From August 2010 *High Frequency Electronics*

Bluetooth Class-1 Modules With Low Power Consumption

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This article offers analysis of Bluetooth system architectures, modulation modes, and control options that can reduce power consumption for both voice and data applications

One of the most popular wireless personal area networks (WPAN) technologies is the well-known Bluetooth Standard [1]. While use of Bluetooth is widespread for different applications, there is a growing need for longer communication links, which require higher output power. Class-3 and class-2 Bluetooth chips are popular in the market with about 0 dBm and 4 dBm maximum transmit (TX) power respectively, which is enough for a link in the range of 10 meters or more. The standard also allows class-1 operation with 20 dBm power at the antenna connector. Link range in this case can be extended up to several tens or even hundreds of meters. Certainly, an external PA is needed for that. As we move to more mobile and handheld applications, with more functions using the same device battery, power saving technologies become very important. Bluetooth 3.0, with higher data rates, has even more stringent requirements.

This article presents different architectures of Bluetooth class-1 modules, emphasizing low current consumption. There is simulation included as well for the main modes for Bluetooth links, with different power control technologies applied.

Class-1 Bluetooth Module Architectures

Many Bluetooth solutions provide the same RF pins for transmit (TX) and receive (RX) operation, with the TX-RX switch function implemented inside the chip. This helps reduce size and cost of the whole system. Usually those TX-RX pins are differential to simplify on-chip common-mode noise rejection. For this type of Bluetooth chip two different class-1 Bluetooth module architectures are presented in Figure 1, on the next page.

A low-temperature co-fired ceramic (LTCC) band-pass filter (BPF) is typically used as a common device for transmit and receive chains, simultaneously reducing unwanted out of band radiation in TX mode and protecting the highly sensitive receiver low noise amplifier (LNA) from high power neighboring transmitting devices (e.g., mobile). Two SPDT RF switches are used to enable transmit/receive modes. Architectures in Figure 1a and 1b allow external LNA insertion into the receiver chain to enhance sensitivity. In Figure 1a, a low-cost lumped-element or LTCC balun can be implemented at a Bluetooth common TX-RX RF port to convert differential signals into single-ended ones, as typically required for RF switches and antenna operation.

One needs to note that architecture of the module in Figure 1a requires taking care of the passband shape at frequencies below operating ones, as the Bluetooth chip RF output signal is usually only low-pass filtered and may have different "spurs" at fairly low frequencies. Certainly, the balun can provide some level of filtering below and above the operating frequency band.

Another solution for a class-1 Bluetooth module is presented in Figure 1b. An LTCC differential band-pass filter (DBPF) is used here at Bluetooth chip RF port, which saves power consumption in TX mode. Usually DBPF can provide better filtering performance compared to single-ended solutions,

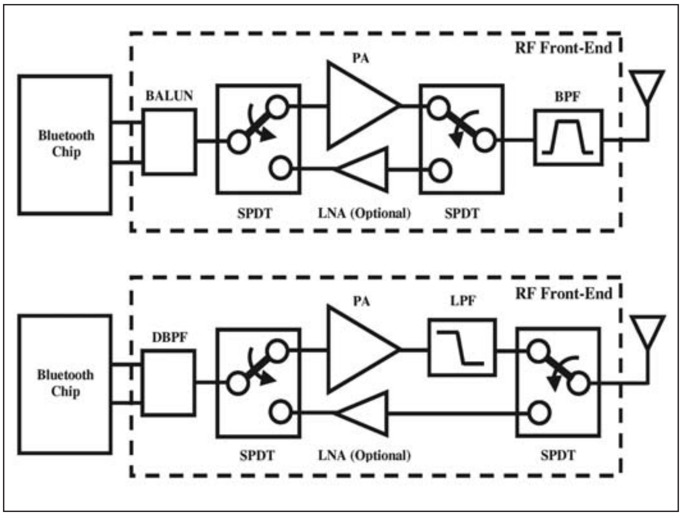

Figure 1 · Two different architectures of a class-1 Bluetooth module.

while both filters' typical loss is in the range of 1.5-2.5 dB. Receive mode characteristics are similar to the previous case in Figure 1a. To reach an acceptable level of harmonics in TX mode at antenna connector, a low-pass rejection filter can be used at PA output using discrete surface mount (SMT) components, with an insertion loss typically below 0.5 dB.

