On the Cost-Effectiveness of Using Beamforming at the Ground Station for Aeronautical Communications

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***Abstract*—In recent years, beamforming techniques have become increasingly popular, primarily because of their ability to enhance the performance of communication systems. These techniques might also yield improvements in aeronautical communications systems. However, the deployment of beamforming techniques comes with additional cost. In this paper, we assess the cost-effectiveness of employing beamforming techniques for air-ground communications to determine its feasibility. The study compares the antenna gain-cost ratio of using beamforming techniques to using a single-omnidirectional antenna. The cost function is determined by both the number of antenna elements in a single station and the total number of ground stations needed to cover an area. The cost-effectiveness evaluations are conducted for two use cases: The L-band Digital Aeronautical Communications System (LDACS) and the implementation of beamforming at higher frequencies. Our findings indicate that beamforming is not cost-effective at frequencies below 4 GHz, including LDACS.**

***Index Terms*—Beamforming, aeronautical communications, LDACS, cost-effectiveness.**

I. INTRODUCTION

As the demand for air transportation continues to grow, there is a need to enhance the performance of aeronautical communications systems to cope with future challenges. [1]. Employing beamforming techniques at the ground station (GS)s is one approach to improve the air-ground (A/G) communications performance. By utilizing beamforming techniques, the antenna gain can be substantially enhanced. This leads to the possibility of either increasing the cell size or achieving higher data rates without compromising the bit error rate (BER) [2].

While beamforming can significantly improve the antenna gain, it is nevertheless important to consider the underlying cost. To be able to apply beamforming techniques, a multiple antenna (MA) system is required. This necessitates antenna elements, phase shifters for beam steering, and a beamforming network for the signal combination from the various antennas, in addition to other radio frequency (RF) equipment. However, it can be argued that the overall cost of hardware equipment primarily depends on the number of antenna elements, unless it is a mass production. A key consideration here is that the increase in antenna gain achieved by beamforming does not scale linearly with the number of antenna elements. Instead, the number of antenna elements grows exponentially, while the gain improvement follows a logarithmic pattern [3]. This can have implications on the overall feasibility and cost-effectiveness of implementing beamforming techniques.

In this paper, the cost of a single GS is defined as the number of antenna elements used. This assumption is based on the fact that mass production of GSs for aeronautical communications is not anticipated in the next few years. This is because while the cellular industry deploys millions of base stations, aeronautical communications operates in the thousands, making it a relatively small industry. This assumption is crucial since mass production has the potential to yield significant cost reductions. Moreover, the beamforming enabled increase in antenna gain can be leveraged to expand cell sizes, thereby reducing the required number of GSs for a given area. This consideration is factored into the overall cost calculations.

The objective of this paper is to investigate the cost effectiveness of beamforming in the GS for A/G communications. To assess the cost-effectiveness, we compare the antenna gain-cost ratio for both MA and single-omnidirectional antenna (SA) systems. Moreover, we examine the cost-effectiveness for two use cases. Firstly, our evaluation focuses on the L-band Digital Aeronautical Communications System (LDACS) as a single antenna system, which is expected to complement existing air-ground aeronautical communication systems in the near future [4]. Secondly, we extend our analysis to encompass higher frequency spectrums to address other possible A/G communications systems in S-band and C-band.

After this introduction, the paper is organized as follows: In Section II, we introduce the system model, which provides the antenna gain, the cost function, and the cost-effectiveness calculations. Moving to Section III, we present our findings, which encompass an evaluation of antenna tilt's impact on the overall gain, the minimum number of antenna elements required for a desired gain, and the cost-effectiveness results. In Section IV, we discuss the limitations of our work. Finally, a summary of our work and an outlook for the future is provided in Section V.

