Understanding Regulations For Short-Range Radios

The choice of operating frequencies for a short-range radio system is usually based on controlling where harmonically generated signals fall and avoiding possible sources of interference.

Short-range radios provide the means for function control and limited data access between electronic systems. But these radios must perform in accordance with applicable regulatory agencies, such as the Federal Communications Commission (FCC) in the US and the European Telecommunications Standard Institute (ETSI). Part 2 of this four-part article series on short-range radios will review various global radio-transmission regulations and their implications for the design of low-cost short-range radios.

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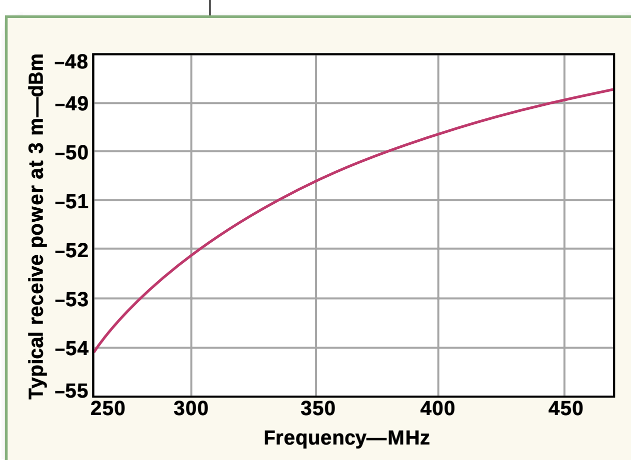
Classical short-range radios for control and security applications are typically in the 300-to-500-MHz range, with transmit-power levels from 2 30 to +10 dBm. These radios are generally certified, a form of approval where the manufacturer has the product tested in an approved laboratory that will confirm that the product meets specifications, and assists in submitting a report to regulatory agencies such as the FCC. The regulatory agency will then grant approval for production, and the end customer will never have to deal with any licensing issues. European and US rules require that the antenna of the certified equipment be integrated or use a customized connector to prevent users from substituting other antenna types.

The FCC rules officially govern operation only in the US, but also are adopted in varying degrees by many other nations in the Americas and the Pacific rim. There are four specific FCC rules



1. This plot shows the change in link budget (received power) with frequency when following FCC 15.231 rules, with an approximate 5-dB improvement in link budget over frequency.

of high interest to designers of control and security class short-range radio systems, with interrelationships between the four that must be understood. These four sections are 15.209, 15.231, 15.205, and 15.35. The rules for industrial-scientific-medical (ISM) band radios are provided in 15.249 for 1-mW (0-dBm)-class narrowband systems, and 15.247 for spread-spectrum systems up to 1 W (+30 dBm).

The so-called "general" rule, 15.209, restricts the RF energy that electronic equipment may parasitically emit. The specific level of emissions is 200 mV/m at 3-m test range below 960 MHz, and 500 mV/m above. These field strengths are equivalent to approximately 2 49- and 2 41-dBm effective radiated power (ERP), respectively.

Rule 15.231 is the major authorization for control and security-class equipment. For control applications, the permitted peak transmit level varies linearly from 260 to 470 MHz as provided by Eq. 8,

$$E_{SS}(f) = 0.041667(f - 260) + 3.75(control\ operations) \quad (8)$$

where:

E_{SS} = the permitted steady-state field strength [in root mean square (RMS) mV/m at 3 m for control applications], and

f = frequency (in megahertz).

For frequencies above 470 MHz, the permitted power is equal to that at 470 MHz. Equation 6 can be used to show that the transmitted ERP range is 2 24 to 2 13 dBm. These increasing FCC permitted power levels actually exceed the effects of decreasing antenna aperture with increasing frequency **(Fig. 1).** The band is approximately 5 dB better at the high end than at the low end, a fact that is apparently not well-known, but one whose positive effect may be reduced by the interference of television second harmonics. The permitted harmonic levels are 20 dB below these levels, except where they fall in restricted bands (below). Note that television-broadcast channel 13 ranges from 210 to 216 MHz, and then allocation skips to channel 14 at 470 to 476 MHz, so direct-television interference is not a problem throughout this range (though second harmonics can be a problem). The permitted RMS steady-state field strength for periodic operation (such as status reporting) not limited to control is approximately 8 dB lower. In addition, it must meet timing restrictions (except in emergencies) by having an off time of at least 30 times the transmit time, with transmissions that do not occur more often than once per every 10 s. (Under FCC 15.205, 260 to 285 MHz falls into a restricted band and may not actually be used.)

