ATSC 3.0 – Boosting the Signal Strength - MISO

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Abstract - *The new ATSC 3.0 broadcast standard will provide new transmission capabilities. Broadcasters will have options and flexibility to best serve populations with defined, high data rate services. In order to increase the probability that indoor, pedestrian, and mobile users will receive reliable service, the ATSC 3.0 network will need to saturate the intended coverage area with a signal level above the required target level. In previous work, boosting the signal strength with the addition of high null fill in the main antenna as well as adding a single frequency network (SFN), have been investigated. Various hypothetical situation were used to analysis the impact of performance of these methods on different services. In this paper, the use of diversity at the transit locations will be considered. Specifically, different modes of polarization diversity will be compared.*

BOOSTING THE SIGNAL STRENTH

As discussed in recent papers [1], [2], there are four basic methods of boosting the signal strength in selected areas within the defined FCC 41 dBu contour.

1. Increase transmitter power.
2. Increase null fill or beam tilt.
3. Add a single frequency network (SFN).
4. Provide diversity gain though MISO.

Assuming increasing the transmitter power up to 10 times is not an option, the benefits of increasing the main antennas null fill as well as adding an SFN have shown to produce the necessary signal strengths required for ATSC data intensive services. The focus of this paper will be to analyze the benefit of adding MISO (Multiple Input Single Output) diversity to a ATSC 3.0 network.

THE USE OF MISO IN AN ATSC 3.0 NETWORK

ATSC 3.0 has adopted a Multiple-Input Single Output (MISO) antenna scheme to improve the overall performance in a SFN, known as Transmit Diversity Code Filter Sets (TDCFS) [5], [6]. TDCFS is similar to the MISO scheme adapted in DVB-T2, which is based on Alamouti coding, but with TDCFS there is no need to double the pilot overhead and it can be extended to more than two transmitters [6]. Alamouti argued that the only way of achieving the requirements of next generation wireless systems in a cost effective way was to increase the transmitter complexity and not that of the receiver [3]. In an ATSC 3.0 network, both the main antenna and the accompanying SFN sites will serve hundreds of thousands of receivers. It is therefore more economical to add equipment at the transmit site rather than the remote units, allowing the user devices to have only one antenna, keeping them small and affordable to promote public acceptance. MISO diversity techniques such as TDCFS and Alamouti coding can be deployed in either a co-located or distributed configuration.

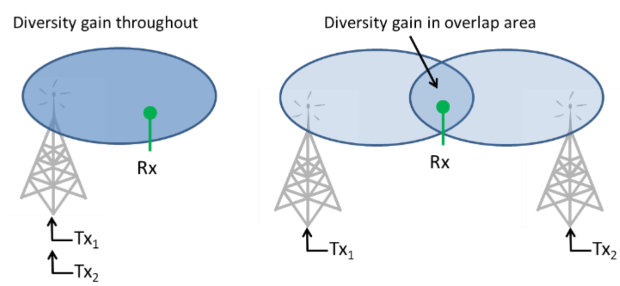

Figure 1: Co-located vs. distributed MISO.

The benefit to co-located MISO is that diversity gain is observed throughout the coverage area and not just in the overlap areas as in the case of distributed MISO. The advantage of distributed MISO is that is does not require any new RF equipment within an existing SFN, where co-location of the MISO system requires the doubling of transmitters. The maximum diversity gain, $G_{max,}$ is based on the total number of independent signal paths that exist between the transmitter and the receiver. For M transmit antennas and N receive antennas, the diversity gain can be bracketed by:

$$1 \leq G_d \leq G_{max} = M * N \quad (1)$$

This simply translates to an expected 3 dB improvement in apparent signal strength that can be achieved when a MISO diversity technique is applied.

