IEEE 802.11
Wireless Access Method and Physical Layer Specification

Title: **Recommendations For 2.4 GHz Frequency Hop Receiver Specifications of Sensitivity, Intermodulation And Desensitization**

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Abstract: In order for the 802.11 standard for Frequency Hop to be broadly embraced, the performance expectations associated with the standard should be consistent with what can be achieved with low cost but yet state-of-the-art components and design technology. The receiver specifications proposed here are consistent with that goal. This paper address three important RF performance specifications for the 2.4 GHz frequency hop PHY layer, i.e., receiver sensitivity, intermodulation protection and desensitization protection. Performance specifications are proposed which are consistent with both analysis of fundamental receiver design considerations and measured data on a prototype receiver.

Introduction

The receiver performance expectations discussed in this submission represent realistic performance expectations based on practical technology. A basic block diagram is presented which represents realistic implementation parameters. Based on this block diagram, performance expectations are derived. In addition, data from a prototype receiver is shown that demonstrates the capabilities of an actual radio. Following a discussion of these results, specifications for sensitivity, intermodulation protection (IMp), and Desensitization protection (Dp) are proposed.

Block Diagram

The block diagram of Figure #1 is generic in form, but provides a format for listing the principle receiver parameters relative to receiver sensitivity, IMp, and Dp.

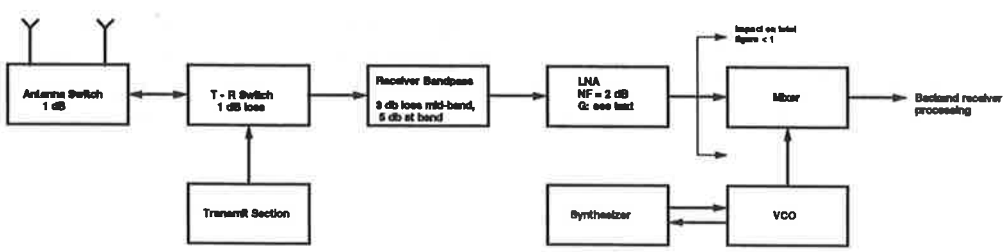

Figure #1 - Block

This block diagram assumes the use of antenna diversity and thus the use of an RF switch for antenna choice. A second RF switch provides the ability to connect the chosen antenna to either the receiver or transmitter sections of the 2.4 GHz transceiver. Each of these switches is estimated to have no more than 1 dB of loss in the closed or pass state. In the receiver line up, an input bandpass filter is shown which would have no more than 3 dB of loss at center frequency and less than 2 dB of additional loss at the band edges of 2.4 and 2.5 GHz.

The received input RF signal is coupled from the RF bandpass filter to the Low Noise Amplifier, LNA. It is reasonable to assume that the LNA will have a noise figure of 2 dB. The gain requirement for the LNA is quite implementation specific. In order to keep the discussion generic, it will be assumed here that the gain of the LNA is high enough to render the noise figure contributions of the remaining stages to 1 dB or less. This would occur, for instance, if the single side band noise figure of the stages that follow the LNA is 12 dB or less and the gain of the LNA is 18 dB or more.

The second receiver parameter considered is third order input intercept, IP_{i3}. As in the above discussion of noise figure, the issues are design or product specific. It is reasonable, however, to estimate that with moderate power consumption receiver front end components, a IP_{i3} on the order of -15 to -20 dBm can be achieved. For the basis of discussion, an overall input IP_{i3} of -20 dBm will be assumed.

The third receiver parameter discussed here is VCO sideband noise. What is of particular importance to the 2.4 GHz Frequency Hop Standard is the magnitude of sideband noise associated with the VCO removed from the nominal carrier by 1.5 MHz to 2.5 MHz on either side (alternate channel), by 2.5 MHz to 3.5 MHz on either side (third channel removed), etc. While each hardware manufacturer will evaluate its own source of information, Motorola's examination of applicable commercial VCOs, as well in-house engineering results, indicate that the alternate channel noise can be expected to be in the -126 to -132 dBc/Hz range. In the third channel removed, the sideband noise can be expected to be 4 dB lower. For the purpose of this discussion, the VCO noise in the alternate channel will be assumed to be -126 dBc/Hz, and in the next channel and other channels more removed, a noise level of -130 dBc/Hz will be assumed.