Section 15.205 of the FCC regulations documents the "restricted bands" where only spurious emissions are permitted, and where those must meet the general levels of 15.209. Above 1000 MHz, averaging as described in FCC 15.35 may be used. From these restricted bands, a list of desirable frequencies can be formed **(Table 1).**

From a link-budget point of view, the most desirable segment is 410 to 470 MHz. This section may be used at the maximum allowed power if approximately 28 dB of third-harmonic rejection is attained. Frequencies above 432 MHz also have the virtue of avoiding television harmonics. If a simple unfiltered loop antenna, required by cost considerations, does not attain this rejection, then an option is to use the reduced segment from 413.33 to 433.33 MHz. This segment is only 1 dB below the maximum link budget, and places no harmonics below the sixth harmonic in restricted bands. However, the 420-to-450-MHz range is an amateur-radio band. There is some land-mobile-radio operation from 421 to 430 MHz, and 418 MHz is a popular surface-acoustic-wave (SAW)-based frequency that some users might wish to avoid when possible. Based on this potential interference, the segments from 413.33 to 417.90 and 418.1 to 420.0 MHz would be superior. These segments do, however, fall into the second harmonic of television channel 12. The 307-to-320-MHz range would be preferred as a band that avoids direct interference and television harmonics, at the cost of

Table 1: Primary restricted frequencies under FCC 15.205

RESTRICTED FREQUENCY RANGE (MHz)	IMPACT
240 to 285	No fundamental usage here
322.0 to 335.4	No fundamental usage here
399.9 to 410.0	No fundamental usage here
608 to 614	Medical telemetry band, second harmonics from 304 to 307 MHz must meet the general requirement in this segment
960 to 1240	Note that third harmonic of 320.00 to 413.33 MHz must meet general
1300 to 1427	433.33 to 470.0 MHz must meet general with third harmonic
1435.0 to 1626.5	287.0 to 325.3 MHz must meet general with fifth harmonic

requiring the fourth harmonic of 307 to 310 MHz to meet the general level specification (500 mV, 2 41-dBm ERP) and suffering approximately a 3-dB link-budget degradation compared to the high end of the band. The subrange from 310 to 320 MHz is clear of television harmonics and its own harmonics dodge restricted bands through the fourth harmonic.

FCC section 15.35 covers the permitted increase of peak transmit-power levels when averaged with off times that use amplitude-shift-keying (ASK) modulation. The use of this averaging is popular in the US due to an apparent accidental misinterpretation of the rules that have since become accepted as standard practice. The original intent of the rules was probably to support averaging for maintaining constant energy per bit. However, due to the FCC standard practice of using electric-field strength instead of ERP, the rule was, in its early usage, interpreted to allow for the maintenance of average field strength, up to 10 times the maximum steady-state field strength. Since power is increasing as the square of field strength, this permitted peak power to increase up to 100 times, and average power to increase up to 10 times. The decrease in transmit time results in an increase in signal bandwidth that is exactly proportional to the increase in transmit power. There is no increase in signal-to-noise ratio (SNR) if receiver (Rx) bandwidth tracks. However, there are two exceptions to this, which will be discussed later.

The precise mathematics of ASK averaging may be derived in short order, using the following definitions:

D_C = the total digital duty cycle (FCC uses the 100-ms segment in the protocol with highest duty cycle). Note that if the bit density is 50-percent digital "ones" and if transmission is not made during digital zeroes, then the duty cycle is down to 0.5 even before any bit shortening of digital ones is applied.

D_{C1} = the duty cycle of each individual "one" counting bit shortening. Note that if the length of a one were cut in half (such as standard Manchester), then D_{C1} = 0.5 and with 50-percent digital ones, D_C = 0.25.