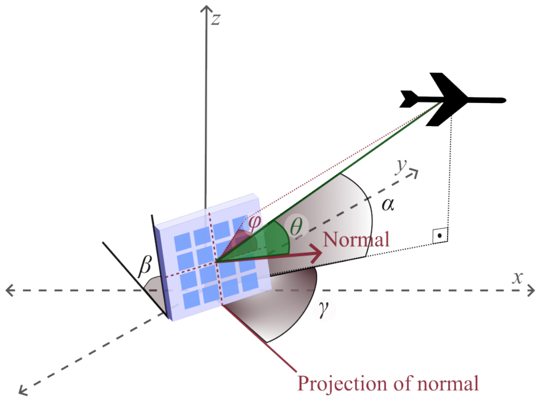
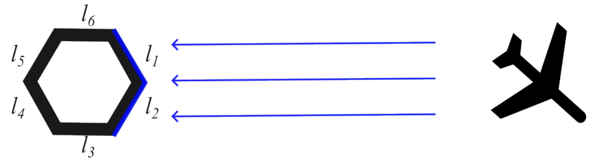
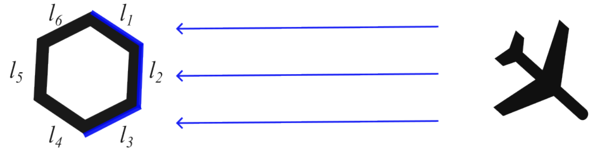


Figure 1: Geometry of single planar rectangular antenna array, l_i.



(a) l_1 and l_2 receive the LOS signal coming from the aircraft



(b) l_1, l_2 and l_3 receive the LOS signal coming from the aircraft

Figure 2: Top View of Antenna System for $L = 6$ and $\beta = 90°$.

II. SYSTEM MODEL

We assume that in a GS there are L planar rectangular antenna arrays, as defined in [5], placed back to back in a cell, and that the i^{th} antenna array is denoted as l_i. Each array has a size of $M \times M$, consisting of M^2 antenna elements. In total, a GS has $K = M^2L$ antenna elements. The MA system performance is evaluated for all combinations of $M \in \{1, 2, 3, 4, 5, 8, 10, 15, 20\}$ and $L \in \{2, 3, 4, ..., 10\}$. We assume that there is one aircraft in the cell, and that the main beam of the antenna system is tracking the aircraft.

A. Geometry

The geometry considered for a single planar rectangular array is shown in Fig. 1. The origin of the coordinate system is at the GS. The following parameters apply:

- α is the angle between the line-of sight (LOS) rays coming from the aircraft and the horizontal surface.
- γ is the azimuth angle between the projections of the aircraft and of the normal to the antenna array surface on the horizontal plane.
- β, the antenna tilt, is the angle between the horizontal surface and the antenna array.
- θ, the angle of incidence, is the angle between the LOS rays coming from the aircraft and the line normal to the antenna array's surface.
- ϕ is the azimuth angle between the projection of the aircraft on the antenna array surface and the horizontal line across the antenna array's surface.

The angles θ and ϕ are derived from the angles α, γ, and β as

$$\theta = \arccos(\cos\alpha \sin\gamma \sin\beta + \sin\alpha \cos\beta); \qquad (1)$$

$$\phi = \arctan\left(\frac{-\cos(\alpha + \beta)}{\cos\alpha \sin\gamma}\right). \qquad (2)$$

It is worth noting that the angle of arrival for l_i is represented by θ_i and ϕ_i and that β is the same for all antenna arrays.

For the purpose of this work, we use a curved Earth model with an Earth radius of $6371\,\mathrm{km}$ [6]. The altitude of the aircraft is $10\,\mathrm{km}$ above the mean sea level (MSL), while the GS is at $500\,\mathrm{m}$ above the MSL. The radii of the cells are denoted by r_{sa} and r_{ma} for SA and MA, respectively. Theoretically, the cell radius can be increased up to the point where the aircraft disappears into the horizon due to the curvature of the Earth. For the given geometry, the radio horizon is computed to be $357\,\mathrm{km}$ using the maritime radio horizon equation from [7]. To take into account possible dependencies on the terain, in this paper we increase r_{ma} up to $352\,\mathrm{km}$ and assume that the aircraft is visible to the GS in this range.

B. Scenarios

We divide the cost-effectiveness evaluations into two use cases.