Several component vendors provide different Bluetooth PAs. There are two distinctive modes of operation for the Bluetooth PA, either non-linear or linear depending on the data rate required. With a data rate below about 700 kbps, a GFSK (Gaussian frequency shift keying) modulated signal is used with constant RF envelope, allowing non-linear PA operation. PSK (phase shift keying) modulated signals with variable RF envelope—requiring a linear PA—is used for data rates up to 3 Mbps.

The two different modes of PA operation are presented in Figures 2 and 3. Typical gain versus output power for non-linear and linear modes of operation is presented in Figure 2, while operating current for both modes is shown in Figure 3. Control of non-linear and linear modes is usually provided by proper voltage applied to the regulator pin of the PA, setting the quiescent current. Below a certain level of quiescent current PA operates in non-linear mode resulting in increased efficiency at all power levels (see collector current in Fig. 3). Taking into account SPDT switch and BPF loss, one can see operating current of 90 mA to 110 mA can be achieved for 20 dBm power at antenna connector, depending on non-linear or linear mode of operation for the circuit of Figure 1b. The same power level requires 130 to 150 mA of operating current for the architecture shown in Figure 1a. Power savings are obvious for the architecture in Figure 1b. This architecture is beneficial and the RFIC described in [2] with high power handling capability in the receive chain is well suited for class-1 Bluetooth applications.

Power Savings in a Bluetooth Link

The operating current discussed above presents numbers for a continuous wave (CW) RF signal. In real operation there is a modulation applied to RF signal, along with the burst nature of a data transfer through an air interface. Consider the following Bluetooth link operation basics for understanding the current delivered by the battery, which is directly related to the life time of a Bluetooth enabled system between re-charges, which is crucial for handheld devices. Bluetooth operates in a time domain duplex mode (TDD) when two nodes are communicating with each other. One of nodes is called "master" and another is "slave." Time frame is divided by nominal 625 microsecond slots (which is equivalent to 1600 hops per second), and there is a sequence of transmit-receive oper-

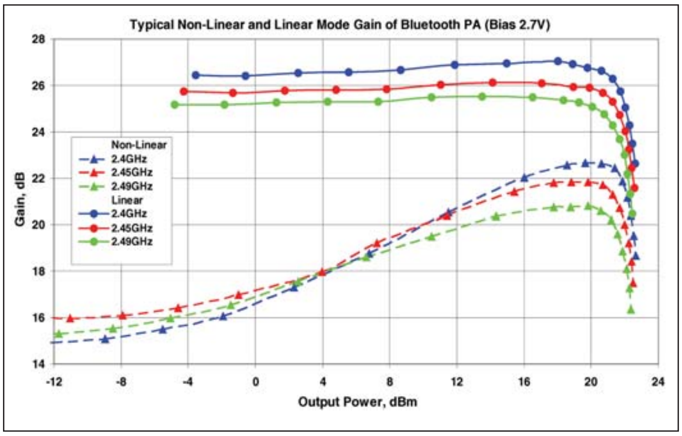

Figure 2 · Typical gain characteristics of a Bluetooth PA in non-linear and linear modes of operation (all voltages are fixed and PA is driven at input by different RF signal level).