D_{C0} = the duty cycle of each individual digital zero. For simple ASK, this could be 0; for standard Manchester it is also 0.5; for a nonstandard Manchester, it could vary from 0 to 1 depending upon averaging desired (which also applies to D_{C1}).

D_0 = the logical duty cycle of zeroes in bit stream, typically 0.5.

D_1 = the logical duty cycle of ones in bit stream, typically 0.5.

Now, for the total duty cycle (fraction of time carrier is transmitted):

$$D_C = D_O D_{C0} + D_1 D_{C1} \qquad (9)$$

Eq. 10 can be shown by defining:

E_{SS} = the field-strength steady state, which equals the permitted RMS field strength at a particular frequency when not averaging, and

E_{pa} = the field-strength peak averaging, the permitted peak field strength at a particular duty cycle and frequency when averaging. According to FCC convention, this "peak" is not the true RF peak. It is the RMS carrier strength in volts per meter at the peak of the envelope:

$$E_{pa} = E_{SS} / D_C \qquad (10)$$

which shows the maximum permitted peak field strength under the rules, to a limit of 10 times the steady state allowed (E_{SS}).

Eq. 9 can be substituted into Eq. 10 and solved in Eq. 11 (p. 86) for the necessary duty cycle within the bits given permitted (regulatory) and attainable (hardware-limited) field-strength levels. This can be shown in power terms as Eq. 12 (p. 86).

The averaging effect may be used to reduce harmonic-attenuation requirements above 1000 MHz, where "in the restricted bands," a level of 500 mV/m is generally required. The 500-mV/m level corresponds to 7.5 3 $10^{2\ 8}$ W ERP or 2 41.2-dBm ERP.

The effect of averaging strongly influences the choice between ASK and frequency shift keying (FSK) in FCC follower countries, which may be quantified as follows. For the case of nonreturn-to-zero (NRZ) ASK data with possible pulse shortening, one may write for the average ASK power, P_{ASK}:

$$P_{ASK} = 0.5 D_{C1} P_{pa} \qquad (13)$$

In Eq. 13, D_{C1} = 1 if no pulse narrowing is not used. If the Rx bandwidth is the reciprocal of the symbol time with pulse narrowing, T_{NS}, and without pulse narrowing, T_S, and taking into account the 50-percent duty cycle of simple ASK, then it may be shown that the ratio of the SNRs for ASK transmit power, P_{pa}, between 0 and 6 dB over the steady-state limit, P_{SS}, and FSK transmit power at P_{SS} is shown in Eq. 14 (on p. 86).

This advantage scales from 0 to 3 dB as P_{pa} advances from 0 to 6 dB over P_{SS}. Substituting Eq. 12 for Eq. 14 will show that for P_{pa} greater than 6 dB over P_{SS}, the advantage for ASK tops out at 3 dB, so as long as Rx bandwidth is at the reciprocal of symbol time. However, low-cost Rxs for this class of equipment are often unable to match their noise bandwidth to be only the reciprocal of symbol time so, in practice, averaging is often a significant improvement.

It may be apparent that US rules for control and security operation are not particularly easy to follow, being spread over four sections, lacking in some definitions, and not written in a tutorial fashion. However, they are pleasant reading compared to the European rules, which are spread out over many documents, often seem to lack references to essential supporting data and, in general, seem to feature considerable disregard for reader convenience. These rules have been

$$D_0 D_{C0} + D_1 D_{C1} = E_{SS} / E_{pa} = (allowed\ electric\text{–}field\ strength) / (attainable\ electric\text{–}field\ strength) \quad (11)$$

$$D_0 D_{C0} + D_1 D_{C1} = (P_{SS} / P_{pa})^{0.5} = (allowed\ steady\text{–}state\ power / allowed\ peak\ power)^{0.5} \quad (12)$$

$$SNR_{ASK} / SNR_{FSK} = (0.5 D_{C1^2})(P_{pa} / P_{SS}) \quad (14)$$

reviewed here in as practical a way as possible, although there may be mistakes made in these interpretations of the European regulations. Fortunately, there is a fairly high degree of standardization on bands and transmit-power levels throughout Europe, with most disagreements coming in the permitted modes and transmit duty cycles. This is achieved under the regional authority of the European Conference of Postal and Telecommunications Administrations (CEPT), which has 43 member nations. ETSI develops technical standards for CEPT countries.

