IET Microwaves, Antennas & Propagation

Research Article

Reconfigurable antennas: quantifying payoffs for pattern, frequency, and polarisation reconfiguration

ISSN 1751-8725
Received on 2nd July 2019
Revised 14th October 2019
Accepted on 5th November 2019
E-First on 21st November 2019
doi: 10.1049/iet-map.2019.0473
www.ietdl.org

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Abstract: The authors map the differences between various reconfigurable antennas and present a payoff metric for each type. They evaluate three distinct schemes of reconfiguration: pattern, frequency, and polarisation. They show that the often neglected losses play a pivotal role in the effectiveness of reconfigurable systems. For each of the pattern, polarisation and frequency reconfigurable antennas, they define a quantity that reflects the number of non-overlapping radiation patterns, orthogonality of the polarisation states, and the covered fractional bandwidth, respectively. Then, these quantities are divided by the amount of added losses. Thus, these metrics capture both the increased diversity due to the reconfiguration states and the associated losses. Moreover, the relationship between these metrics and the capacity of a communication system is discussed. Finally, application of the payoff metrics is demonstrated by comparing several reconfigurable antenna architectures from the literature. They show that established payoff metrics can be successfully used to evaluate and quantify the merits of reconfigurable antennas by using only antenna parameters rather than going through system-level analysis.

1 Introduction

In recent years, with the increasing demand in wireless communications, the integration of multiple antennas into a single device is required. A single reconfigurable antenna can be used for various radiation pattern, frequency, and polarisation requirements. Reconfigurability and adaptability are crucial features of the future millimetre-wave communication systems, so that they could adapt their characteristics to achieve optimal transmission. For instance, employing reconfigurable antennas in multiple-input-multiple-output (MIMO) systems offer an increased diversity without an increase in the number of antenna elements and the associated radio-frequency (RF) chains. However, by introducing reconfigurability, losses also increase, which counteract the added functionality. Even though there is an extensive literature on the design and implementation of reconfigurable antennas [1–3], there is a lack of quantitative study on the effectiveness of the reconfiguration and the performance comparison of the designs. Namely, when antennas are made reconfigurable, substantial losses are added.

Reconfigurable antennas can be implemented using various methods. Electrically tunable elements such as PIN diodes [4–9], varactors [10, 11], gallium arsenide (GaAs) switches [12] and RF micro-electro-mechanical systems (MEMS) [13–16] are integrated with antennas to change the current distribution and alter the antenna radiation characteristics. Tunable materials such as liquid crystals [17, 18] and barium strontium titanate [19] are used to create reconfiguration by changing the permittivity. Each of these elements alters the current distribution on the antennas and consequently changes the antenna parameters. Based on the antenna parameters that are dynamically adjusted, antennas can be classified as pattern, polarisation or frequency reconfigurable antennas.

Integration of reconfigurable antenna elements with signalling schemes provides an extra degree of freedom for the joint optimisation of adaptive system parameters; thus, significant channel capacity gains are possible [20]. Employing pattern reconfigurable antennas in MIMO systems has shown that significant performance gains are possible when the antenna pattern configurations are optimal. The increase in capacity is achieved through an increase in diversity and also enhanced signal-to-noise ratio (SNR) [21]. A similar study has been carried out in [22] where an antenna array capable of both pattern and polarisation reconfigurations is used in a 2×2 MIMO system. It is shown that the increase in capacity depends on the diversity achieved through uncorrelated reconfigurable states, antenna efficiency and the multipath propagation environment. The effect of polarisation diversity on MIMO system capacity is also analysed in [23, 24]. It is shown in [23] that capacity improvements of 35% are achievable for a 2×2 MIMO system. However, the capacity improvements significantly decrease (15%) when the efficiency of the antennas is accounted. Moreover, in special multipath environments, it is shown that with an antenna array with three distinct orthogonal polarisation states, a three-fold increase in the capacity is possible [24]. For all of the aforementioned studies, a complex system-level measurement or simulation is carried out in a specific multipath environment and system capacity is measured. Results of these studies depend on the choice of the propagation environment, frequency characteristics of the channel, number of antenna elements and optimality of the antenna reconfigurable states. However, from an antenna engineering perspective, a simple metric for each of the pattern, polarisation or frequency reconfiguration is required to compare antenna designs based solely on the antenna parameters without going through system-level analysis. These metrics are essential for optimising reconfigurable antenna designs and gauging their merits.

