PEAK INSTANTANEOUS POWER RATING OF ANTENNAS

Preamble

There are a number of significant antenna specifications that determine the selection of an appropriate antenna for a particular application. These may include bandwidth, directivity, gain, pattern stability, and, due to the growing recognition of the intermodulation problems that may be associated with transmitter antennas serving multicarrier combiners, the Passive Intermodulation specification (or PIM rating).

The power rating of the antenna, in particular when utilised in a multicarrier transmitter combiner application, is a critical specification that must also be considered. This specification has traditionally been limited to the maximum continuous power that can be handled by the antenna. Incidentally, this power rating *should* be referenced to an acceptable temperature rise above ambient of critical antenna elements (when subjected to the specified maximum continuous power). Obviously, this is a crucial specification since the continuous presence of maximum power at the antenna causes significant internal heating at susceptible elements (such as harness junctions, input cabling, & cable terminations); the consequences of which will be drastic if the antenna is not capable of handling this power continuously.

However, there is another power-related specification which needs to be considered in today's high powered multicarrier transmitter combiner applications. This is the Peak Instantaneous Power (PIP) rating, and although its inclusion as an important specification is novel, its relevance has always been important in legacy systems, particularly when selecting suitable lightning protectors for multicarrier transmitter combiner applications. In fact, the dimensioning of suitable lightning protectors in these applications has traditionally remained somewhat of a mysterious art - perhaps due to a lack of understanding of the physics behind the resultant voltage waveform envelope in multicarrier environments.

PIP ratings become even more relevant with emerging digital modulation technologies, since we are no longer dealing with modulation peak-to-average ratios of 0dB that have been prevalent in, for example, analogue FM and P25 (phase 1) digital modulation schemes. The higher modulation peak-to-average ratios of the latest generation of digital modulation schemes, such as TETRA and P25 (phase 2) cause higher PIP levels, which will be illustrated and mathematically treated further.

Peak Instantaneous Power (PIP) explained

The PIP rating is actually a little misleading in terms of understanding its relevance as an antenna specification. Whilst we talk of peak instantaneous power, these "peaks" are, as the specification alludes to, instantaneous and not continuous in nature. The *generalised* heating effect of the power peaks is a lot less significant than that of the continuous power rating with which we are all familiar.

What *is* significant nonetheless is the peak instantaneous *voltage* associated with the PIP rating. These are the peak voltages that occur when the individual voltage waveform peaks in a multicarrier environment align in phase with each other periodically, and sum to give rise to significant peak voltage occurrences.

These voltage peaks can be high enough to initiate arcing across vital junctions within certain antenna elements. The ensuing carbonisation and/or *localised* heating will cause component breakdowns at these junctions resulting in premature antenna failure.

Laboratory Analysis

A variety of tests were performed using a multicarrier signal generator operating into an attenuator as a load. Carrier power levels, the number of carriers, channel spacing, and modulation schemes were all varied in order to obtain a broad spectrum of results.

Figure 1 shows 8 x CW (unmodulated) carriers centred at 410MHz, with an even carrier spacing of 100kHz. The waveform is analysed after passing the carriers through an attenuator with a VSWR of 1.1:1. The power level of the carriers into the spectrum analyser is -30dBm (1µW), as shown.

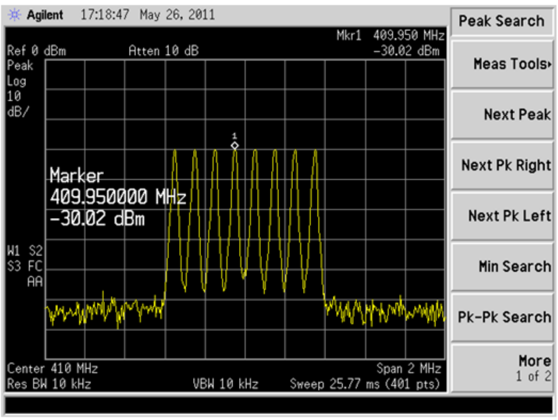

Figure 1

Figure 2 shows the resultant voltage waveform envelope of the CW carriers shown in figure 1, measured into a 50Ω digital storage oscilloscope port. Note that the peak voltage occurrences are easily identified, and are spaced at exactly the period representing the even channel spacing (that is, given the channel spacing is 100kHz, the voltage peak period is 1/100kHz or 10µs).