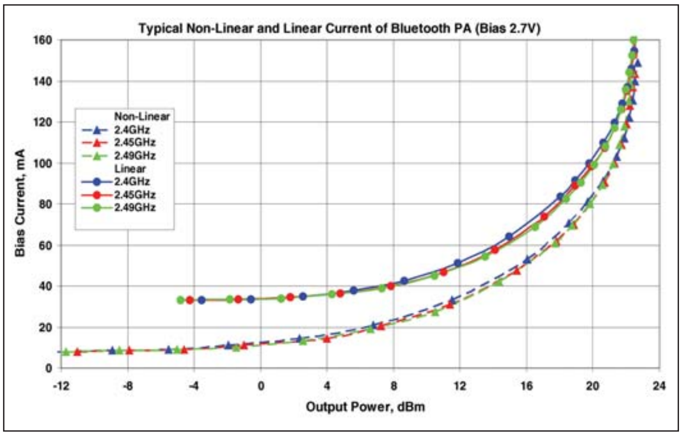

Figure 3 · Typical bias supply current of a Bluetooth PA in non-linear and linear modes of operation (all voltages are fixed and PA is driven at input by different RF signal level).

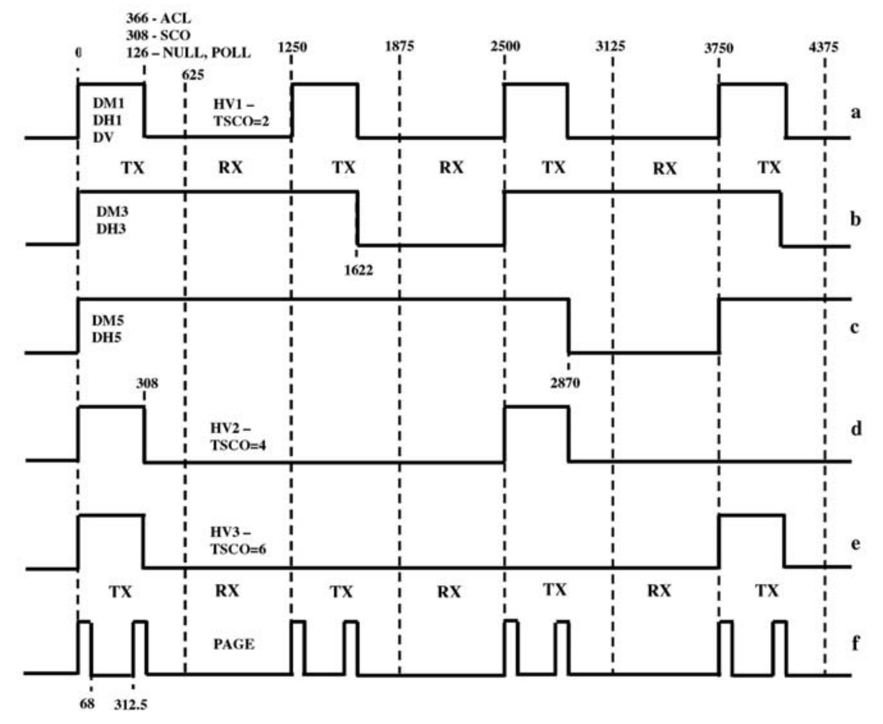

Figure 4 · Timing diagram for main modes of Bluetooth operation (timing noted in microseconds).

ations for each node. “Master” is allowed to transmit in even slots and receive in odd slots, while the “slave” transmit-receive sequence is opposite. Each transmit slot (and immediately next after this receive slot) corresponds to the particular frequency, and hopping of frequency occurs at a next transmit (receive) slot. A total of 79 hopping frequencies with 1 MHz interval are pertinent to the Bluetooth system. A hopping sequence is coded in a pseudo-random manner. Synchronization information along with slot mapping and hopping sequence is contained at the beginning of each transmit signal sent to the counterpart node, while the rest of an appropriate burst is filled by the desired information (payload).