In this work, for the first time, we define three distinct payoff metrics for pattern, polarisation and frequency reconfigurable antennas considering the penalties for loss of efficiency. Payoff metrics for pattern and polarisation reconfigurable antennas represent the number of uncorrelated and independent reconfiguration states for 1 dB of loss. On the other hand, for the frequency reconfigurable antenna, payoff metric is based on the total fractional bandwidth for 1 dB of efficiency loss. For communication systems, each of these metrics is related to the capacity through their relation to channel matrix, bandwidth and SNR. Note that reconfigurable antennas can also be used in radar [25] and sensing applications [26]; however, for the purpose of this paper, we have focused our discussion on communication systems.

In Sections 2–4, a series of new payoff metrics for three cases of pattern, frequency, and polarisation reconfiguration are introduced. In each section, the practical use of the metrics is demonstrated by comparing several reconfigurable antenna designs. Finally, concluding remarks are included in Section 5.

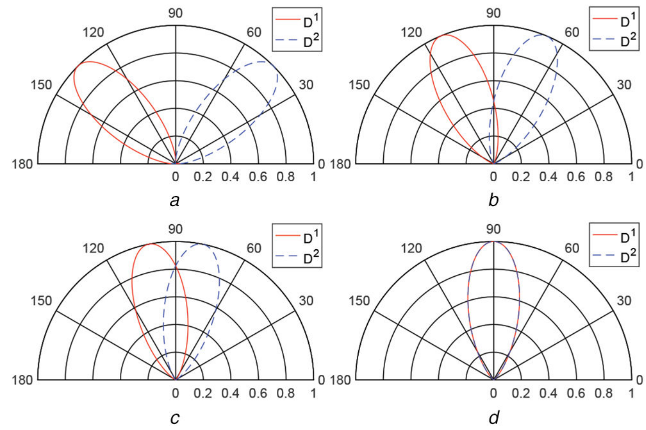

Fig. 1 *Radiation pattern for the reconfigurable antenna with* $\cos^{10}\theta$ *type directivity for the cases of where the separation of beams is*
(a) 90°, ***(b)*** 45°, ***(c)*** 22.5° and, ***(d)*** 0°

Table 1 Summary of the study for pattern reconfigurable antenna with $\cos^{10}\theta$-type directivity for the cases of $\Delta\theta = 90°$, 45°, 22.5°, 0°

$\Delta\theta$, deg	N	N_{eq}	Loss, dB	SDP, dB^{-1}
90	2	2	1.24	1.61
45	2	1.90	1.24	1.44
22.5	2	1.46	1.24	1.18
0	2	1	1.24	0.81

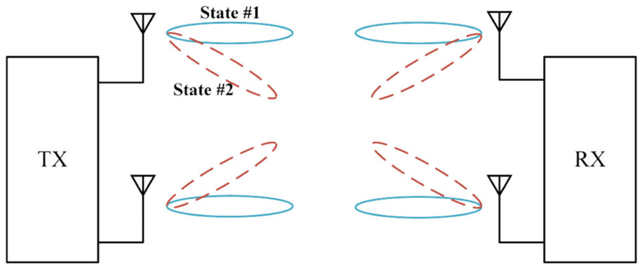

Fig. 2 *Schematic diagram of a 2 2 MIMO system with 2-state pattern reconfigurable antennas*

2 Pattern reconfiguration payoff

2.1 Definition

In the previous studies on the multiband [27] and ultra-wideband antennas [28], figures-of-merit that focuses on the similarities of antenna patterns at different frequencies has been defined. However, in a pattern reconfigurable antenna, the dissimilarity between radiation pattern states is of interest. To quantify the non-overlapping patterns of a reconfigurable antenna, an equivalent number of states is proposed in [29]. An equivalent number, N_{eq}, of pattern configurations is defined by averaging the maximum achievable gain for each θ and ϕ over the entire space Ω [29]

$$N_{\text{eq}} = \frac{1}{4\pi}\int\int_{\Omega} \max_{i=1,\ldots,N} G^{i}(\theta,\phi)\,\mathrm{d}\Omega \tag{1}$$

where $G^{i}(\theta,\phi)$ is the realised gain for each state of the reconfigurable antenna and N is the total number of configurations. Note that, N_{eq} is bounded by the maximum number of configurations (N) and its lower bound is limited by the total efficiency. N_{eq} quantifies the degree of overlap between different radiation patterns considering that the polarisation of the antenna and its frequency response remains unchanged for different beam configurations. However, the antenna directivity can be used instead of the realised gain to limit N_{eq} to $1 < N_{\text{eq}} < N$. Hence, N_{eq} can be defined using the directivity of each state $D^{i}(\theta,\phi)$ as follows:

$$N_{\text{eq}} = \frac{1}{4\pi}\int\int_{\Omega} \max_{i=1,\ldots,N} D^{i}(\theta,\phi)\,\mathrm{d}\Omega\,. \tag{2}$$

