in BiCMOS represents a state of the art solution to help realize these advantages. System noise figures can be reduced by a factor of two or three, and the use of the high efficiency PA will also save current drain, thereby extending the range and increasing useable throughput. In addition, this increased efficiency is offered in a small, cost-effective package.

Author Information

Alex Gorbachov is RFaxis CTO and Chief Scientist. He has worked 28+ years in the electronics and semiconductors industry (different engineering and management positions). He has a Ph.D. in Electrical Engineering from Kiev Polytechnic Institute. His current work includes low-cost, small-sized and high-performance RF integrated circuits and modules for wireless communications.

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