The final basic receiver parameter discussed here is the synthesizer spurs that occur as narrowband noise on the VCO sidebands when the VCO is operating within a closed loop synthesizer. It is projected that the synthesizer spurs will be low enough that they will have no greater impact on receiver performance than VCO sideband noise.

Performance Expectations

Performance expectations and proposed specifications discussed in this submission are based on a hardwired 50 Ohm reference. In addition, it is understood that the test conditions utilize the 1 Mb/s Foundation modulation format of 0.5 GFSK where the deviation is set to a nominal +-170 KHz.

Sensitivity

Sensitivity of the receiver is defined as the minimum RF level, coupled through a 50 Ohm connector into the transceiver input in place of one of its antennas, that will produce a bit error rate, BER, of 10^{-5}.

Based on the block diagram discussed above, the input noise figure is the summation of the following factors:

Div Sw:	1 dB
T/R Sw:	1 dB
Filter:	3 dB
LNA:	2 dB
Rec. backend:	1 dB
Total:	8 dB

Note that this is the mid-band noise figure. An additional 2 dB of noise figure is allowed at the band edges of 2.4 and 2.5 GHz.

A noise figure of 8 dB translates directly to a 1 MHz noise floor of:

kTB	-174 dBm/Hz
Bandwidth:	60 dB
Noise Figure:	8 dB
Noise Floor:	-106 dBm

From an earlier submission, 93/102, by this author, the required SNR for reception at a BER, of 10^{-5} with the Foundation modulation format was determined to be 19.3 dB. The RF sensitivity of the nominal receiver is then:

Noise Floor:	-106 dBm
SNR:	19.3 dBm
Sensitivity:	-86.7 dBm

It is reasonable to provide an allocation for tolerance. Thus, a proposed mid-band sensitivity of -84 dBm is appropriate with -82 dBm limits applied to the band edges of 2.4 and 2.5 GHz.

Intermodulation

Intermodulation protection, IMp, is an important specification for a receiver functioning within a network of many operational RF links in close physical proximity. For instance, assume that a particular receiver is receiving a signal on channel #20 (assuming the channels, with 1 MHz spacing, are numbered in order) and that there are other signals present, one on channel #24 and one on channel #28. These two signals have the potential to combine in a nonlinear device to produce interference on channel #20. Protection from such forms of interference is quite important especially in a high capacity communications system. It can be argued that in high capacity systems, IMp is a dominant consideration. It is thus appropriate that an IMp specification be included in the proposed 802.11 standard. Patterning an IMp specification after the procedures of EIA for communications equipment, the following IMp measurement process is proposed.

Accordingly, the desired on channel signal, is increased to a level 3 dB above the measured sensitivity of the receiver under test. Two IM producing signals are then introduced, one at 4 MHz above the desired signal and the other a 8 MHz above the desired signal. Each of these signals is modulated with the Foundation modulation but with data streams not correlated to each other or to the data stream being received by the receiver under test. The two IM producing RF signals are maintained at equal levels and increased together until the BER recovered by the receiver under test is reduced to 10^{-5}. The ratio of one of the IM producing signals to the measured sensitivity, S, is the measured IM protection ratio, IMp. The test is repeated wen the interfering sources are at -4 and -8 MHz.

With this definition in mind, the expected IMp of the receiver indicated in the block diagram can be estimated. From the definition of third order intercept:
$P = 3*U - 2*IP_{i3}.$,
where,
U = The magnitude of two IM producing signals in dBm
P = the IM product in dBm produced by the two IM producing signals of magnitude U in dBm, and
$IP_{i3}.$ = the third order intercept of the receiver, in dBm.

In the current consideration, the bandwidth of the IM product is larger than the receiver bandwidth. Thus some of the RF power from the IM product is lost. The resulting filtered IM product, however, is not constant amplitude and thus contributes to the overall noise floor in a manner similar to Gaussian noise. The effective inband IM product, P_e, is approximately,
$P_e = P - 3$ dB

IP_{i3} of the receiver under consideration is assumed to be -20 dBm. When IMp is being measured, P_e is equal to the effective kTB noise floor. Noting that the specified receiver sensitivity is -84 dBm, the effective kTB noise floor, N_f, is:
N_f = -84 dBm -19.3 dB = -103.3 dBm.
Thus,
P_e = -103.3 dBm.