1) LDACS Evaluation: In this case, we follow the LDACS specifications for the reverse link [8]. The gain of the SA at the GS, G_{sa}, is $12\,\mathrm{dBi}$, the carrier frequency, f_c, is $987\,\mathrm{MHz}$, and r_{sa} is $222\,\mathrm{km}$. This results in a free-space path loss (FSPL) at the cell edge of $139\,\mathrm{dB}$. We evaluate beamforming techniques while keeping r_{sa} constant and increasing r_{ma} up to $352\,\mathrm{km}$.

2) Higher Frequency Evaluation: The same G_{sa} of $12\,\mathrm{dBi}$ is maintained as for the LDACS case. However, we vary the f_c between 2 and $8\,\mathrm{GHz}$. As the f_c increases, so does the FSPL. To compensate, r_{sa} is reduced such that the FSPL at the cell edge is the same as in LDACS, while r_{ma} remains at $222\,\mathrm{km}$.

C. Overbound Gain Calculation

In this section, we obtain the highest possible gain attainable in the direction of the LOS signal when using the described MA system. It is important to note, that this calculation does not represent a realistic gain; instead, our aim is to establish an upper limit on the potential gain achievable with this system.

The radiation pattern estimate of the single antenna element is derived from the cosine pattern distribution, which is a close estimate of a patch antenna [3]. The gain of the single element is assumed to be $4.7\,\mathrm{dBi}$. To calculate the radiation pattern of a single planar rectangular antenna array, the radiation pattern estimate of the single element estimate is multiplied by the array factor. The array factor is computed by the discrete Fourier transform of the antenna array excitations [5]. Calculations are performed for the case where the array elements have uniform amplitude and are evenly spaced at half wavelengths. In order to calculate the overbound gain, we do not take into account the mutual coupling between the array elements.

It is assumed that l_i is not receiving the LOS signal, when $90° \leq \theta_i \leq 270°$. For instance, consider two scenarios when $L = 6$ and $\beta = 90°$, as illustrated in Fig. 2. In Figure 2a, only l_1 and l_2 receive the LOS signal coming from the aircraft, whereas in Fig. 2b, l_1, l_2, and l_3 receive the signal.

Every antenna array that can receive the LOS signal steers its main beam toward the aircraft. The gain of l_i in the aircraft's direction is denoted as g_i. The total gain of the system, represented as G_{ma}, is computed as:

$$G_{\mathrm{ma}} = \sum_i g_i, \text{ for } \theta_i < 90° \text{ or } \theta_i > 270°. \tag{3}$$

When calculating the total system gain, we omitted the antenna arrays that do not receive the LOS signal.

To assess the performance of the antenna system, we define two metrics. To obtain the first metric, the position of the aircraft is uniformly distributed within a cell with a radius of r_{ma}. The arithmetic mean, $\overline{G}_{\mathrm{ma}}$, is calculated by averaging the values of G_{ma} at each aircraft position. To compute the second metric, the aircraft position is uniformly distributed only along the edge of the cell where the FSPL is the highest. The second metric is denoted by $\overline{G}^*_{\mathrm{ma}}$.

D. Cost Function and Measure of Effectiveness

The number of required GSs for the MA and SA systems, GS_{ma} and GS_{sa}, respectively, is calculated each by

$$GS_{\mathrm{ma}} = \frac{A}{\pi r^2_{\mathrm{ma}}},\ GS_{\mathrm{sa}} = \frac{A}{\pi r^2_{\mathrm{sa}}}, \tag{4}$$

where A is the area to be covered, and r_{ma} and r_{sa} are the radii of the circular cells.

The cost of the MA system, C_{ma}, is estimated by

$$C_{\mathrm{ma}} = GS_{\mathrm{ma}} \cdot f(K), \tag{5}$$

where $f(K)$ is a function that represents the cost of the beamforming hardware equipment in a single GS, and this cost depends on the number of antenna elements in that GS, denoted as K. To calculate the most optimistic cost, we set $f(K) = K$. In practice, we expect $f(K)$ to be higher than K, since in addition to antenna elements it includes hardware such as phase shifters, beamforming network, etc.