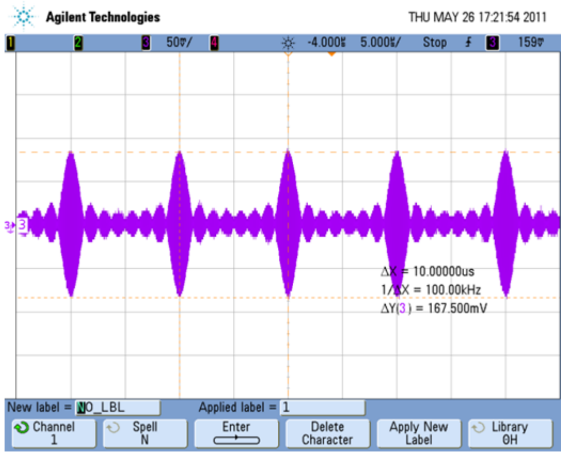

Figure 2 – No modulation (CW)
(8 x -30dBm carriers, 100KHz spacing)

The waveform in figure 2 shows that for 8 x CW carriers at a power level of -30dBm into a 50Ω load with a VSWR of 1.1:1, the resultant peak to peak envelope voltage is 167.5mV, or more importantly the peak envelope voltage is 83.8mV.

The channel spacing was then increased to 500kHz, keeping all other parameters constant. The resultant voltage waveform envelope is shown in figure 3.

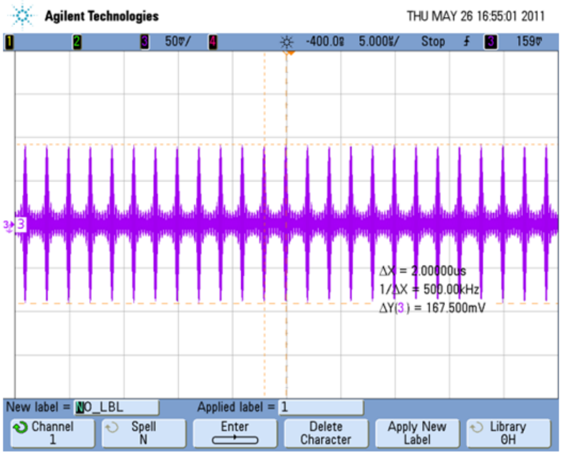

Figure 3 – No modulation (CW)
(8 x -30dBm carriers, 500KHz spacing)

The voltage waveform envelope has the same peak amplitude as that for the 100kHz spaced carriers; however the period has decreased to 2µs, as expected.

The number of carriers was then reduced to 4, keeping the power of the individual carrier levels at -30dBm, and the channel spacing was again reduced to 100kHz. Figure 4 shows the resultant voltage waveform.

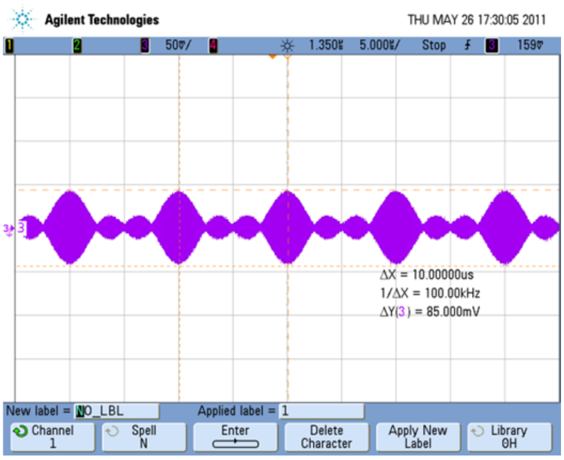

Figure 4 – No modulation (CW)
(4 x -30dBm carriers, 100KHz spacing)

It is evident that in this case, the resultant peak to peak envelope voltage has reduced and in fact is 85.0mV, hence the peak envelope voltage is 42.5mV.

Note that when compared to the 8-carrier result shown in figure 2, bearing in mind that the only variable that changed between the two configurations was the number of carriers, the energy in the peaks for the 4-carrier configuration is spread over a longer period of time, albeit the peak value is considerably lower.

The final CW test was carried out using 8 x carriers, at 100kHz spacing, but in this case the power level was raised to -20dBm (10µW) per carrier. The resultant voltage waveform envelope is shown in figure 5.

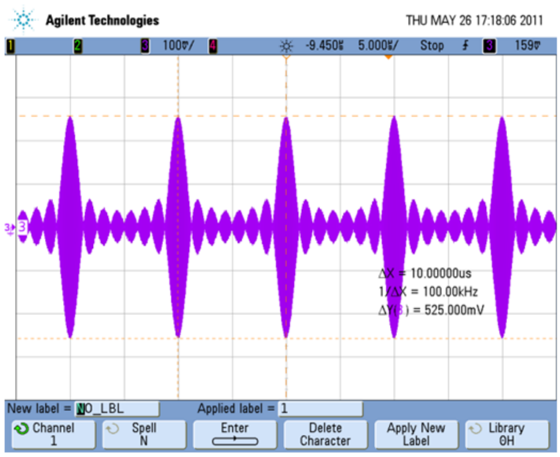

Figure 5 – No modulation (CW)
(8 x -20dBm carriers, 100KHz spacing)

Not surprisingly, the peak to peak envelope voltage has risen sharply to 525mV, hence the peak envelope voltage is 262.5mV. Note that the period of the voltage peaks remains constant (10µs).