A significant philosophical difference in the European rules are provisions that go beyond preventing interference to other systems attempting to guarantee acceptable system performance. Most electronic equipment sold in the European Union must comply with EMC Directive 89/336/EEC and be labeled with the CE mark, in conformance with this policy. After April 8, 2000, compliance with these requirements could be self-certified by certain procedures (see www.ero.dk). Another important document governing required performance its ETS 300 683, "Electromagnetic Compatibility (EMC) Standard for Short Range Devices Operating Between 9 kHz and 25 GHz." This document's performance requirements are centered on interference immunity from outside EM fields and disturbances on power-supply and control inputs. The document refers to other documents for many measurement details. Designers of finished radio equipment to be marketed in Europe must review this set of documents in some detail.

For control and security applications the most fundamental document is CEPT ERC Recommendation 70-03 (which can be downloaded at www.ero.dk). Further details on test methodology to confirm compliance are provided in ETSI EN 300 220-1 (which can be downloaded from ETSI's site at www.etsi.org). EMC compliance is described in ETSI ETS 300 683. For ISM-band operation, which generally includes higher-end applications such as Bluetooth and wireless local-area networks (WLANs), ETSI 300 328 is, in general, the applicable document. Europe does not have the 902-to-928-MHz ISM band, but does use the same 2400-to-2483.5-MHz ISM band that is authorized by the FCC, though at a reduced spread-spectrum power level of 100 mW (the US is up to 1 W). Note that up to 10-mW ERP narrowband is authorized in the European 2400-MHz band, though this is not mentioned in ETSI 300 328 with the other 2400-MHz rules. Instead, this is authorized in CEPT recommendation 70-03 under Annex 1 (see **Table 2** and references).

For classic control and security applications that are similar to FCC 15.231, the European rules support the use of 433.05 to 434.79 MHz under the "non-specific short-range device" rules of Annex 1 under ERC 70-03E. This band segment just misses the second harmonic of television channel 13, a likely reason for its selection. The approval process is similar to US certification where individual licenses are not required. The basic rules here are up to 10-mW ERP, at less than 10-percent duty cycle, with some countries having differing duty-cycle limits. This generous transmit power has the capability to provide an excellent short-range link. Though applications are not specifically limited, the 10-percent duty-cycle limit inherently restricts applications to control, intermittent status reporting, and low-end data acquisition (DAQ). There is no designated frequency-accuracy specification provided, but since the band is not channelized, the general wide band 6 100-PPM requirement of Table 7 in ETSI 300 220-1 (p. 24 of the regulation) should apply. This would appear to be a difficult requirement for untuned low-cost SAW-based devices to meet, but the apparent practical interpretation of this rule is that it covers temperature and power-supply drift, allowing tuned SAW-based devices to meet it with the assumption that set on error is negligible. The harmonics are not specifically called out, but the general spurious limits of 250 nW below 1000 MHz and 1 mW above 1000 MHz provided in Table 13 of ETSI 300 220-1 (on p. 34 of that regulation) should apply. Note that at full power of 10 mW, this is 2 46 dBc for the second harmonic and 2 40 dBc for higher harmonics. Since this limit is not set as strictly in dBc, for a typical ERP of 2 10 to 2 20 dBm attained with a printed-loop antenna, the limit to the second harmonic is closer to –26 to –16 dBc. Note that there are certain band segments where the operating-mode parasitics are limited to 4 nW, including 470 to 862

Table 2: These FCC 15.231 frequencies can be used to avoid carriers, second, and third harmonics in restricted bands below 1000 MHz

FREQUENCY (MHz)	COMMENT
285 to 304	Stop at 304 MHz to avoid placing second harmonic in medical band
307 to 320	Stop to avoid third harmonic from 960 to 1000 MHz. Note that the fourth harmonic of 307 to 310 MHz is restricted
335.4 to 399.9	Stop to avoid direct restricted
410 to 470	Power tops out at 470 MHz

MHz. At 2 10 dBm ERP, there is 2 44-dBc required spurious suppression in these band segments.