DIVERSITY IMPLEMENTATION

Traditionally, both spatial and polarization diversity have been employed for improving connectivity in the wireless industry. For maximum performance using spatial diversity, antenna separations on the order of 10 to 30 wavelengths are needed. Due to the broadcast operating frequencies and subsequent tower space limitations, this may be difficult or impossible to implement. Polarization diversity utilizes the antenna elements that are co-located and orthogonal in antenna polarization, making this a more attractive alternative in terms of aperture space. The most common type of polarization diversity is the transmission of two independent slant linear (+/- 45°) signals. A slant linear antenna element excites both slant components equally in amplitude with no relative phase assigned to either element. Another alternative is to use a pair of circularly polarized antennas. Again, the antenna element uses crossed dipoles and excites both equally in amplitude but the relative phase difference is set to 90 degrees. A dual circularly polarized antenna can be created from a dual slant linear antenna simply by adding a 90 degree hybrid at the input.

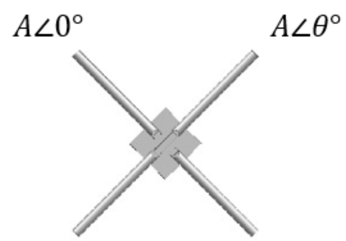

Figure 2: Crossed dipoles used for slant linear and circularly polarized antenna configurations.

MODES OF OPERATION – SLANT LINEAR / CP

Crossed dipole configurations are commonly used to produce elliptically polarized transmission in the broadcast industry. Typically for high power applications, they are in the form of an array of individual dual input panels with each input feeding one of the crossed dipoles. The array of panels are then connected by a corporate feed system leading to two main inputs.

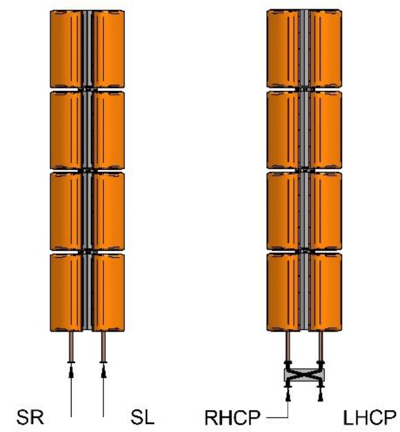

Figure 3: Two basic modes of polarization diversity operation into a dual input broadcast antenna array. Slant right / slant left vs. Right hand circular polarization / left hand circular polarization.

POLARIZATION DIVERSITY – FIGURE OF MERIT

Implementation of polarization diversity depends on spreading the power evenly between different polarizations. Discrepancy between the pair of signals results in reduced diversity gain. This occurs when one of the pairs of signals cannot be adequately resolved. The power imbalance between the paired transmitted signals is caused by the nature of electromagnetic propagation, including fading, attenuation, and scatter with constructive and destructive interference. Since diversity gain is directly dependent on the power imbalance between paired signals, the figure of merit is cross polarization discrimination (XPD). XPD is defined as the ratio between the available power in the vertical polarization and the horizontal polarization. For optimal diversity performance, the XPD=0dB [4].

$$XPD = \frac{\langle |R_v|^2 \rangle}{\langle |R_h|^2 \rangle} \quad (2)$$

$\langle |R|^2 \rangle$ is the expected value of the powers in each polarization. In order to compare and evaluate polarization diversity techniques, the first step is to understand their static response to cross polarization discrimination (XPD). The second step is then to compare the techniques' performance characteristics in real mobile environments when a linearly polarized receiver is in motion.

TRANSMISSION CHANNEL

At the transmitter, a pair of crossed linearly polarized dipoles, V_1 and V_2, which are always orthogonal to each other is considered. The dipole pair is orientated in space by a tilt angle α [4].

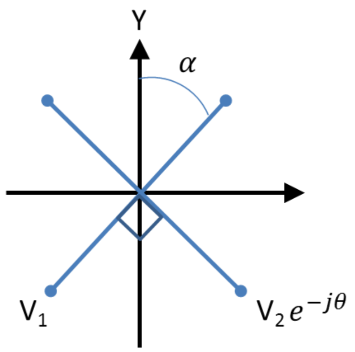

Figure 4: Two crossed dipoles oriented in space.