The carriers were then modulated with standard analogue Frequency Modulation, digital P25 (phase 1) modulation, and TETRA modulation schemes. Analogue FM and P25 (phase 1) modulation schemes have modulation peak-to-average ratios of 0dB; hence, as mentioned earlier in the preamble, it is expected that the amplitude of the voltage peaks remains the same as those measured in the CW carrier tests.

Figure 6 shows the voltage waveform created by 8 x carriers at -30dBm power levels, but in this case each carrier is modulated using standard analogue FM settings. Carrier spacing remained at 100kHz.

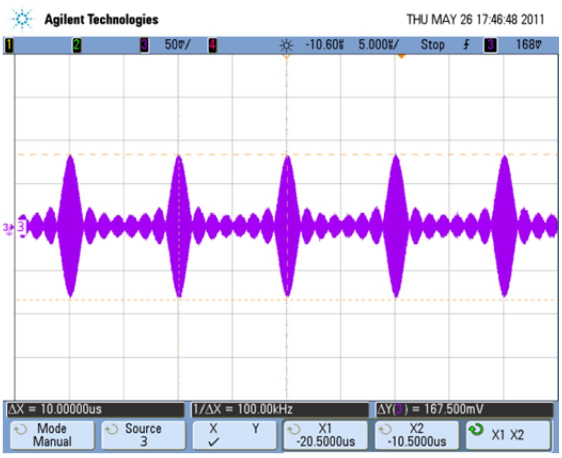

Figure 6 - Frequency Modulation (8 x -30dBm carriers, 100kHz spacing)

As expected, the peak to peak envelope voltage has remained the same as that for the unmodulated carrier scenario. That is, the peak to peak envelope voltage is 167.5mV, hence the peak envelope voltage is 83.8mV. Note also that the period of the peaks remains unchanged (10µs).

The same can be said for an identical set-up with the exception of changing the modulation to digital P25 (phase 1). This is shown in figure 7.

Figure 7 - P25 (phase 1) modulation (8 x -30dBm carriers, 100kHz spacing)

The final test was to use the same set-up but this time using TETRA modulated carriers. The modulation peak-to-average ratio of TETRA modulation is 3.4dB, and hence the peak envelope voltage is expected to increase due to this. Figure 8 shows the resultant voltage waveform envelope.

Figure 8 – TETRA modulation
(8 x -30dBm carriers, 100kHz spacing)

The TETRA modulation has clearly increased the peak envelope voltage. The highest peak to peak envelope voltage in the waveform depicted in figure 8 is 251.3mV; hence the peak envelope voltage is 125.6mV.

Note that the waveform peaks are not constant in level; this is a characteristic of the modulation so care needs to be taken to ensure that the recurrent *maximum* peak is captured in the measurements. However, the waveform peaks still occur at the period represented by the channel spacing (10µs).

Mathematical analysis

A formula will be derived to calculate the Peak Instantaneous Power (PIP) at the antenna, and the corresponding peak voltage associated with this PIP level. The analysis assumes that in a multicarrier environment, all carriers are equal in level and that the same modulation scheme is used for each carrier in the analysis.

We start by defining some variables:

P_c ≡ Power per carrier at the antenna (Watts)

Z ≡ System impedance (50Ω)

V_{rms} ≡ RMS voltage per carrier at the antenna (Volts)

V_{pk} ≡ Peak voltage per carrier at the antenna (Volts)

N ≡ Number of carriers

V_{Tpk} ≡ Summed total peak voltage at the antenna; all carriers considered (Volts)

PIP_{CW} ≡ Peak Instantaneous Power at the antenna with unmodulated carriers (Watts)

PIP_{CWdBW} ≡ Peak Instantaneous Power at the antenna with unmodulated carriers (dBW)

M ≡ Modulation peak-to average ratio (dB)

PIP_{dBW} ≡ Peak Instantaneous Power at the antenna with modulated carriers (dBW)

PIP ≡ Peak Instantaneous Power at the antenna with modulated carriers (Watts)

$VSWR$ ≡ Voltage Standing Wave Ratio at the antenna

ρ ≡ Reflection coefficient magnitude at the antenna

V_{pip} ≡ Maximum peak voltage at the antenna due to the PIP and VSWR

We begin by calculating the peak instantaneous power at the antenna, and then derive the peak voltage at the antenna based on the peak instantaneous power, which will include the effect of the modulation scheme and antenna VSWR.