Although television-station frequency allocation skips over the US 260-to-470-MHz band, the frequencies are so powerful that their second harmonics are still a potential interference problem. Television stations 7 through 13 are permitted to have power levels to 316 kW, with harmonics for analog stations that are limited to 2 60 dBc or better (future digital TV is expected to feature much lower harmonics, reported as 2 110 dBc). **Table 3** shows television and FM channels and frequency allocations. The segment 285 to 348 MHz avoids television harmonics, and the segment 324 to 348 MHz avoids television and FM broadcast harmonics. However, the band from 322 to 335.4 MHz is directly restricted by FCC section 15.205, and there are restricted band-harmonic issues that make other segments less than optimum as well.

To gauge the potential problem, a standard handbook is referred to, such as ref. 3 for graphs of electric-field strength from broadcast stations. One approximation is 10 to 90 dBmV at the carrier frequency for distances from the broadcast transmitter (Tx) from 200 to 5 km per kilowatt of transmit power. Converting to watts for a 100-kW station with a Tx tower 100 m tall that are picked up at the 2 60-dBc second harmonic by a quarter-wave whip at 400 MHz shows a receive power of 1.7 3 $10^{2\,21}$ to 1.6 3 $10^{2\,13}$ W that is spread over the 12-MHz (at the second harmonic) television bandwidth.

Converting to dBm/Hz, the spectral density of this interfering source is approximately 2 225 dBm/Hz at 200 km up to 2 146 dBm/Hz at 5 km. The farther ranges are negligible as interference, but the shorter ranges definitely exceed the 2 174-dBm/Hz thermal noise floor that Rx sensitivities and link budgets are typically calculated against. With a typical inverse-forth power-propagation constant in this environment, interference could be expected up to approximately 20 to 40 km.This is conservative since the Rx antenna height is 9 m in the graph used. Actual power density may be 10 to 20 dB lower at the typical 1-to-2-m antenna height of short-range radio Rxs, reducing these interference ranges by a factor of two to four, but it does illustrate the potential seriousness of the issue. Some systems are likely to be suffering interference from this source that significantly reduces range and reliability, without designers being aware of the cause. Narrowband Rx systems can reduce this problem by using frequencies that are placed at the band edges of the television harmonics, such as 420 MHz, where energy density is approximately 20 dB lower. Fortunately, improved filtering in newer digital television stations should reduce the incidence of this interference in the future.

The effects of regulations on frequency choices may be summarized as follows. The European choices are restricted to 433.05 to 434.79 MHz at 10-percent duty cycle (most countries) and a maximum power of +10 dBm among the lower ultra-high frequencies (UHF). If this is not adequate, the user may step up to 868 to 870 MHz with some segments, allowing up to +14 dBm at up to 100-percent duty cycle. The US choice of carrier frequency is a more complicated subject. The segments from 413.33 to 417.90 and 418.1 to 420.0 MHz are excellent for avoiding placing harmonics through the fifth harmonic in restricted bands that require more Tx filtering circuitry, while simultaneously dodging direct interference. They do suffer broadcast-television second-harmonic interference, the seriousness of which depends on location, frequency placement, and Rx bandwidth. The segment from 432 to 470 MHz is excellent for enabling near-maximum link budget and avoiding television and FM second and third harmonics, but does require up to 2 28-dBc harmonic rejection of its own third harmonic, which may be difficult to attain with an unfiltered loop antenna. The segment of 310 to 320 MHz is clear of television harmonics, and its own harmonics dodge restricted bands through the fourth harmonic. It does suffer from the third harmonic of FM broadcasting and its link budget is 3 to 5 dB inferior to the higher frequencies, but is suitable for low-cost applications that cannot pay for Tx filtering. In general, the 285-to-470-MHz band that is available in the US under FCC 15.231 is an under-used resource with many short-range-radio business opportunities.

By giving up segments of usable frequency to dodge "restricted bands" in the US, it is generally possible at typical transmit powers (0 dBm driving a 5-to-10-percent efficient loop antenna) to satisfy US and European rules with approximately 20 to 30 dB of harmonic suppression. For example, for US operation at steady-state output power in the 413.33-to-433.33-MHz band, only 20-dB suppression is needed through the fifth harmonic, and then 26 dB for the sixth harmonic. That same Tx, when reset to 433.92 MHz for the European market, needs at least 22 dB for all harmonics. If the European 0-dBm ERP Tx uses an efficient quarter-wave whip, then it needs a minimum of 36-dB second-harmonic suppression.