From above it is apparent that,
$U = (P_e + 3 + 2*IP_{i3}.)/3$

Which for the above condition is,
U = (-103.3 + 3 +2* (-20))/3 = -46.8 dBm

IMp is then,
IMp = U - S = -46.7 + 84 = 37.2 dB

(Note that for the nominal sensitivity of -86.7 dBm, the IMp corresponding to the same $IP_{i3}.$ is 39.1 dB)

Providing a margin for manufacturing, a specification of 35 dB is proposed.

Selectivity or Desensitization Protection, Dp

Overview of Desensitization Issues

In a filter context one specifies selectivity in terms of bandwidth and attenuation at certain frequencies. While filters are required in a receiver, the issue of receiver selectivity encompasses a wide variety of parameters that determine the receiver's ability to receive a signal on one frequency while other signals or interference are present on other channels. IM protection, IMp, discussed above is a part of the total picture. In this section however, the focus is protection against a single frequency interferer, termed desensitization protection, Dp. Specifically, the issue here is like signals within the 2.4 to 2.5 GHz band. Such signals will be considered to reside within one of three channel locations relative to the channel of operation for the receiver under test. These are:

Adjacent channel: This channel is located from 0.5 to 1.5 MHz removed, either above or below, from the desired channel of operation. It is generally concluded that since there is no guardband between this channel and the desired channel there is limited effective selectivity.
Alternate channel: This channel is located from 1.5 to 2.5 MHz removed, either above or below, from the desired channel of operation.
Remote channels: These channels are 1 MHz wide and located on center frequencies removed by at least 3 MHz from the desired frequency of operation.

Desensitization is measured by setting the desired signal at a level 3 dB above the measured sensitivity and then introducing an interfering like modulated signal, I, at an offset frequency and increasing the magnitude of the interference until the BER returns to 10^{-5}. For the purpose of these desensitization test, the sideband noise of the interference signal or generator shall be low enough, exclusive of modulation components, so as not to effect the results of the tests.

Expectations for Desensitization Protection

There are four principle issues that limit the desensitization protection to a level less than what might be expected from a simple consideration of receiver filters. Each of these will be considered in turn for both the alternate and remote channel conditions. The adjacent channel is not considered at this time. These results will then be summarized, from which final recommendations for a specification are made.

These issues are:

1. Receiver non linearity or overload

Single tone interference protection can be described as an intermodulation effect which can be predicted based on third order intercept. These results, however, are typically optimistic. Keeping this in mind, and assuming a 10 dB correction factor, the apparent level of desensitization, D_p, is estimated.

$Dp = IP_{i3}$.- 10 dB - (-84 dBm) = -20 -10 +84 = 54 dB

This number applies to both the alternate and the remote channel scenarios. Thus,

Dp (alternate ch) = 54 dB

Dp (remote ch) = 54 dB

2. VCO noise

VCO signals used in the receiver's mixing operation have noise components 2, 3 and more MHz removed from the nominal frequency of the VCO. These noise components mix with undesired off channel signals to produce on channel interference. From the block diagram discussion above, the VCO noise at 2 MHz from the nominal frequency will be assumed to be -126 dBc and at 3 or more MHz from the center frequency, -130 dBc. In a 1 MHz bandwidth, the total noise is -66 dBc and -70 dBc respectively. Noting the requirement for 19 dB of SNR at the receiver, the Dp for the alternate and remote channels due to VCO noise only is estimated at,

Dp (alternate channel) = 47 dB

Dp (remote channel) = 51 dB

3. Modulation splatter

A transmitted signal in an adjacent channel will have modulation components that fall within the receive passband of the receiver under consideration. Motorola

simulations have shown that with an ideal bandpass filter, i.e., a brickwall bandpass filter, and the Foundation modulation format, the intercepted power of an alternate channel transmitter is -70 dBc. With practical filters, 6 dB increase in intercepted power is a reasonable expectation. The expected Dp at the alternate channel would then be,
Dp (alternate channel) = 70 -6 -19 = 45 dB
Dp (remote channel) = NA