N_{eq} in (2) is only associated with diversity and does not reflect the efficiency of the antenna. In order to determine the pattern diversity gain considering the losses associated with the reconfiguration, a spatial diversity payoff (SDP) metric can be defined as

$$\text{SDP} = \frac{N_{\text{eq}}}{\max_{i}\left(-10\log(e_{T}^{i})\right)} \tag{3}$$

where e_{T}^{i} is the total efficiency of each state. This figure-of-merit represents the number of non-overlapping reconfigurable pattern states per 1 dB of introduced loss.

As an example, consider that an antenna has two states with normalised pattern of $\cos^{10}\theta$. In addition, the angular distance between the main beams of these two states is $\Delta\theta$. Consider four versions of this reconfigurable antenna where $\Delta\theta = 90°$, 45°, 22.5°, 0°. Normalised radiation patterns of these four cases are plotted in Figs. 1*a–d*. Calculated N_{eq} for the four cases of $\Delta\theta = 90°$, 45°, 22.5°, 0° are 2, 1.9, 1.46, 1, respectively. Assuming that the minimum antenna efficiency is 75%, the maximum loss is 1.24 dB. The SDP of the antenna for these four cases and the summary of results are shown in Table 1. According to the results, as $\Delta\theta$ decreases, SDP is also decreasing, which is a result of increased over-lapping of radiation patters.

2.2 System application

One of the applications of reconfigurable antennas is in MIMO communication systems. A 2×2 MIMO system with pattern reconfigurable antennas that has two states is shown in Fig. 2. SDP defined in (3) can be used to qualitatively evaluate the performance of MIMO system. Assuming that the channel is unknown at the transmitter and each transmitting antenna has equal power, the capacity is given by

$$C = B\log_{2}\left(\det\left(\boldsymbol{I}_{N_r} + \frac{\text{SNR}}{N_t}\boldsymbol{H}\boldsymbol{H}^{\dagger}\right)\right) \tag{4}$$

where B is the bandwidth, N_r and N_t are the number of receiving and transmitting antennas, respectively. $\boldsymbol{I}_{N_r}$ is the $N_r \times N_r$ identity matrix, $\boldsymbol{H}$ is the normalised channel matrix and $\{\cdot\}^{\dagger}$ denotes the complex conjugate transpose. It can be shown that for a channel with a large SNR, capacity depends on the rank of $\boldsymbol{H}$ [20, 24]. In free space, N_{eq} corresponds to the non-overlapping, uncorrelated channels with minimum crosstalk and in turn is directly related to the rank of $\boldsymbol{H}$. Consequently, as N_{eq} increases the diversity and the rank of channel matrix increases. On the other hand, as efficiency increases, SNR also increases, which results in a higher capacity. It can be concluded that as the SDP increases, the channel capacity also increases. Note that the SDP value is for the initial evaluation and optimisation of pattern reconfigurable antenna and the amount of increase in the channel capacity depends on the multipath propagation channel and the choice of optimal scenario for spatial multiplexing [20, 21].

2.3 Evaluation

To demonstrate the application of SDP defined in (3), five different pattern reconfigurable antennas proposed in [10, 13, 14, 30, 31] are compared and the calculated SDP values are shown in Table 2. Data in the table are sorted according to increasing SDP and reconfigurable parasitic array proposed in [30] has the highest SDP due to its high efficiency and relatively high N_{eq}. A high SDP value of 9.16 dB^{-1} suggests that in an adaptive communication system, this antenna is capable of switching between different radiation

Table 2 Comparison of pattern reconfigurable antenna architectures [10, 13, 14, 30, 31]. Data are sorted with respect to SDP values

Ref.	f, GHz	No. of tunable elements	N	N_{eq}	Loss, dB	SDP, dB^{-1}
[30]	3.65	4	3	1.79	0.19	9.16
[10]	2.4	2	2	2	1.59	1.29
[13]	5.8	3	3	1.98	1.64	1.21
[31]	3.5	6	2	1.44	1.31	1.10
[14]	10	3	5	1.33	2	0.67

