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T-LINC Architecture with Digital Combination and Mismatch Correction in the Receiver

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***Abstract*—In this paper a novel outphasing amplification architecture, Transmitted Linear Amplification with Nonlinear Components (T-LINC), is proposed and evaluated. Different from conventional LINC techniques that combine the outphased signals before transmission, the proposed architecture transmits both outphased signals and implements the signal combination in the base-band domain at the receiver side. By digitally combining the signals in the receiver, it is easier to correct gain or phase mismatch existing between the two outphased signals, without adding any extra complexity in the transmitter. Additionally, a power combiner is no longer required in the transmitter. Simulations show that the proposed technique is able to correct transmitter gain and phase imbalance and achieve an ACPR level of -42 dBc and EVM below 2.5 % for 16-QAM signals.**

***Index Terms*—Digital combination, digital mismatch correction, linear amplification with nonlinear components (LINC), outphasing amplification, Transmitted LINC (T-LINC).**

I. Introduction

A radio architecture that allows to carry out linear amplification by means of nonlinear power amplifiers was introduced by H. Chireix in 1935 [1]. The motivation was to realize linear amplification with enhanced power efficiency, which was achieved by using efficient nonlinear amplifiers to amplify two outphased and constant envelope signals that are combined after the amplification and then transmitted. The idea introduced by Chireix was revisited by D. Cox in 1974 [2]. In the revised architecture a passive matched power combiner was added to carry out the signal combination and to isolate the power amplifiers output, which leads to reduced power efficiency due to the attenuation of the combiner. The resulting architecture is known as Linear amplification with Nonlinear Components (LINC). Although the outphasing amplification concept has been widely studied and used over the years, Chireix's architecture presents the inconvenience of non-isolated output power amplifiers, whereas LINC has the disadvantage of an lossy power combiner and lower power efficiency [3]. Additionally, since the outphasing amplification relies on vector cancellation this architecture is very sensitive to any amplitude or phase mismatch between the two amplification paths. This can be fixed but adds complexity in the transmitter [4], [5]. With this new approach the receiver is able to correct in the digital domain the amplification mismatch happening in the transmitted. By doing this way, it is possible to reduce transmitter complexity.

This work is organized as follows: Section II describes the background of a classical outphasing amplification as well as the implementation effort done so far. In Section III the novel architecture of this work is introduced and analyzed. Section IV presents a range of simulation results that proves the validity of the new technique. Finally, the conclusions of this work are presented in Section V.

II. Background

A. LINC architecture

A block diagram of the conventional LINC architecture is shown in Fig. 1(a). Here amplitude and phase varying input signal $S(t)$ splits on the RF Signal Component Separator (RF-SCS) into two outphased and constant envelope signals $S_1(t)$ and $S_2(t)$. The signals can be described as

$$S(t) = E(t)\cos\left[\omega_c t + \phi(t)\right], \tag{1}$$

$$S_1(t) = \frac{E_{max}}{2}\cos\left[\omega_c t + \phi(t) + \alpha(t)\right], \tag{2}$$

$$S_2(t) = \frac{E_{max}}{2}\cos\left[\omega_c t + \phi(t) - \alpha(t)\right], \tag{3}$$

where $\alpha(t) = \cos^{-1}[E(t)/E_{max}]$. The two outphased signals are amplified by nonlinear power amplifiers and combined before transmission. The resultant signal after the combination is

$$S_{out}(t) = G(S_1(t) + S_2(t)) = GS(t)\,. \tag{4}$$

B. Previously implemented architectures and their limitations

Much of the literature published so far regarding LINC focuses on two methods:

1) Gain and phase adjustment at transmitter: The linearity of the combined output is determined by the gain and phase mismatch between the two transmitter paths. To avoid distortion in the combined signal an alternating and outphasing modulator into the transmitter path is introduced [6]. Special effort has been done on the power combiner at the two TX output to improve the overall efficiency of the outphasing amplifiers [7]–[10]. However, there is a trade-off between combiner loss and signal distortion due to isolation. In addition, combiners suffer from insertion loss of 1–2 dB even if the isolation is not a concern.