The random orientation of the crossed dipoles can be projected into the x and y components using a rotation transformation matrix thus representing the horizontal (HPOL) and vertical (VPOL) components. The phase difference between V_1 and V_2 is θ.

$$\begin{pmatrix} V_h \\ V_v \end{pmatrix} = \begin{bmatrix} sin\alpha & -cos\alpha \\ cos\alpha & sin\alpha \end{bmatrix} \begin{pmatrix} V_1 \\ V_2 e^{-j\theta} \end{pmatrix} \quad (3)$$

The channel modeling is based on the approach by Lee and Yeh [7] and describes the four channel links between the transmitter and the receiver.

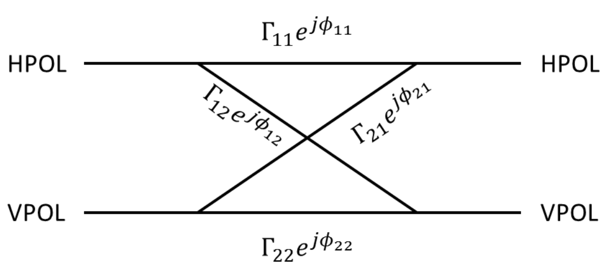

Figure 5: Channel representation

$$\Gamma_{11} e^{j\phi_{11}} = \ HPOL\ to\ HPOL\ link$$

$$\Gamma_{22} e^{j\phi_{22}} = \ VPOL\ to\ VPOL\ link$$

$$\Gamma_{21} e^{j\phi_{21}} = \ VPOL\ to\ HPOL\ cross\ coupling$$

$$\Gamma_{12} e^{j\phi_{12}} = \ HPOL\ to\ VPOL\ cross\ coupling$$

The Γ parameters are random variables used to model the multipath fading while the ϕ parameters are the result of the random phase introduced by the channel and are given by a uniform distribution about 0, 2π [4]. After the signal has propagated through the channel, the resultant signal present at the receiver in both the horizontal and vertical polarization can be determined.

$$\begin{pmatrix} R_h \\ R_v \end{pmatrix} = \begin{bmatrix} \Gamma_{11} e^{j\phi_{11}} & \Gamma_{12} e^{j\phi_{12}} \\ \Gamma_{21} e^{j\phi_{21}} & \Gamma_{22} e^{j\phi_{22}} \end{bmatrix} \begin{pmatrix} V_h \\ V_v \end{pmatrix} \quad (4)$$

$$= \begin{bmatrix} \Gamma_{11} e^{j\phi_{11}} & \Gamma_{12} e^{j\phi_{12}} \\ \Gamma_{21} e^{j\phi_{21}} & \Gamma_{22} e^{j\phi_{22}} \end{bmatrix} \begin{bmatrix} sin\alpha & -cos\alpha \\ cos\alpha & sin\alpha \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & e^{j\theta} \end{bmatrix} \begin{pmatrix} V_1 \\ V_2 \end{pmatrix} (5)$$

In order to calculate the XPD for comparative purposes, the expected powers in each polarization must be derived. Finding the power in each polarization is found by taking the magnitude squared of R_h and R_v.

$$|R_h|^2 = V_1{}^2\left[\Gamma_{11}{}^2 sin^2\alpha + \Gamma_{12}{}^2 cos^2\alpha + 2\Gamma_{11}\Gamma_{12} sin\alpha cos\alpha cos(\phi_{11} - \phi_{12})\right] + V_2{}^2\left[\Gamma_{12}{}^2 sin^2\alpha + \Gamma_{11}{}^2 cos^2\alpha + 2\Gamma_{11}\Gamma_{12} sin\alpha cos\alpha cos(\phi_{11} - \phi_{12})\right] + 2V_1V_2 cos\theta\left[\Gamma_{11}\Gamma_{12}(sin^2\alpha - cos^2\alpha)cos(\phi_{11} - \phi_{12}) + \left(\Gamma_{12}{}^2 - \Gamma_{11}{}^2\right) sin\alpha cos\alpha\right] \quad (6)$$