Basically, a transmitting (and receiving) burst (packet) can fill up to one, three or five dedicated slots dependent on the payload required. There are two main modes of operation (see Fig. 4) when link is already established: synchronous connection oriented (SCO) for voice, and asynchronous connection link (ACL) for data transfer (although mixed voice/data mode is also possible). Figure 4 depicts transmit-receive sequence slots along with packet types.

The numbers in Figure 4 are in microseconds, and for each packet they present maximum allowed burst time. DM1, DM3 and DM5 ACL packets represent medium data rate packets (with forward error correction) while DH1, DH3 and DH5 packets resemble previous ones without forward error correction. DM1 (DH1) packet has maximum 366 µsec duration while DM3 (DH3) is 1622 µsec and DM5 (DH5) packet maximum duration is 2870 µsec. Although multi-slot packets DM3 (DH3) and DM5 (DH5) are shown for simplicity, in continuously repeated mode they are usually operating in mixed mode when each next transmit burst can differ from preceding one.

Synchronous types of packets HV1, HV2 and HV3 have smaller burst length of up to 308 µsec and usually are conveying an average of 64 kbps information. One can see in Figure 4 that transmitting a packet once in every two transmit slots (HV1 – TSCO = 2), once in every four transmit slots (HV2 – TSCO = 4) or once in every six transmit slots (HV3 – TSCO = 6) saves on average power consumption during transmit time. (TSCO depicts number of consecutive transmit slots allowed for burst transmission and it can be higher than 6.) At the same time the different number of TSCO depends on several “slave” devices, which can communicate simultaneously with one “master,” and there are dedicated slots for synchronous connection with each node. However this topic is outside of our discussion.

Figure 4 presents data for Bluetooth v.1.1 and v.1.2 with GFSK modulation of a signal with maximum dada rate of 723 kbps. For Bluetooth v.2.0 with EDR (enhanced data rate) there is a similar timing diagram with just different modulation applied to RF signal—π/4 DQPSK and 8PSK, as required for conveying the information with double and triple the volume respectively [1]. One has to notice that synchronization information at the beginning of each packet is always GFSK type so it contains a modulation type that is compatible with all types of data.

Taking into account a typical Bluetooth chip’s current consumption characteristics (baseband and RF is included and pertinent to the 0.13 µm through 0.18 µm silicon semiconductor technologies), and according to the timing diagram in Figure 4, an average current consumption of class-1 Bluetooth module with nonlinear and linear mode of PA operation discussed in a previous paragraph is presented in Figure 5 for different data packet types operating continuously at a fairly long period of time in the circuit architecture of Figure 1b. Different color columns depict multiple types of PA operation: output power at antenna connector is fixed at 20 dBm power level (and current consumption certainly is higher for linear mode), with power control of 4 dBm through 20 dBm which is mandatory, required by 802.15.1 Standard. and optionally extended by 20 dB with power control range from –16 to 20 dBm (although it is not the full allowed range of control, which may go down below –30 dBm at the expense of increased circuit complexity). For the power control case it is assumed that 2 dB gain control steps are fitted and (for long term operation under different conditions, and moving back and force "slave" relative to "master") each gain step is equally distributed in time—in other words, with a flat probability distribution function for output power over time. The PA is supposed to operate only during the transmit burst (which is usually implemented by a special shut-down pin in PA or setting control voltage below of certain level), while non-linear and linear modes of operation are characterized by 8 and 33 mA quiescent current provided by different control voltages applied to regulator pin.

An average current consumption separately for a Bluetooth chip and PA itself are presented in Figure 6 for synchronous voice communications modes. Remember that 2EV and 3EV modes are characterized only for linear operation.

One can see in Figure 4 that the highest total average current consumption is carrying out through the module during data transfer at DM5 (DH5) packet operation and then decaying through DM3 (DH3) to DM1 (DH1). This is easily understood as a Bluetooth chip during the transmit and receive mode has almost the same current consumption with fairly low level and mostly PA contributes to consumption (70% to 50% of total) dependent on burst duty cycle when PA is ON (see Fig. 4).