4. Synthesizer Spurs
When the VCO is performing within a synthesizer loop, the synthesizing function imparts spurs on the VCO RF output. These spurs typically appear as discrete sideband tones on the VCO spectrum. The impact of these spurs on selectivity is similar to that of VCO noise. Rather than tying to predict the level of spurs and relate that to limitations in desensitization protection here, suffice it to say that the spurs should be controlled to the point where their impact on Dp is no greater than the sideband noise of the VCO. Thus,
Dp (alternate channel) = 47 dB
Dp (remote channel) = 51 dB

Summary of Exemplar Desense Issues

Issue	Dp (Alt Ch)	Dp (Rmt Ch)
Strong signal overload	54 dB	54 dB
VCO noise	47 dB	51 dB
Splatter	45 dB	NA
Synthesizer Spurs	47 dB	51 dB

Based on this review, a Dp specification of 40 dB at the alternate channel and 45 dB at remote channels is appropriate.

Receiver Data
In order to demonstrate that the scope of conclusions presented in this paper are reasonable, data from a prototype transceiver, with diversity is presented. Actual measurements are:

Sensitivity

BER vs RF level:

RF level	BER
-91 dBm	3.6×10^{-3}
-90 dBm	1.9×10^{-3}
-89 dBm	8.0×10^{-4}
-88 dBm	2.6×10^{-4}
-87 dBm	7.0×10^{-5}
-86 dBm	1.6×10^{-5}
-85 dBm	2.6×10^{-6}
-84 dBm	2.0×10^{-7}

Sensitivity at BER = 1×10^{-5} is -85.7 dBm.

Intermodulation

Intermodulation protection, IMp:
at +4 and +8 MHz, IMp = 41.1 dB
at -4 and -8 MHz, IMp = 38.6 dB

Desensitization

Desensitization protection, Dp:

at -4 MHz	51.6 dB,	at +4 MHz	54.5 dB
at -3 MHz	49.3 dB,	at +3 MHz	51.7 dB
at -2 MHz	37.0 dB,	at +2 MHz	36.3 dB

Discussion Of Data

Sensitivity, S
The data presented above indicates that the sensitivity of the receiver with both T-R and Diversity switch meets the proposed specification by 1.7 dB. This is the margin that the discussion above predicted.

Intermodulation Protection, IMp
The data presented demonstrates that the receiver meets the proposed IMp specification by 3.6 dB which is close to the margin predicted.

Desensitization
The data listed above indicates that the receiver meets the proposed desensitization specification at 3 MHz separation and above but not at the alternate channel, 2 MHz separation. The margin at 3 MHz separation is 4.3 dB. At 2 MHz separation the short fall is 3.7 dB. Motorola has evaluated the shortfall and determined that it is due to insufficient close-in selectivity in the IF filtering. This issue will be addressed as the product concept matures, thus bringing the design into compliance with the proposed specification.

Summary Of Proposed PHY Receiver 50 Ohm Specifications

Sensitivity

Sensitivity is the minimum signal level required to produce a BER of 10^{-5}.

Sensitivity at BER of 10-5:	-84 dBm midband, -82 dBm at the band edges

Intermodulation protection

IMp is the ratio to measured sensitivity of the minimum amplitude of one of two equal level interfering signals at 4 and 8 MHz removed from center frequency, both on the same side of center frequency, that cause the BER of the receiver to be reduced to 10^{-5}, when the desired signal is 3 dB above sensitivity. Each interferer is modulated with the Foundation modulation uncorrolated in time to each other or the desired signal.

IMp for Is at 4 and 8 MHz removed:	35 dB

Desensitization

Dp is the ratio to measured sensitivity of the minimum amplitude of an interfering signal that causes the BER of the receiver to be reduced to 10^{-5} when the desired interferer is 3 dB above sensitivity. The interferer is modulated with the Foundation modulation uncorrolated in time to the desired signal.

Dp for I 2 MHz removed	40 dB
Dp for I 3 or more MHz removed	45 dB