Table 3 Comparison of frequency reconfigurable antenna architectures [4, 11, 12, 15, 16]. Data are sorted with respect to FRP values

Ref.	No. of tunable elements	N	f_L, GHz	f_H, GHz	FBW, %	Loss, dB	FRP, dB^{-1}
[12]	2	4	2.048	5.590	52.80	1.34	0.55
[15]	2	4	26.98	37.07	20.77	1.85	0.35
[11]	2	continuous	0.946	1.829	63.6	2.24	0.27
[4]	4	4	0.535	0.907	12.30	3.28	0.04
[16]	2	continuous	97.5	103.5	6	1.64	0.04

patterns without losing SNR due to the loss of efficiency. On the other hand, antenna in [13] has similar N and N_{eq} values. However, because of higher loss, its SDP is significantly lower than the design in [30].

In contrast, the antenna proposed in [10] has the highest N_{eq}, since two reconfigurable pattern states have minimal overlapping. However, due to the losses in PIN diodes, SDP decreases significantly. Reconfigurable antenna in [14] has five reconfigurable states, which is the highest number of states among the designs listed in Table 2. However, it has an N_{eq} of 1.33, since the patterns are highly overlapping. Using this antenna in an adaptive communication system could not contribute to the capacity through spatial diversity due to the similarities of the radiation patterns.

As shown in the table, the total number of states N is not sufficient to compare the performance of the reconfigurable antennas. Whereas, a comprehensive comparison can be obtained using SDP based on both the N_{eq} and the total efficiency.

3 Frequency reconfiguration payoff (FRP)

3.1 Definition

For a frequency reconfigurable antenna, it is desired to maximise the bandwidth coverage while maintaining high efficiency. To quantify the performance of a frequency reconfigurable antenna, we define an FRP metric as follows:

$$\mathrm{FRP} = \frac{\mathrm{FBW}}{\max_i\left(-10\log(e_T^i)\right)}, \tag{5}$$

where FBW is the fractional bandwidth of the reconfigurable antenna and e_T^i is the total efficiency of ith state. For a continuously frequency reconfigurable antenna, bandwidth can be defined by the highest and lowest achieved frequencies with a return loss of >10 dB. However, for the antennas with a discrete frequency reconfiguration, there could be gaps in the covered bandwidth between the lowest and the highest achieved frequencies. For this purpose, bandwidth is defined as the sum of the impedance bandwidth ($S_{11} < -10\,\mathrm{dB}$) of each reconfigurable state. In this case, a bandwidth function can be defined as follows:

$$\mathrm{BW} = \int_0^{\infty} \max_{i=1,\ldots,N} \mathrm{MRL}^i(f)\mathrm{d}f \tag{6}$$

where N is the total number of states and $\mathrm{MRL}^i(f)$ is the matched return loss function of the ith state defined as

$$\mathrm{MRL}^i(f) = \begin{cases} 1 & \mathrm{RL} > 10\,\mathrm{dB} \\ 0 & \mathrm{RL} < 10\,\mathrm{dB} \end{cases} \tag{7}$$

where RL is the return loss of the antenna. Bandwidth, defined in (6) quantifies the total bandwidth covered by all the states of the antenna. Then, the FBW can be defined as

$$\mathrm{FBW} = 2\frac{\mathrm{BW}}{f_{\mathrm{H}} + f_{\mathrm{L}}}. \tag{8}$$

FRP metric defined in (5), quantifies the gain achieved through an increase in bandwidth with respect to the increased losses. Therefore, a reconfigurable antenna has a high FRP when the fractional bandwidth and the efficiency are maximised simultaneously.

3.2 System application

In a communication system, higher channel capacity can be achieved by increasing the bandwidth and SNR ($C = B\log_2(1 + \mathrm{SNR})$). Considering this, maximising the payoff metric defined in (5), ensures the increase of bandwidth with a minimum amount of loss, which contributes to higher SNR. In addition, frequency reconfigurable antennas can be used in a MIMO system with orthogonal frequency division multiplexing (OFDM). In this system, the overall achievable channel capacity, averaged over all the subcarriers, can be calculated as [22]

$$C_{\mathrm{OFDM}} = \frac{1}{m}\sum_i^m\left(\det\left(\boldsymbol{I}_{N_r} + \frac{\mathrm{SNR}_i}{N_t}\boldsymbol{H}_i\boldsymbol{H}_i^{\dagger}\right)\right) \tag{9}$$

where $\boldsymbol{H}_i$ and SNR_i are the normalised channel matrix and SNR for the ith subcarrier, respectively. In this scenario, the higher values for FRP correspond to the higher number of subcarriers with a 1 dB reduction in SNR. Note that FRP is a metric for evaluating and comparing the different frequency reconfigurable antenna designs. However, in order to fully evaluate the performance gain, a complete system-level analysis is required.