Despite the improved energy per bit that is possible with averaging in the US, the actual link quality remains little affected if Rx bandwidth tracks transmitted spectral occupancy. An exception to this generalization is that ASK averaging without symbol shortening can yield an up to 6-dB improvement over nonaveraged ASK and up to 3-dB SNR improvement over FSK. In general, if narrowband Rxs can be provided in a particular application, better system design will result due to an equivalent link being maintained with more spectral efficiency (more channels and less interference) and with smaller Txs (smaller antennas and batteries). But if cost constraints force use of a wideband Rx, then averaging a shorter (wider-bandwidth) pulse of higher power will yield a significant link improvement for that nonideal case as compared to not averaging.

In high-mobility systems such as cellular networks, angle modulation [FSK or phase-shift keying (PSK)] is generally technically superior due to its improved multipath performance and greater interference immunity. Since Europe does not allow any ASK-friendly averaging effect, European FSK supports an inherently 3-dB improved link budget by the simple virtue of its 100-percent duty cycle. For low-mobility systems (most short-range radio applications) where Rx detectors are properly designed to provide a capture effect, FSK has little inherent link advantage. Therefore, in the US and other FCC countries, the choice between ASK and FSK, as far as link budget is concerned, depends on where the transmit power that a particular Tx, battery, and antenna may attain falls relative to the maximum permitted steady-state values. If the maximum attainable value is less than the steady-state limit, then FSK is superior since it will again show a 3-dB link-budget improvement. But if the maximum attainable power falls between the steady-state limit and 6 dB above the limit, ASK shows an advantage because the data duty cycle may be averaged without shortening pulses and widening Rx noise bandwidth. This net link improvement will be 3 dB over FSK if the ones bits may be transmitted at 6 dB above the steady-state limit. For transmit peak power that is more than 6 dB above the steady-state limit pulse shortening must be used, which widens Rx-noise bandwidth. This limits the advantage of ASK to at most 3 dB compared to FSK if the Rx bandwidth can be controlled to match transmitted spectral occupancy.

The European rules, specifically ETSI EN 300-220-1 section 6.6, can also be inferred to set a phase-noise specification. Those regulations indicate that the spurious noise must meet the general European 250-nW spurious level (2 36 dBm) using a 10-kHz spectrum-analyzer resolution bandwidth for carriers up to 25 MHz, using a 100-kHz analyzer-resolution bandwidth for carriers from 25 to 1000 MHz, and using a 1-MHz analyzer-resolution bandwidth for carriers above 1000 MHz. It would not be logical for this to be interpreted as a phase-noise requirement when the phase-noise offset frequency is still in an allocated band, such as 433.05 to 434.79 MHz (it is not a spurious product when it is in the permitted band), but it makes sense from the regulatory perspective to require integrated phase noise over these spectrum-analyzer bandwidths outside of the assigned bands to meet these spurious levels. Based on transmitted ERP, the inferred phase-noise requirement thus becomes Eq. 15 (p. 96)).

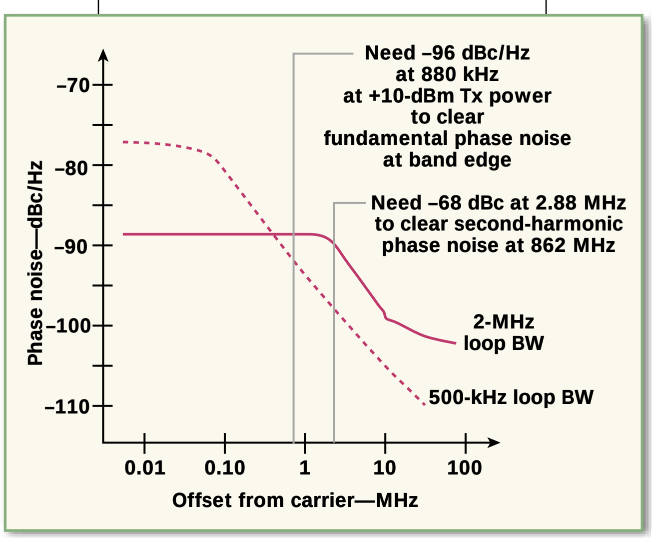
At +10 dBm in the 434-MHz band, there is an implied out-of-band phase noise of 2 96 dBc/Hz. If a carrier is set at a nominal frequency of 433.92 MHz, then at 100-PPM maximum error it can get to within 880 kHz of the band edge, which is where this 2 96 dBc/Hz becomes applicable. The far-from-the-carrier transmitted phase noise (which may be helped by the frequency response of the antenna) must meet the 4-nW limit of the European "restricted" segments from 174 to 230 MHz and 470 to 862 MHz (Eq. 16).