The hardware equipment cost for the SA system is also simplified to the number of antenna elements in a single GS, as is done for the MA system. Consequently, the cost of the SA, C_{sa}, is equal to GS_{sa}.

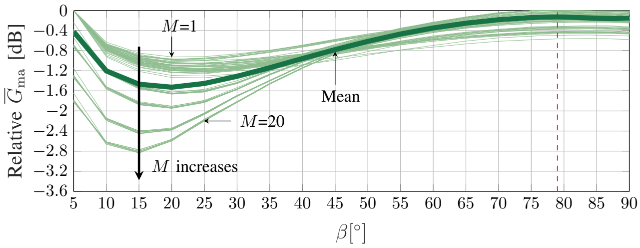


Figure 3: Impact of antenna tilt, β, on average gain within the cell, $\overline{G}_{\mathrm{ma}}$.

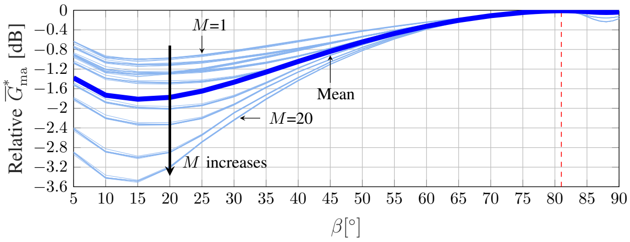


Figure 4: Impact of antenna tilt, β, on average gain at the cell edge, $\overline{G}_{\mathrm{multi}^*}$.

In order to evaluate whether it is worth using a MA system instead of a SA, the system effectiveness metric, η, is defined, which compares the antenna gain-cost ratio of using beamforming techniques to using a SA system as follows

$$\eta = \frac{\dfrac{\overline{G}^*_{\mathrm{ma}}}{C_{\mathrm{ma}}}}{\dfrac{G_{\mathrm{sa}}}{C_{\mathrm{sa}}}} = \frac{\overline{G}^*_{\mathrm{ma}} \cdot r^2_{\mathrm{ma}}}{G_{\mathrm{sa}} \cdot r^2_{\mathrm{sa}} \cdot K}. \tag{6}$$

For the gain of MA system, the average gain at the cell edge, $\overline{G}^*_{\mathrm{ma}}$, is used since the antenna gain is more critical for the farthest aircraft. G_{sa} is 12 dB. In our evaluations, we deem the use of beamforming techniques as not cost-effective when η is less than 1.

III. RESULTS AND DISCUSSION

In the following, we analyzed the effect of the antenna tilt, β, on the system performance. Afterwards, the average antenna gain, $\overline{G}_{\mathrm{ma}}$, is calculated for a fixed value of β. Finally, the cost-effectiveness of using beamforming techniques is investigated for the LDACS as well as for higher frequency use cases.

A. Antenna Tilt

The average gain within the cell, $\overline{G}_{\mathrm{ma}}$, and the average gain at the cell edge, $\overline{G}^*_{\mathrm{ma}}$, are computed for all combinations of M and L values outlined in Section II, for $\beta \in [5, 90]$, correspondingly the optimal value of β is obtained for each pair of M and L. Please note that $\beta = 0$ would imply a single large antenna array rather than L separate antenna arrays. Therefore, we deliberately omit $\beta < 5$ since values below this threshold do not align with the intended configuration of multiple separate antenna arrays.

For each M and L combination, we compute the relative $\overline{G}_{\mathrm{ma}}$ and $\overline{G}^*_{\mathrm{ma}}$ over all β values compared to the gain achieved at its optimal β value. This means that for each M and L pair, the relative $\overline{G}_{\text{ma}}$ and $\overline{G}^*_{\text{ma}}$ are equal to $0\,\text{dB}$ at their optimal β value.