3.3 Evaluation

To demonstrate the application of the proposed FRP, five frequency reconfigurable antenna designs in [4, 11, 12, 15, 16] are compared and FRP values are given in Table 3. Fractional bandwidth and FRP for these antennas are calculated using (5)–(8).

Reconfigurable monopole antenna designed in [12] achieved the highest FRP value since it has a relatively high fractional bandwidth of 52.8% and has the highest efficiency thanks to the low loss FET switches. The high value of FRP implies that this antenna offers high fractional bandwidth with minimum loss of

Table 4 Comparison of polarisation reconfigurable antenna architectures [6–9]. Data are sorted with respect to POF values

Ref.	f, GHz	No. of tunable elements	N	$N_{\rm eq}^{\rm pol}$	Loss, dB	PDP, dB^{-1}
[6]	5.8	6	3	2	0.8	2.41
[9]	1	6	4	2.67	1.25	2.14
[6]	5.2	6	2	2	0.96	2.09
[8]	5.6	2	4	2.67	1.65	1.62
[7]	2	6	3	2.25	2.21	1.01

efficiency. Continuously reconfigurable slot antenna in [11] has the highest fractional bandwidth, however, FRP value is reduced due to the low efficiency at low-frequency end. At millimetre-wave frequencies, since the losses of tunable elements such as PIN diodes and varactors increase, RF MEMS switches and variable capacitors are used. Two millimetre-wave slot antenna designs in [15, 16] employ MEMS variable capacitors and have comparable loss values, however, FRP is higher for [15] since it has higher fractional bandwidth. These examples illustrate that FRP is an essential and practical metric for comparing frequency reconfigurable antennas in which both bandwidth and losses are considered.

4 Polarisation reconfiguration payoff

4.1 Definition

In order to quantify the polarisation reconfigurability of the antenna, orthogonality of different states can be used. A polarisation orthogonality factor (POF) for a pair of polarisation unit vectors ($\hat{\boldsymbol{e}}_i$) can be defined as

$$\mathrm{POF} = 1 - \left|\hat{\boldsymbol{e}}_i \cdot \hat{\boldsymbol{e}}_j^*\right|^2 . \tag{10}$$

POF is equal to 1 for the orthogonal pair and it is zero when two polarisation unit vectors are identical. For an antenna with N polarisation states, a normalised POF for all possible polarisation pairs can be calculated as

$$\mathrm{POF_{norm}} = \frac{\sum_{j=1}^{N}\sum_{i>j}^{N}\left(1 - \left|\hat{\boldsymbol{e}}_i \cdot \hat{\boldsymbol{e}}_j^*\right|^2\right)}{\binom{N}{2}} . \tag{11}$$

Summation calculates the total POF for all polarisation pairs and $\binom{N}{2}$ is the total number of the pairs. An equivalent number of orthogonal polarisation states can be defined as

$$N_{\rm eq}^{\rm pol} = N\mathrm{POF_{norm}} \tag{12}$$

The maximum value of $N_{\rm eq}^{\rm pol}$ is N when all of the polarisation states are mutually orthogonal. Using the definition of the $N_{\rm eq}^{\rm pol}$ and the efficiency of the states, polarisation diversity payoff (PDP) can be defined as

$$\mathrm{PDP} = \frac{N_{\rm eq}^{\rm pol}}{\max_i\left(-10\log(e_T^i)\right)} . \tag{13}$$

PDP quantifies the number of orthogonal polarisation states for 1 dB of loss. PDP increases with the number of the orthogonal polarisation states and increasing efficiency.