(See Eq. 16 on p. 96.)

At +10 dBm and neglecting antenna bandwidth, this

Table 3: Television and FM frequency assignments

CHANNEL	CARRIER (MHz)	SECOND HARMONIC (MHz)
6	82 to 88	164 to 176
7	174 to 180	348 to 360
8	180 to 186	360 to 372
9	186 to 192	372 to 384
10	192 to 198	384 to 396
11	198 to 204	396 to 408
12	204 to 210	408 to 420
13	210 to 216	420 to 432
14	470 to 476	940 to 952
FM stereo	88 to 108	Third harmonic = 264 to 324



2. This plot compares the typical integrated Tx phase noise at two sample PLL bandwidths with the inferred phase-noise requirements for European (and US) short-range radio systems. At the full transmit power of +10 dBm, the phase noise fails by approximately 3 dB for the 500-kHz loop filter and about 8 dB for the 2-MHz loop filter.

is a transmitted phase noise of 2 114 dBc/Hz.

It may also be inferred that the restricted band from 470 to 862 MHz, with its 4-nW spurious specification, sets phase noise and spurious limits for the second harmonic of the transmitted level, which could come in as low as 867.76 MHz with 100-PPM crystals. This implies that at 2.88 MHz offset from carrier, the transmitted phase noise must be at 2 68 dBc/Hz, and any discrete spurious must be 18 dB below the carrier if the second harmonic is at the 250-nW upper limit. These limits may usually be neglected since the carrier-frequency limits turn out to be the worst case.

This same rules section also sets the inferred synthesizer reference (phase-detector sampling rate) spurious specification shown in Eqs. 17 and 18 (see above).

The reference spurious component of 2 36 dBc for 0-dBm Txs is not difficult, but at +10 dBm and 2 46 dBc, care is required. The phase-noise specifications are not difficult for good-quality discrete designs, but may become more troublesome for low-quality-factor (Q) integrated designs, particularly at +10 -dBm ERP. This leads to a need for high loop bandwidths to suppress phase noise, which then tends to worsen synthesizer spurs. **Figure 2** shows phase-noise limits derived from these rules compared to typical performance of an integrated Tx at two different phase-locked-loop (PLL) bandwidths. The inferred mask, which is suitable for use in the US, is from a regulatory perspective. Acceptable performance for narrowband FSK in terms of phase-noise-limited SNR is an issue that shall be addressed in the next part of this article series. MRF

$$\phi_N(close\,in) = -\left[P_{ERP}(dBm) + 36 + 10\log(BW)\right] \qquad (15)$$

$$\phi_N\,(far\ out) = -\left[P_{ERP}(dBm) + 54 + 10\log(BW)\right] \qquad (16)$$

$$-\left[P_{erp}(dBm) + 36\right]\ for\ spurs\ in\ the\ 250–nW\ segments \qquad (17)$$

$$-\left[P_{erp}(dBm) + 54\right]\ for\ spurs\ in\ the\ 4–nW\ segments \qquad (18)$$

ACKNOWLEDGMENTS

The author wishes to express appreciation for the valuable reviews and inputs from other members of the Microchip RF Products Group, and from Didar Islam, David Saar of Saar Associates, Alan Bensky of Ateret Radio Engineering, Paul True of Linx Technologies, Frank Perkins of RF Monolithics, and Andreas Laute of Melexis.

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