ATSC 3.0 Ready – Designing Antennas for Higher OFDM PAPR

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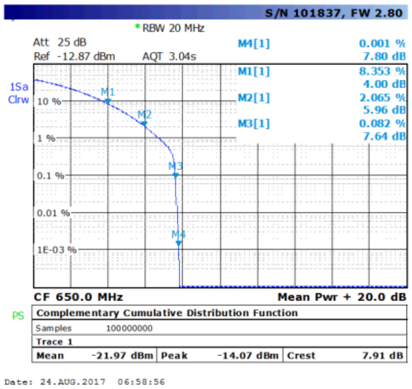
Abstract - *The new ATSC 3.0 broadcast standard will provide new transmission capabilities. The OFDM based modulation will present higher peak to average power ratios that are currently observed in the 8-VSB standard we know today. This paper discusses how the higher PAPR impose new limitations on RF transmission system specifications. The new RF systems, transmission lines and antennas being installed in the current re-pack process need to be designed to safely withstand these peaks. Due to voltage additions, the design criteria becomes more complex when more than one station is combined into one transmission system and statistical probability of occurrence must be taken into account. This paper will also examine the dependence of breakdown field on pulse length as well as the guidelines on how single pulse breakdown statistics should be applied. Finally, practical solutions to increase the voltage handling capability of RF carrying structures will be examined.*

Peak to Average Power Ratio

Transmitter manufactures are continually working on methods to reduce the peak to average power ratio (PAPR) [1]. The ATSC 3.0 standard includes tone reservation (TR) and active constellation extension (ACE) as PAPR reduction techniques [8]. To date, the author is not aware of any transmitter manufacture that has implemented the PAPR reduction techniques in the ATSC 3.0 standard. It appears that most will implement their own proprietary solutions and they feel comfortable stating that 9 dB is the statistical maximum PAPR out of the transmitter.


S/N 101837, FW 2.80

RBW 20 MHz

Att 25 dB

Ref -12.87 dBm AQT 3.04s

M4[1] 0.001 % 7.80 dB

M1[1] 8.353 % 4.00 dB

M2[1] 2.065 % 5.96 dB

M3[1] 0.082 % 7.64 dB

CF 650.0 MHz Mean Pwr + 20.0 dB

Complementary Cumulative Distribution Function

Samples 100000000

Trace 1

Mean -21.97 dBm Peak -14.07 dBm Crest 7.91 dB

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Figure 1: Transmitter output crest factor probability measurements. Courtesy of Rohde & Schwartz.

OFDM - Probability of Co-phased Voltage Additions

Orthogonal Frequency Division Multiplexing (OFDM) consists of several closely spaced orthogonal sub-carrier signals, each individually modulated in both amplitude and phase [1]. There is a finite probability that all of these carriers will add in phase at their max amplitude [2].

It can be shown that the probability density function of a single OFDM signal is Rayleigh and is discussed extensively in reference [9]. The reference defines the exceedance probability (p_e) as the probability that a peak will exceed the PAPR and is given by equation (1).

$$p_e = e^{\left(\frac{-x^2}{2\sigma^2}\right)} = e^{-PAPR_{linear}} \quad (1)$$

Where x^2 represents the instantaneous power, and $2\sigma^2$ the mean power which equates to exp(-PAPR). According to the exceedance formula, if the individual OFDM signal is clipped at 6 dB, the probability of clipping taking place is .0187 or 1 in 50 chance of an occurrence or 5.9×10^7 seconds per year. If two channels are combined into a single transmission line and antenna, the probability of two clipped peaks coinciding is (.0187) x (.0187). In general, the total probability (p_t) of all peaks coinciding is given by equation (2) where n is the number of stations [9].

$$p_t = (p_e)^n \quad (2)$$

For multi-station operation, the total probable event time (t_e) within a 100 year period is given by:

$$t_e = p_t \cdot seconds\ in\ 100\ years \quad (3)$$

It cannot be predicted precisely how many exceedance events will take place within the given time period, however, the total duration (T_d) of each event will be approximate to the reciprocal of the total occupied bandwidth and is given by equation (4) where n is the number of combined stations.

$$T_d = \frac{1}{n \cdot BW} \quad (4)$$

Therefore, the number of probable event occurrences (N_e) is given by equation (5).

$$N_e = t_e \cdot \frac{1}{T_d} \quad (5)$$

In general, by defining the breakdown condition as the point where the co-phased voltages coincide to a level exceeding the PAPR used in the power and voltage handling calculations, the number of probable voltage breakdown events in a time frame is given by equation (6) [10].

$$N_e = n \cdot Y \cdot B(e^{-PAPR_{linear}})^n \quad (6)$$

Where n is the number of combined stations; Y is the number of seconds in the given time frame; and B is the bandwidth of an individual channel and PAPR is the peak to average power ratio [10].