For instance, consider that a reconfigurable antenna has four polarisation states as follows:

$$\hat{\boldsymbol{e}}_1 = \hat{\boldsymbol{a}}_x \tag{14a}$$

$$\hat{\boldsymbol{e}}_2 = \hat{\boldsymbol{a}}_y \tag{14b}$$

$$\hat{\boldsymbol{e}}_3 = \frac{1}{\sqrt{2}}(\hat{\boldsymbol{a}}_x + j\hat{\boldsymbol{a}}_y) \tag{14c}$$

$$\hat{\boldsymbol{e}}_4 = \frac{1}{\sqrt{2}}(\hat{\boldsymbol{a}}_x - j\hat{\boldsymbol{a}}_y) . \tag{14d}$$

In this case, only $\hat{\boldsymbol{e}}_1 \perp \hat{\boldsymbol{e}}_2$ and $\hat{\boldsymbol{e}}_3 \perp \hat{\boldsymbol{e}}_4$, therefore, $N_{\rm eq}^{\rm pol} = 2.67$ which is less than the total number of polarisation states. If we assume that the antenna has a minimum efficiency of 75%, the PDP is calculated to be 2.15 dB^{-1}.

4.2 System application

In a communication system, using space-time modulation, polarisation diversity can increase the capacity up to an order of magnitude [32]. It is also shown that using a polarisation reconfigurable antenna for a fixed bit error rate, SNR gain of up to 30 dB is possible [20]. This performance gain is possible under certain conditions by jointly optimising the antenna properties and associated transmission algorithm.

Considering the capacity of a MIMO system given in (4), channel capacity can be maximised by maximising the rank of the channel matrix $\boldsymbol{H}$. Rank of the $\boldsymbol{H}$ depends on the number of orthogonal polarisation states which results in uncorrelated channel coefficients with minimum crosstalk. Therefore, maximising the PDP in (13) will contribute to increase in channel capacity by maximising the number of orthogonal states and SNR.

4.3 Evaluation

We have evaluated PDP for five polarisation reconfigurable antennas proposed in [6–9] and compare their performance. According to the results shown in Table 4, rhombic patch antenna in [6] at 5.8 GHz has the highest PDP value due to the low loss. Although this antenna has three states of RHCP, LHCP and LP, the linear polarisation is not orthogonal to either of the circularly polarised states; hence, $N_{\rm eq}^{\rm pol}$ is equal to two. The same antenna at its lower band of 5.2 GHz has the same $N_{\rm eq}^{\rm pol}$ but since it has a higher loss, has a lower PDP.

Antennas with the highest $N_{\rm eq}^{\rm pol}$ are presented in [8, 9] that have two orthogonal CP states and two orthogonal LP states using switchable feeding networks. Nevertheless, LP states and CP states are not orthogonal to each other; therefore, $N_{\rm eq}^{\rm pol}$ for both of these antennas are 2.67. However, because the antenna in [9] has higher efficiency, it has a higher PDP.

In [7], a circular cavity antenna is proposed that the angle of the linear polarisation is switched between six states by changing the position of the radiating aperture. However, only three states with 0°, 60°, and 120°, are non-redundant. These linear polarised states are not orthogonal to each other, therefore, $N_{\rm eq}^{\rm pol}$ is equal to 2.25.

One can conclude from Table 4 that a number of the states are not representative measure of polarisation diversity. However, PDP is a metric that shows the orthogonality of the polarisation states which is crucial to obtain a channel with minimum crosstalk. In addition, PDP decreases with the increasing losses of the system which deteriorates the SNR.

5 Conclusion

In order to evaluate the performance of reconfigurable antennas, spatial diversity, polarisation diversity and FRP metric are defined for pattern, frequency and polarisation reconfiguration, respectively. These metrics are based on the efficiency of the antenna and the following parameters:

- Number of non-overlapping radiation patterns for pattern reconfigurable antenna
- Number of non-orthogonal polarisation states for polarisation reconfigurable antenna
- Total non-overlapping bandwidth of frequency reconfigurable antenna.

The effectiveness of these definitions is demonstrated by comparing different architectures in the literature. This definition emphasises the trade-offs between the increased reconfiguration capability/complexity and increased losses due to the reconfiguring element and modified radiation characteristics. It was demonstrated that maximising each of the frequency reconfiguration, spatial and polarisation diversity payoffs would result in a performance gain in terms of communication system capacity. These payoff metrics are useful tools for optimising the designs and comparing the capabilities of the reconfigurable antennas based on the antenna parameters without going through system-level analysis.

6 Acknowledgment

This work was partially supported by the National Science Foundation under grant no. 1408228. The authors thank the reviewers for their comments and suggestions.

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