Figures 5 and 6 obviously show how efficient PA control can be done for different modes. If for Bluetooth chip itself at 4 dBm maximum output power (class-2) there is just 10% difference in current consumption between DM1 (DH1) and DM5 (DH5) modes, without power control implemented at a fixed 20 dBm output power (although power control is mandatory in this case) there is almost twice difference in an average current for class-1 module due to PA current contribution.

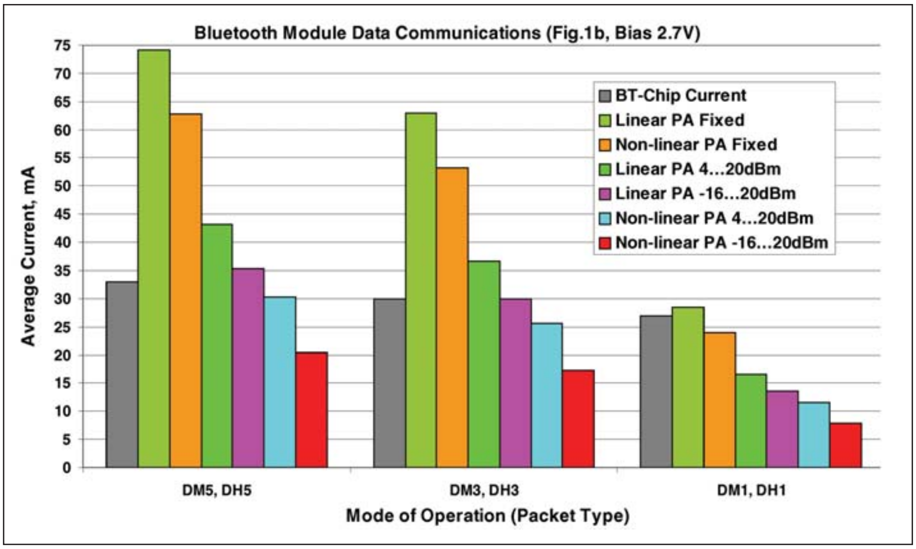

Figure 5 · Average current of a Bluetooth chip and PA in Fig.1b for several power control scenarios in different modes of data communications (control is provided by adjustment of RF power at a Bluetooth chip output).

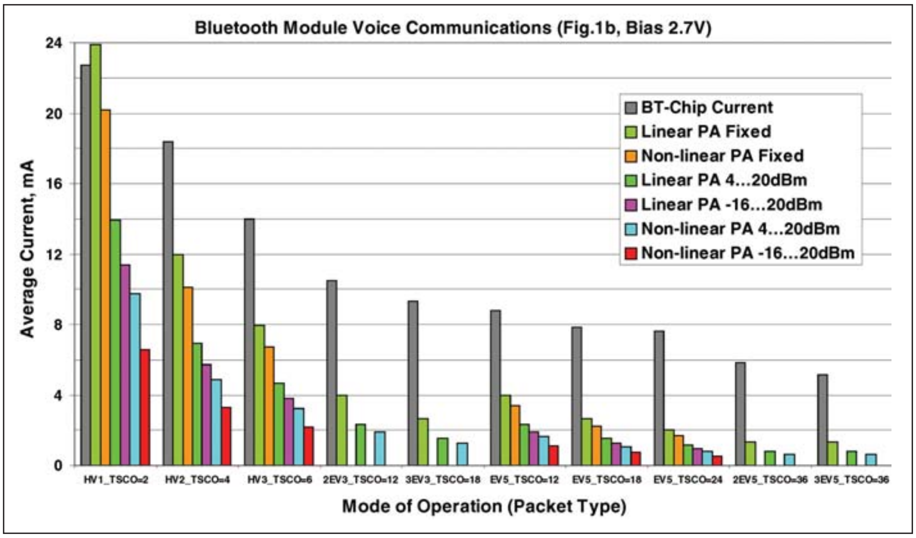

Figure 6 · Average current of a Bluetooth chip and PA in Fig. 1b for several power control scenarios in synchronous voice modes of operation (control is provided by an adjustment of RF power at a Bluetooth chip output).