$$|R_v|^2 = V_1{}^2\left[\Gamma_{21}{}^2 sin^2\alpha + \Gamma_{22}{}^2 cos^2\alpha + 2\Gamma_{21}\Gamma_{22} sin\alpha cos\alpha cos(\phi_{21} - \phi_{22})\right] + V_2{}^2\left[\Gamma_{22}{}^2 sin^2\alpha + \Gamma_{21}{}^2 cos^2\alpha + 2\Gamma_{21}\Gamma_{22} sin\alpha cos\alpha cos(\phi_{21} - \phi_{22})\right] + 2V_1V_2 cos\theta\left[\Gamma_{21}\Gamma_{22}(sin^2\alpha - cos^2\alpha)cos(\phi_{21} - \phi_{22}) + \left(\Gamma_{22}{}^2 - \Gamma_{21}{}^2\right) sin\alpha cos\alpha\right] \quad (7)$$

By the definition of the expected value and using integration by parts, the expected value of the cosine of the random phase differences introduced by the channel bounded by 0 to 2π can be shown to be zero.

$$\langle cos(\emptyset_1 - \emptyset_2)\rangle = \int_0^{2\pi} (\emptyset_1 - \emptyset_2)\, cos(\emptyset_1 - \emptyset_2) dx = 0 \ (8)$$

This allows the expected value of the magnitude squared of R_h and R_v to be rewritten as:

$$\langle |R_h|^2\rangle = \langle \Gamma_{11}{}^2\rangle\left(V_1{}^2 sin^2\alpha + V_2{}^2 cos^2\alpha - 2V_1V_2 sin\alpha cos\alpha cos\theta\right) + \langle \Gamma_{12}{}^2\rangle\left(V_1{}^2 cos^2\alpha + V_2{}^2 sin^2\alpha + 2V_1V_2 sin\alpha cos\alpha cos\theta\right) \quad (9)$$

$$\langle|R_v|^2\rangle = \langle{\Gamma_{21}}^2\rangle\left({V_1}^2 sin^2\alpha + {V_2}^2 cos^2\alpha - 2V_1V_2 sin\alpha cos\alpha cos\theta\right) + \langle{\Gamma_{22}}^2\rangle\left({V_1}^2 cos^2\alpha + {V_2}^2 sin^2\alpha + 2V_1V_2 sin\alpha cos\alpha cos\theta\right) \quad (10)$$

Letting A and B equal:

$$A = {V_1}^2 sin^2\alpha + {V_2}^2 cos^2\alpha - 2V_1V_2 sin\alpha cos\alpha cos\theta \quad (11)$$

$$B = {V_1}^2 cos^2\alpha + {V_2}^2 sin^2\alpha + 2V_1V_2 sin\alpha cos\alpha cos\theta \quad (12)$$

The definition of XPD yields:

$$XPD = \frac{\langle|R_v|^2\rangle}{\langle|R_h|^2\rangle} = \frac{A\langle{\Gamma_{21}}^2\rangle + B\langle{\Gamma_{22}}^2\rangle}{A\langle{\Gamma_{11}}^2\rangle + B\langle{\Gamma_{12}}^2\rangle} \quad (13)$$

SLANT LINEAR OR CP FOR ATSC 3.0 MISO?

The impact of slant linear and circularly polarized antennas transmitting MISO to a linearly polarized receive antenna in an ATSC 3.0 network are examined and their performance compared. The different types of polarization diversity can described by the coefficients A and B.

Table 1: Slant right / slant left linear polarization MISO compared to right and left hand circular polarization MISO.