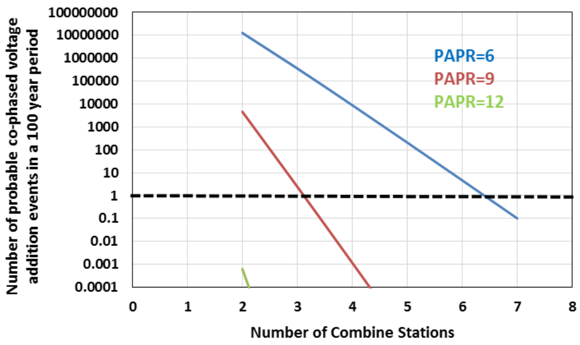

Figure 2: Number of probable co-phased voltage additions versus the number of combined ATSC 3.0 stations for different PAPR in a 100 year period.

This analysis indicates that if one exceedance event within a 100 year period of co-phased voltage addition of all the combined stations is acceptable, 3 stations must be included in the voltage breakdown and power handling calculations of all the RF components in the system when using a PAPR of 9 dB for all. If more than 3 stations are being combined, the voltage additions will be limited to 3 stations, and the system will most likely begin to be total average power limited. This statistical approach has one major drawback. It does not guarantee that an over voltage will not occur. If 100 years is specified for the average occurrence, there is no guarantee that the breakdown event will not occur in the first 5 minutes or two or three events will occur within 100 years. The odds are very small, but they are simply that, odds [2].

Pulse Width Breakdown Dependence

The dependence of breakdown field on pulse length as well as the guidelines used to determine if single pulse breakdown statistics can be used is well defined in reference [3]. The physics behind the ionization of air requires an understanding of the dynamic evolution and relaxation of the physical processes which determine the voltage breakdown and is beyond the scope of this paper. If the pulse duration is less than the defined critical pulse length, the amount of voltage required to induce breakdown increases as in the case of ATSC 3.0. If the pulse length is greater than the critical pulse length, the breakdown condition is unaffected by pulse length and equal to the continuous wave (CW) condition.

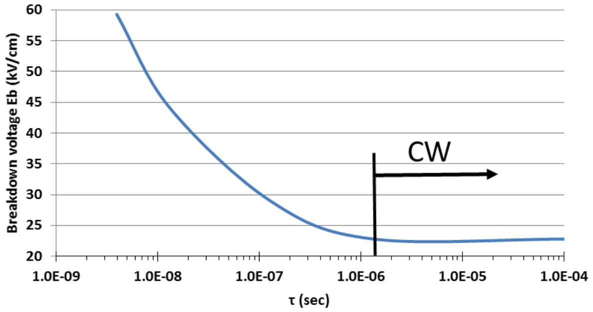

Figure 3: Threshold field for single pulse breakdown at sea level [3].

The single pulse breakdown condition should smoothly join the CW condition as the pulse length increases. The critical pulse length (τ_c) above which the breakdown condition is unaffected by pulse length and equal to the CW condition is given in equation (7), where p is the pressure in torr [3].

$$\tau_c = \frac{10^{-3}}{p} \quad (7)$$

At sea level where p=760 torr, the critical pulse length is 1.315 micro-seconds.

Based on the curve in Figure 3, the breakdown voltage Eb in kV/cm can be described by the pulse width τ in seconds by Equation (8)

$$E_b\left(\frac{kV}{cm}\right) = 22.22 + \frac{87.24}{1 + \left(\frac{\tau}{2.47x10^{-9}}\right)^{.648}} \quad (8)$$

It has been found that for pressures around one atmosphere (760 torr.), the electric field breakdown is relatively unaffected by change in frequency [4], and has been experimentally measured at 22.8 kV/cm in air [5], a much lower value than predicted by DC breakdown using Paschen's law. Historically, the industry accepted DC breakdown level is 29 kV/ cm and a 70% factor is applied to the RF voltage breakdown level.

$$V_{Peak\ RF} = .7xV_{DC} \quad (9)$$

This is obviously a conservative approach since .7 x 29 is only 20.3 kV/cm. A more accurate method for analyzing ionization breakdown in an RF environment that involves a semi-analytical approach leads to equation (10), and can be used to calculate the air ionization breakdown threshold (electric field strength in RMS value, V/cm) as a function of frequency (Hz), pressure (torr) and pulse length (s) [6], [7].

$$E_p = 3.75p\left(1+\frac{\omega^2}{25x10^{18}p^2}\right)^{1/2} x \left(\frac{10^6}{p^2{L_{eff}}^2} + 6.4x10^4 + \frac{20}{p\tau_p}\right)^{3/16} \quad (10)$$

Where

$$p = p_0\frac{273}{273+T_0}$$

Where

$p_0 =$ Air pressure in torr

$T_o =$ Temperature in C

$\omega =$ Angular frequency

$L_{eff} =$ Effective diffusion length in cm. For practical purposes, one often approximates it as half of the gap size.