The light blue and green lines in Figures 3 and 4 illustrate the relative $\overline{G}_{\text{ma}}$ and $\overline{G}^*_{\text{ma}}$ for each M and L pairs. The dark bold blue and green lines are the mean of all M and L combinations. The vertical dashed red lines indicate the optimum β value for the mean relative gains. According to Figures 3 and 4, the highest $\overline{G}_{\text{ma}}$ can be achieved at $\beta = 79°$, while the highest $\overline{G}^*_{\text{ma}}$ at $\beta = 81°$. Not surprisingly, the required β is higher for the best $\overline{G}^*_{\text{ma}}$. This is because the antenna array achieves its highest gain perpendicular to its surface. The farther away the aircraft is, the more LOS signals arrive at a low α angle. Additionally, a correlation between β and M is observed: the higher the M is, the larger the impact of a change in β on $\overline{G}_{\text{ma}}$ and $\overline{G}^*_{\text{ma}}$.

To obtain the best antenna gain for the most distant aircraft, we selected the antenna tilt, β, value that opitmizes the gain at the edge of the cell. Accordingly, the β value that gives the best $\overline{G}^*_{\text{ma}}$ is calculated for r_{ma} values ranging from $222\,\text{km}$ to $352\,\text{km}$. Specifically, for $r_{\text{ma}} \in [222, 241]\text{km}$, the optimized β is $81°$; for $r_{\text{ma}} \in [242, 301]\text{km}$, the optimized β is $82°$; and for $r_{\text{ma}} \in [302, 352]\text{km}$, the optimized β is $83°$. In the following sections, the corresponding β values are applied for the respective radius ranges.

B. Antenna Gain vs. Element Count

Figure 5 shows the average gain within the cell, $\overline{G}_{\text{ma}}$, for all combinations of M and L values. β equals $81°$ and r_{ma} is $222\,\text{km}$. The number of antenna elements, K, needed to attain the specified antenna gain for each combination is indicated in blue and depicted on the right y-axis in the plot. Given that $\overline{G}_{\text{ma}}$ represents the overbound gain K denotes the minimum number of antenna elements needed to attain this level of average gain in a cell. For instance, to achieve an average gain of $20\,\text{dB}$ within the cell, we need a minimum of 100 antenna elements. This can be accomplished by either $M = 5$ & $L = 4$ or $M = 4$ & $L = 7$.

C. Cost-Effectiveness for LDACS

Beamforming techniques can be used to enhance LDACS's data rate, R_b, and/or the cell size.

One aspect is increasing the data rates on its own. Table I lists the receiver sensitivity (RS) required to achieve higher R_b using higher coding rate (CR) and modulation schemes for LDACS. Accordingly, it shows the necessary number of antennas, K, to achieve the required RS. In this case, both r_{sa} and r_{ma} equal $222\,\text{km}$. We observe that η decreases slightly when higher data rates are attempted; but there is no significant change. Overall, η is always less than 1, which means that it is not cost-effective to use beamforming techniques just to achieve higher data rates without changing the cell size in LDACS.

Another aspect that we investigating is the use of higher CRs and modulation schemes together with the larger cell sizes that can be achieved by beamforming techniques. Figure 6 shows the relationship between η and r_{ma} for different modulation schemes and CRs. As r_{ma} increase to maintain the needed signal strength for the farthest aircraft, both $\overline{G}^*_{\text{ma}}$ and K must increase. While a larger r_{ma} quadratically improves η, increasing $\overline{G}^*_{\text{ma}}$ and K leads to a logarithmic decline in η. In Fig. 6, we see that increasing r_{ma} leads to an improvement in η to the extent that it offsets the reduction in η resulting from attempts at higher data rates. However, because of the curvature of the Earth, r_{ma} cannot be increased to a point where η is greater than 1. To conclude, the results of this section suggest that the use of beamforming techniques is not cost-effective for the LDACS system.