Polarization	V1	V2	α	θ	A	B
Slant Left	1	0	-45	0	0.5	0.5
Slant Right	1	0	45	0	0.5	0.5
RHCP (Slant 45)	0.707	0.707	45	90	0.5	0.5
LHCP (Slant 45)	0.707	0.707	45	-90	0.5	0.5
RHCP (H/V)	0.707	0.707	0	90	0.5	0.5
LHCP (H/V)	0.707	0.707	0	-90	0.5	0.5

Since the A and B coefficients are the same in all 6 cases, the equations that describe the XPD, equation (13), are identical in all 6 cases. Therefore it can be said that slant linear and circularly polarized antennas transmit the same average performance in a static MISO based system. The expected diversity gain of slant left / slant right and right hand / left hand circular polarization are on average the same. This analysis assumes the channel characteristics react the same for a linearly polarized transmitted and circularly polarized transmitted signal which makes this analysis independent of any margin improvement that is observed by a linearly polarized receive antenna while in motion.

MARGIN IMPROVEMENT WITH CIRCUALR POLARIZATION

Over the last decade, extensive testing to quantify the benefits of transmitting circular polarization to a linearly polarized receiver in motion has been conducted [8]. To quantify this benefit, margin improvement (MI) is defined as the reduction in signal strength variability when the receiver is in motion, changing both its location and orientation.

$$MI = SNR_{cp} - SNR_{linear} \quad (14)$$

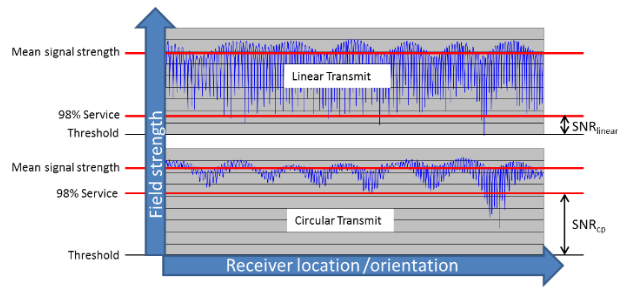

Figure 6: Defining margin improvement (MI).

A decade of testing in both controlled and real world environments and basing measurements on both signal strength (RSS) and bit error rate (BER) have confirmed that transmitting circular polarization to a linearly polarized receiver in motion in a heavy scatter environment provides 5 to 7 dB of margin improvement (MI) over transmitting a linearly polarized signal to the same receiver [8]. As defined, diversity gain (G_d) and margin improvement (MI) are not mutually exclusive but can be considered independent processes in which their benefits are additive. This is due to the fact that the channel characteristics are not the same for transmitted linearly and transmitted circularly polarized signals. This can be explained by understanding that circular polarization helps mitigate the effects of small scale fading which is present both indoors and outdoors. Circular polarization is made up of two orthogonal polarizations time shifted by 90 degrees. When the receiver is in motion in both location and orientation, the statistical odds of both polarizations destructively interfering at the same time, in the same location and same orientation is much less than a single polarization. Therefore, the total system gain of duel right hand / left hand circularly polarized diversity MISO system transmitting to a mobile linearly polarized receiver in motion in a heavy scatter environment is given by:

$$G_T = G_d + MI \ (dB) \quad (15)$$

BRANCH POWER IMBALANCE – SR / SL LINEAR POLARIZATION DIVERSITY

Polarization diversity depends on the ratio of power in both polarizations. For linear polarization, this depends strongly on the environment. It is easier to conceptualize this point when considering transmitting a single linearly polarized signal to two crossed dipole diversity receive antennas. The diversity performance depends on the number of scatters between the transmit and receive sites. In a line of sight path, diversity gain is diminished when one polarization dominates, causing an increase in XPD. Since only a single linear polarization is transmitted, it becomes apparent that environmental scattering is needed to equally distribute the power between its co and cross polarized components. In other words, if XPD is not 0dB, diversity performance is less than optimal. It has been shown that using new transmit diversity schemes using two transmit and one receive antenna can provide the same performance as one transmit and two receive antennas [3]. This is because the propagation medium between the transmitter and receiver in either direction is identical and thus follows the theory of reciprocity. It should therefore be obvious that the same branch power HPOL / VPOL imbalance dependence on diversity performance using slant right / slant left linear polarization diversity holds true for both MISO and SIMO.