$\tau_p =$ Pulse length in seconds

Note that at one atmosphere (760 torr), one would get an electrical field strength of approximately 22.8 kV/cm at the critical pulse width.

The pulse length (τ_p) can be approximated by equation (11) where n is the number of OFDM sub-carriers and Δf is the OFDM sub-carrier frequency spacing.

$$\tau_p \approx \frac{1}{n \cdot \Delta f} = \frac{1}{BW} \quad (11)$$

The occupied bandwidth of a single ATSC 3.0 channel can vary from 5.508 to 5.832 MHz, depending on the carrier coefficient used [8]. The pulse length is .17 to .18 micro-seconds which is less than the critical pulse length and therefore voltage breakdown rating factors can be used. In the case of multiple combined stations, the total occupied bandwidth is applied which again increases the breakdown voltage and can be taken advantage of in the safety factor calculations. Using Figure 3 and/or equation (8), the breakdown voltage at .17 microseconds is 27.5 kV/cm. This is a 20% increase over the 22.8 kV/cm found by using equation (10) and the CW condition described by pulse widths greater than the critical pulse width in Figure 3. As stations are combined, the total occupied bandwidth increases thus decreasing the pulse width and increasing the voltage required for breakdown. This voltage improvement factor (F_v), can be described as the pulse width dependent breakdown divided by the CW condition.

$$F_v = \frac{E_b}{22.8} \quad (12)$$

# Combined Stations	Eb	Fv
1	27.47	1.20
2	30.18	1.32
3	32.3	1.42
4	34.08	1.49
5	35.64	1.56

Table A: Voltage improvement factor for a given number of combined stations

The Affect of VSWR on Voltage Breakdown

The presence of mismatches at any point in the transmission system leads to the occurrence of standing waves that intensifies the electric field. The voltage along a transmission line can be expressed by equation (13).

$$|V_d| = |V_{inc}|[1+|\Gamma|^2 + 2|\Gamma|cos(2\beta d - \theta_r)]^{1/2} \quad (13)$$

Where Γ is the reflection coefficient, β=2π/λ, and θ_r is the phase of the reflection coefficient. The maximum voltage that can occur is then given by:

$$|V_{max}| = |V_{inc}|(1+|\Gamma|) \quad (14)$$

Noting that VSWR is related to the reflection coefficient by:

$$|\Gamma| = \frac{VSWR - 1}{VSWR + 1} \quad (15)$$

Assuming the worst case scenario where the reflection from the mismatches are completely reflected back from the transmitter the maximum voltage can therefore be:

$$|V_{max}| = |V_{inc}| \frac{2\ x\ VSWR}{VSWR + 1} \quad (16)$$

More simply stated; the breakdown voltage magnification correction factor due to VSWR would be expressed as equation (17) [1].

$$C_{VSWR} = \frac{2\ x\ VSWR}{VSWR + 1} \quad (17)$$

Applied Voltage Calculation

The PAPR plays a major role in determining the voltage peaks of the OFDM signal. In order to scale the average power to account for the large peaks presented by the OFDM carriers, it must be multiplied by the PAPR.

$$V_p = \sqrt{2Z_0 P_{avg} PAPR_{Linear}} \quad (18)$$

When combining (n) multiple transmit signals assuming the worst case conservative approach where all the voltages are in co-phased addition, then the total applied voltage is simply the summation of each individual peak voltage. The voltage safety factor for a given component and n combined stations can then be determined by applying the VSWR correction factor and the voltage improvement factor and comparing this to the Hi-Pot test level given in equation (19) [1].

$$SF = \frac{V_{peak\ breakdown}}{\left(\sum_1^n V_p\right) C_{VSWR}} * F_v \quad (19)$$

Improving Voltage Handling

Slotted coaxial antennas have many advantages over traditional broadband panel antennas including much smaller size and lower wind load, higher reliability and a greater degree of azimuth and elevation pattern flexibility. A common approach to producing radiation from a slotted cylinder is to attach a coupling device to the inside of one side of the slot. This results in one side of the outer conductor being closer to the inner conductor than the opposite side. By doing this a potential difference is produced across the slot allowing currents to flow on the outside of the cylinder producing radiation.