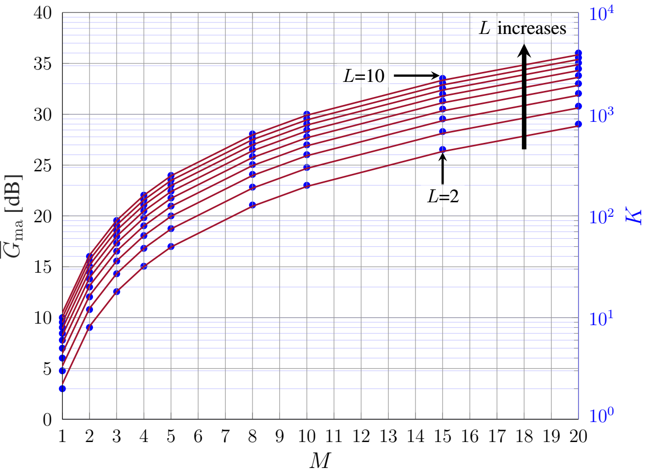


Figure 5: Average gain inside the cell, $\overline{G}_{\text{ma}}$, vs. number of antenna arrays, L, and square root of antenna elements per array, M, with total number of antenna elements, K.

TABLE I: Cost-effectiveness, η, of beamforming to achieve higher data rates, R_b, in LDACS

Modulation	CR	R_b [kbit/s]	RS [dBm]	$\overline{G}^*_{\text{ma}}$ [dB]	K	η
QPSK	1/2	295	-104	12.13	16	0.0644
QPSK	2/3	400	-102	14.32	27	0.0632
QPSK	3/4	464	-101	15.14	32	0.0644
16QAM	1/2	590	-98	18.02	64	0.0624
16QAM	2/3	822	-95	21.03	128	0.0625
64QAM	1/2	948	-93	23.45	225	0.0620
64QAM	2/3	1264	-90	26.38	448	0.0612
64QAM	3/4	1390	-89	27.47	576	0.0611

D. Cost-Effectiveness for $2\,\text{GHz}$ *to* $8\,\text{GHz}$

Typically, when moving to higher frequencies, the effective physical size of the antenna must be reduced to maintain the same radiation pattern [5]. Therefore, to keep the received power the same, the cell size must be scaled down accordingly. In this consideration, r_{sa} is decreased in such a way that the FSPL at the edge of the cell for the SA system remains $139\,\text{dB}$. On the other hand, for the MA system, the cell size, r_{ma}, is kept at $222\,\text{km}$. Table II shows the changes in r_{sa} and the FSPL computed at r_{ma}, denoted as FSPL_{ma}, for each value of f_c. Accordingly, the required number of antenna elements, K, to cope with the increasing FSPL_{ma}, is calculated.

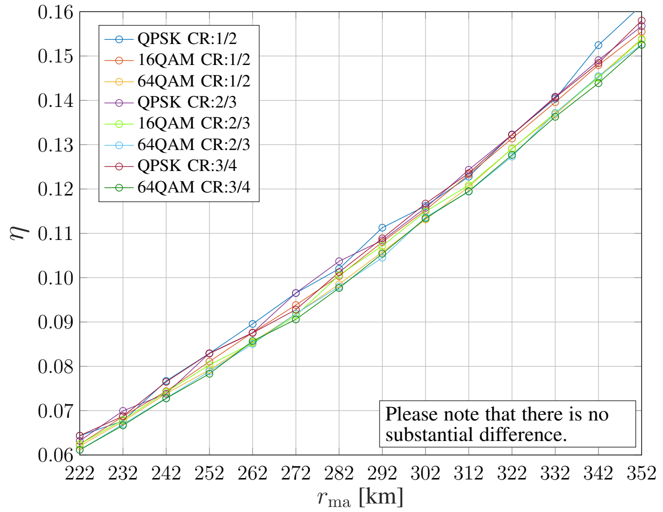


Figure 6: Cost-effectiveness, η, of beamforming for expanding cell coverage, r_{ma}, in LDACS

TABLE II: Cost-effectiveness, η, of beamforming at various carrier frequencies, f_c.

f_c [GHz]	r_{sa} [km]	r_{ma} [km]	$\mathrm{FSPL}_{\mathrm{ma}}$ [dB]	$\overline{G}^*_{\mathrm{ma}}$ [dB]	K	η
2	110	222	145.40	18.56	72	0.2583
3	73	222	148.92	21.69	150	0.5727
4	55	222	151.42	24.66	300	1.0091
5	44	222	153.36	26.38	448	1.5682
6	36	222	154.94	27.92	640	2.2592
7	31	222	156.28	29.36	900	3.0378
8	27	222	157.44	30.34	1125	3.9805

To use a SA system at higher frequencies, the cell sizes for the SA system must be significantly reduced. Thus, to cover the entire area, GS_{sa} must be increased quadratically, resulting in a corresponding quadratic improvement in η. Moreover, for the MA system, as f_c increases, the number of antenna elements, K, grows significantly to achieve the same cell coverage, which has a diminishing effect on η. Overall, as the f_c increases, these contrary impacts result in a substantial increase in η. In summary, in this context, considering the number of GSs, beamforming techniques become more cost-effective than using a SA system at higher frequencies.