BRANCH POWER IMBALANCE – RHCP / LHCP CIRCULAR POLARIZATION DIVERSITY

It has been shown that the use of circular polarization at the transmitter can be used to facilitate power coupling and alleviate the branch power imbalance between the horizontal and vertical polarizations [4], [9]. With the power imbalance problem removed by using a dual circular system, the diversity gain is always optimal and is not dependent on the environment to provide power coupling between polarizations.

CROSS POLARIZATION ISOLATION

Imperfect antennas that couple energy from one polarization to the other increase the correlation and thus affect the maximum achievable diversity gain. The non-correlation between the polarizations, either RH / LH circular or SL / SR linear signals, is ensured by polarization isolation. For SL / SR linear antennas, the isolation is simply dictated by the amount of cross polarization radiated into their orthogonal component. For RH / LH circular it is dictated by the axial ratio of each polarization which in turns defines the purity of the signals. Studies have shown that a cross-pol pattern isolation of 17 dB is sufficient to reach within 1% of the final desired data rate for a fixed port to port isolation of 30dB [10]. A typical specification for cross–pol pattern isolation in today's wireless products is 20dB. The isolation between polarizations for a circularly polarized antenna is given by [11]:

$$I = 10log\left[\frac{\frac{1}{2}+\frac{AR}{AR^2+1}}{\frac{1}{2}\left(\frac{1}{\left(\frac{AR+1}{AR-1}\right)^2}+1\right)+\frac{AR}{AR^2+1}\left(\frac{1}{\left(\frac{AR+1}{AR-1}\right)^2}-1\right)}\right] \qquad (16)$$

Where AR is the axial ratio. A plot of axial ratio vs. cross-pol isolation is shown in Figure 7.

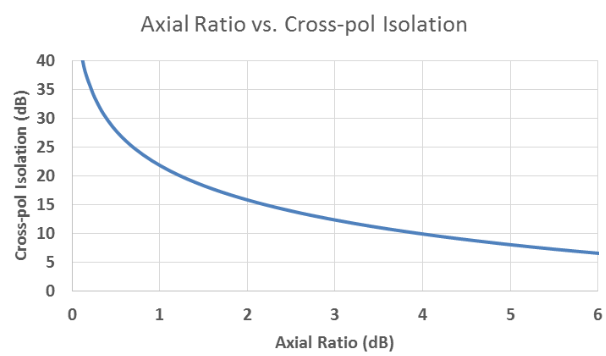

Figure 7: Axial ratio vs. cross-pol isolation for a circularly polarized antenna.

From this analysis, an axial ratio specification of 1.2dB should be placed on the circularly polarized antenna used for MISO diversity in order to provide a cross-pol isolation specification of 20dB.

CONCLUSION

ATSC 3.0 services will require a new definition of received signal strengths. In addition to increasing null fill in the main antenna and the addition of signal frequency network sites, the use of MISO is considered. In order to provide diversity gain throughout the coverage area, a co-located MISO system must be employed. This comes at the expense of doubling the number of transmitters in the network. It has been shown that in an equivalent propagation channel with no power imbalance between polarizations, the use of dual circular polarization diversity provides the same gain benefits as a dual linear diversity system. When considering a mobile, heavy scatter environment where the receiver is in motion, it has been shown that circular polarization provides 5 to 7dB of extra margin improvement over linear transmission. This margin improvement is an added benefit to the diversity gain. Dual circular polarization diversity also provides constant, optimal diversity gain by alleviating the branch power imbalance degradation seen by dual linear systems. Finally, in order to provide the same cross polarization isolation specification used in typical dual linear diversity systems, an axial ratio specification of 1.2dB must be applied to a circularly polarized system.

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