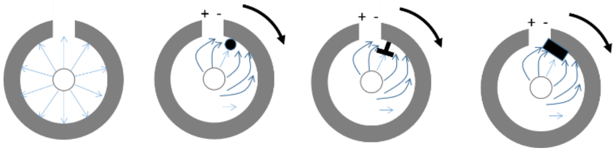

Figure 4: Different slot coupling devices used to couple a slotted coaxial antenna

The electric field intensity near a conductor is inversely proportional to the radius of curvature of the surface and can be approximated by equation (20) where V is the applied voltage [11]. Refer to Figure 4.

$$E_c \approx \frac{2V}{r\left[ln\left(1 + \frac{4d}{r}\right)\right]} \quad (20)$$

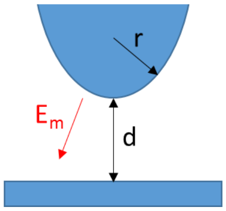

Figure 5: Voltage induced by a curved surface

A sharp edge or point has a very small radius of curvature so the electric field near a sharp edge or point is very large and thus has a greater potential for breakdown of air and sparking [1]. The electric field intensity in a coaxial line is given by:

$$E_0 = \frac{V}{a\left[\ln\left(\frac{b}{a}\right)\right]} \quad (21)$$

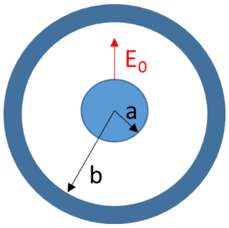

Figure 6: Voltage induced in coaxial line

From equations (20) and (21), the breakdown between the coupler and inner connector on a slotted coaxial antenna can be predicted.

$$V_b = \frac{E_m}{E_0} = \frac{2a\left[ln\left(\frac{b}{a}\right)\right]}{r\left[ln\left(1+\frac{4d}{r}\right)\right]} \qquad (22)$$

Using the equations for the applied voltage and the voltage safety factor, the PAPR and the breakdown voltage is related by equation (23)

$$PAPR = \frac{{V_b}^2 {F_V}^2}{2n^2 SF^2 Z_0 P_{avg} {C_{vswr}}^2} \qquad (23)$$

Therefore

$$PAPR \propto \left(\frac{2a\left[ln\left(\frac{b}{a}\right)\right]}{r\left[ln\left(1+\frac{4d}{r}\right)\right]}\right)^2 \qquad (24)$$

Figure 7 shows the relationship between the expected increase in PAPR that can be applied after increasing the radius of a slot coupling device.

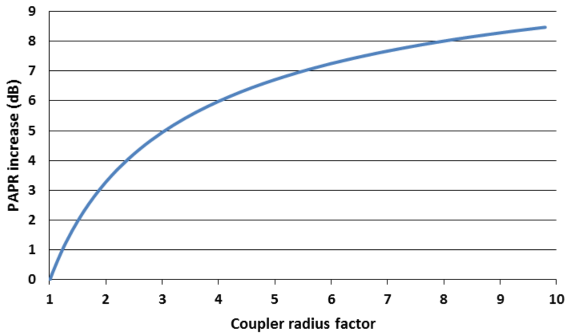

Figure 7: Increase in PAPR that can be applied as a result of increasing the coupling device radius in a slotted coaxial antenna

Basically, it can be shown that doubling the slot coupling device radius can provide a 3 dB increase in PAPR for single station operation. Also note that once very large radiuses are implemented, there becomes a limit of diminishing returns that will be observed.

One method to improve the voltage safety factor in a slotted coaxial antenna is to implement a coupling device shaped like a "D". This will allow large radiuses without decreasing the gap to the inner conductor and thus increase the voltage handling capability.

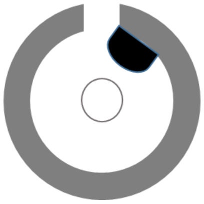

Figure 8: Slotted coaxial antenna, coupling device geometry used to increase the voltage handling capability

The bottom line is when designing for high peak to average power ratios, geometry is key. Other methods to increase the voltage handling capability can be employed such as the use of pressurization. The effect of pressurization can be evaluated from equation (10). Even though this may be a viable technique for RF systems since they are easily accessible, the author would not recommend it be used for antennas due to increased complexity, reliability and maintenance.

Conclusion

When designing RF components and antennas to be future ATSC 3.0 ready, voltage breakdown is one of the major limitations, especially when designing for multi-station operation. The probability of co-phased voltage addition of multiple stations can be calculated as well as the number of probable exceedance events. Due to the fact that the pulse lengths of ATSC 3.0 are less than the critical pulse width, a voltage improvement factor can be applied to the voltage safety factor calculations. This factor increases as the number of combined stations increases due to the larger occupied bandwidth resulting in a higher necessary breakdown voltage. Both voltage addition and pulse width need to be taken into account when analyzing breakdown and safety factors. When designing for higher peak to average power ratios, geometry is key. Applying the combination of analysis, test, and experience will allow RF components and antennas to be adequately designed to handle the higher PAPR's associated with ATSC 3.0.

References

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