Now, V_{rms} is given by:

$$V_{rms} = \sqrt{P_c \times Z}$$

$$\therefore V_{pk} = \sqrt{2} \times \sqrt{P_c \times Z}$$

So, for multiple carriers, we have:

$$V_{Tpk} = N \times V_{pk}$$

$$= N \times \sqrt{2} \times \sqrt{P_c \times Z}$$

Hence:

$$PIP_{CW} = \frac{(V_{Tpk})^2}{Z}$$

$$= N^2 \times P_c \times 2$$

$$\therefore PIP_{CWdBW} = 10log(PIP_{CW})$$

$$= 20log(N) + 10log(P_c) + 10log(2)$$

Now, the PIP_{dBW} value is obtained simply by adding the modulation peak-to average value in dB (M) to the PIP_{CWdBW} figure:

$$\Rightarrow PIP_{dBW} = 20log(N) + 10log(P_c) + 10log(2) + M$$

$$\therefore PIP = 10^{\frac{PIP_{dBw}}{10}}$$

$$= 10^{\left(\frac{20log(N)+10log(P_c)+10log(2)+M}{10}\right)}$$

$$= N^2 \times P_c \times 2 \times 10^{\frac{M}{10}}$$

That is:

$$\boldsymbol{PIP = 2 \times N^2 \times P_c \times 10^{\frac{M}{10}}}$$

Now, the reflection coefficient at the antenna is calculated from the antenna's VSWR by:

$$\rho = \frac{VSWR - 1}{VSWR + 1}$$

The forward and reflected power components that arise due to non-ideal matching at the antenna or indeed within the electrical structure of the antenna itself will affect the peak voltage present within the antenna elements. A voltage peak maximum will occur when the peak voltages of the forward and reflected power components add in phase. In this case, this will equal the forward voltage peak multiplied by $(1 + \rho)$.

We can now simply state the worst case maximum peak voltage within the antenna elements associated with the peak instantaneous power occurrence, including the effect of the antenna's $VSWR$, as:

$$V_{pip} = \sqrt{PIP \times Z} \times (1 + \rho)$$

That is, for a 50Ω network:

$$\boldsymbol{V_{pip} = \sqrt{PIP \times 50} \times \left(1 + \left(\frac{VSWR - 1}{VSWR + 1}\right)\right)}$$

Correlation between lab results and theory

The following table summarises the results of the laboratory measurements against the theoretical values of V_{pip} calculated using the mathematical equation derived herein. The VSWR is 1.1:1 in all cases.

No. Carriers	Power	Modulation ratio (M) in dB	V_{pip} lab result (mV)	V_{pip} theory (mV)
8	1µW	0 (CW)	83.8	83.8
4	1µW	0 (CW)	42.5	41.9
8	10µW	0 (CW)	262.5	265.0
8	1µW	0 (P25 P1)	83.8	83.8
8	1µW	3.4 (TETRA)	125.6	124.0

The tabled values demonstrate a high degree of correlation between the measured results and theory.

We can now confidently apply the formulas to typical radio networks to obtain figures for the peak instantaneous power and maximum peak voltages that will be generated in the antenna.

Consider the following site scenario:

- 12 channels combined
- 100W Tx power/channel
- P25 (P1) modulation
- 3dB combiner/feeder loss
- 1.3:1 antenna VSWR

We obtain:

- PIP = 14.4kW
- V_{pip} = 960V

The same scenario, but with P25 (P2) modulation (M = 2.6dB), yields:

- PIP = 26.3kW
- V_{pip} = 1295V

And finally, the same scenario but with TETRA modulation (M = 3.4dB), yields:

- PIP = 31.6kW
- V_{pip} = 1420V

These three scenarios clearly illustrate the significance of the emerging digital modulation schemes in relation to the resultant PIP and V_{pip} levels.

Conclusion

The significance of the Peak Instantaneous Power rating of antennas cannot be underestimated. The peak voltages that are generated in multicarrier networks can be in the order of kilovolts, and with typical channel spacing ranging between 300kHz and 500kHz, the interval between successive voltage peaks will range from 3.3µs down to 2µs respectively.

Internal antenna elements, such as phasing harness junctions, cable terminations, and the like, need to be appropriately dimensioned and treated to handle the voltage peaks in a variety of atmospheric environments; otherwise the periodic arcing that occurs will lead to premature antenna, and therefore network, failure.

The continuous power rating specification of an antenna is well understood and remains absolutely critical. However, its PIP rating will undoubtedly gain industry acceptance as an equally important specification. The advent and utilisation of today's new digital modulation schemes has increased the significance of the appropriate choice of PIP rated antennas for mission-critical networks.