IV. CAVEATS AND LIMITATIONS

In this paper, the cost estimate of a single GS is based solely on the number of antenna elements employed, a perspective that could be considered overly optimistic, since the implementation of beamforming techniques not only entails additional hardware. However, it also necessitates dedicated research efforts to adapt and optimize them for effective use in aeronautical communications. In addition, we used the upper limit for the gain that can be obtained with such a system in the cost-effectiveness calculations. Consequently, the cost-effectiveness ratios presented in this paper are likely to be too favorable, and we anticipate that in practice, these ratios will be lower than the values calculated herein. As a result, these findings primarily indicate frequency ranges where it is not recommended to use beamforming techniques, rather than specifying when to use them.

V. CONCLUSION AND OUTLOOK

To evaluate the cost-effectiveness of implementing beamforming techniques in aeronautical communications at ground station (GS)s, we first propose a multiple antenna (MA) system with a variable number of antenna arrays and elements. Secondly, the effect of the antenna array tilt on the overall system gain is studied. For the optimal antenna tilt and the given number of antenna elements, the overbound gain is then computed. Finally, the antenna gain-cost relationships between the single-omnidirectional antenna and MA systems are compared using the proposed cost metrics.

Based on our results, the implementation of beamforming in L-band Digital Aeronautical Communications System (LDACS) and for frequencies below 4 GHz is most likely not cost-effective. Nonetheless, it is worth noting that beamforming techniques could find practical utility in higher-frequency scenarios, particularly when omnidirectional antennas' gain is insufficient due to higher free-space path loss.

This paper focuses on beamforming techniques for a single link, i.e., a single transmitter and receiver. In our future work, we aim to investigate MA systems beyond beamforming techniques and study the multi-user scenario, where the GS communicates with multiple aircraft simultaneously. This will allow us to evaluate whether the performance of LDACS can be further improved in a cost-effective manner using MA systems.

ACKNOWLEDGMENT

We would like to express our gratitude to Dr. Stefano Caizzone and Federico Boulos from the German Aerospace Center (DLR) for providing us with the antenna simulation software.

REFERENCES

[1] "Challenges of Growth, Task 4: European AirTraffic in 2035," EUROCONTROL, Tech. Rep., 06 2013. [Online]. Available: http://www.eurocontrol.int/statfor

[2] J. Mietzner, R. Schober, L. Lampe, W. H. Gerstacker, and P. A. Hoeher, "Multiple-antenna techniques for wireless communications - a comprehensive literature survey," *IEEE Communications Surveys Tutorials*, vol. 11, no. 2, pp. 87–105, 2009.

[3] R. Mailloux, "Phased array theory and technology," *Proceedings of the IEEE*, vol. 70, no. 3, pp. 246–291, 1982.

[4] M. Schnell, U. Epple, D. Shutin, and N. Schneckenburger, "Ldacs: future aeronautical communications for air-traffic management," *IEEE Communications Magazine*, vol. 52, no. 5, pp. 104–110, 2014.

[5] C. A. Balanis, *Antenna theory: analysis and design*. Wiley-Interscience, 2005.

[6] H. Moritz, "Geodetic reference system," *Bull. Geodesique*, p. 395–405, 1980.

[7] A. Ghasemi, A. Abedi, and F. Ghasemi, *Propagation Engineering in Radio Links Design*, 07 2013.

[8] EECNS Team, "SESAR2020 PJ14-02-01 - LDACS A/G Specification," SESAR Joint Undertaking, Tech. Rep., 2019.