For the same packet type the most efficient is a control scenario with wider control range both for nonlinear and linear operation. Current consumption savings can reach 40% to 50% of a total current for two dynamic ranges considered. By extending this range to lower power levels these savings will be even more efficient. Here one needs to note that although the PA considered above is operating in a linear mode, its quiescent current is substantially lower than at maximum power levels (PA operates in a mode close to class AB). However many linear PA in the market resemble class-A operation with quiescent current similar to large power current. In this case power savings are not so readily achieved.

Average absolute current savings of 20 to 40 mA may be critical for handheld battery powered devices while operating in DM (DH) data transfer modes (see Fig. 5).

For the voice communications modes of operation considered separately, in Figure 6 it is clearly seen that in a very crowded environment when many Bluetooth nodes (and other devices in ISM band) are operating simultaneously in limited area, the largest current consumption is for the HV1 scenario with forward error correction mechanism applied. In this case PA average current consumption is at the same level as for a Bluetooth chip and power control implemented within –16 dBm to 20 dBm range can reduce PA average current up to two times for linear PA. Usually there is no need for a linear PA in this case (GFSK modulation is enough to convey low data rate information), and implementing non-linear mode can reduce an average current up to three times. With increasing of TSCO number (lower duty cycle of a transmit burst) the PA contribution to an average current consumption becomes less, and the relative contribution of PA to the total consumption can become less than 10% with proper power control range utilized. This trend is especially obvious when a high data rate modulation is applied (EV modes) requiring higher duty cycles to transfer the same amount of a voice containment through air and with a linear PA needed for that. This will result in longer talk time for handheld devices such as a headset. In this case the main concern becomes current consumption of a Bluetooth chip itself (it is about 5 mA at 3EV mode at TSCO = 36 in our case).

Another important mode of operation for power saving discussion is PAGE mode during which a short ID (identification) signal is transmitted by "master" or "slave" trying to get in contact (or link) with its counterpart. Due to short length of this packet (fixed at 68 µsec) there is twice increased repetition rate during transmit slot (312.5 µsec) to get the link. Remember, communication range depends on an average transmitted power and not on a pulsed one; that is why multiple re-transmissions are possible until the link is established. In this case, it seems the scenario of maximum transmit power is the right choice to establish a link, although more sophisticated solutions are possible as well. This can consume quite large current due to PA implementation if the link is not established fast enough in crowded environment (more than 10 mA average only for PA).

An important parameter for the whole module is a standby mode (sleep, sniff etc.) when the current should have small value. Usually the Bluetooth chip itself has current consumption few tens of microamperes. The PA typically can have very low current consumption through collector chains when the control voltage applied to the base of a transistor is below an appropriate level. However, control is usually applied through a current mirror circuit, also sinking some amount of current, which may have fairly large level. Shut-down pins implemented in some PA also consuming current even in OFF mode if control is not chosen properly.

Conclusion

Bluetooth class-1 modules considered in this paper show fairly good current consumption characteristics due to appropriate matching applied at PA output. A Bluetooth chip along with PA can consume an average current just a bit higher than 5 mA during voice communications. The architecture with a BPF inserted at the input of PA can save a large amount of current from the bias supply. The different modes of operation considered here suggest the use of wider range power control at a Bluetooth chip, especially for data transfer modes, by which consumption can be saved up to two times. More sophisticated control can be used, where during power control, PA quiescent current is adjusted along with the Bluetooth chip RF signal level depending on non-linear or linear mode of PA operation (and an appropriate modulation applied to RF signal). For voice mode applications, a proper power control can save as minimum as 10% of the total battery charge for the handheld devices.

References

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