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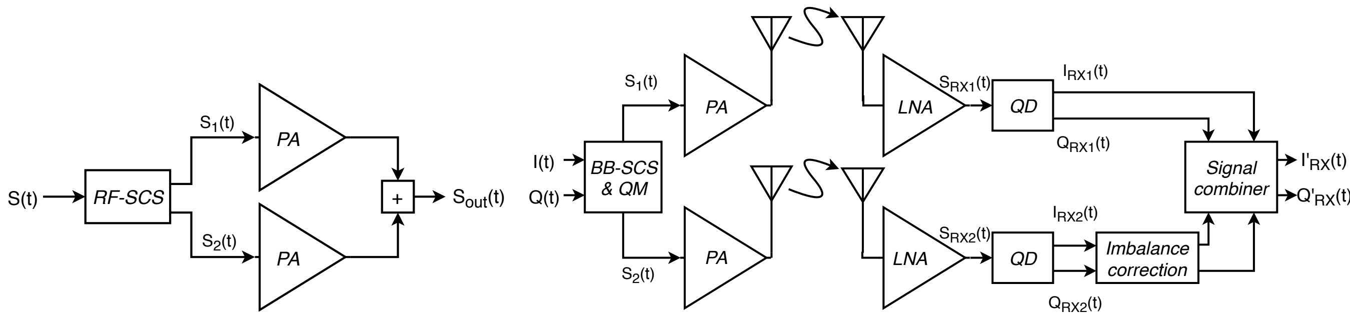


(a) Classic LINC architecture.

(b) T-LINC architecture.

Fig. 1. Block diagram of LINC and T-LINC architectures.

2) Combination with antenna array: Combining with antenna array instead of using a combiner and avoiding the coupling component. This concept has an inherent 3 dB system loss since the signals are combined by a single receiver antenna. Moreover, the receiver must be located within a specific solid angle to receive a valid combined signal [11]–[14]. Additionally, this technique still needs a complex transmitter architecture.

III. Proposed Transmitted-LINC architecture

The proposed Transmitted LINC (T-LINC) architecture simplifies the transmitter design by carrying out the outphased signal combination and the mismatch correction in the digital domain at the receiver side. By doing this the complexity of the transmitter is significantly reduced. A block diagram for the proposed novel T-LINC architecture is shown in Fig. 1(b). The T-LINC architecture is based on the same principle as the LINC in that the input signal, which may be both phase and amplitude modulated, is split into two outphased and constant envelope signals. The difference lies in the fact that outphased signals are corrected and combined in the receiver. With this concept the two outphased signals are amplified, transmitted independently through the channels, received, demodulated and eventually corrected and combined at baseband in the digital domain. This technique finds its most suitable application in those technologies based on line-of-sight channel, such as satellite communications.

A. Baseband Signal Component Separator

For any in-phase and quadrature components of the baseband input signal $I(t) = E(t)\cos\phi(t)$ and $Q(t) = E(t)\sin\phi(t)$, it is possible to define the two outphased signals (2) and (3) as quadrature-modulated signals

$$S_1(t) = \Re\left\{[I_1(t) + i\,Q_1(t)]\,e^{i\omega_c t}\right\} \tag{5}$$

$$S_2(t) = \Re\left\{[I_2(t) + i\,Q_2(t)]\,e^{i\omega_c t}\right\}\,. \tag{6}$$

The baseband signal component separator and quadrature modulator (BB-SCS & QM) can easily generate the baseband outphased signals as a combination of the baseband input signals, and perform the quadrature modulation of those signals to generate (5) and (6).

B. Amplification and transmission

The two outphased signals are independently amplified by nonlinear power amplifiers working close to the compression point, where they present best power efficiency. Both signals are independently transmitted through the channels, received and demodulated by the receiver quadrature demodulators. For this work, it is assumed there is no crosstalk between the channels. The system presents an aggregated gain (G_n) provided by both PAs, LNAs and antennas. Similarly, there are losses (L_n) along the signal path due to insertion loss, path loss, etc. Both gain and loss will modify the amplitude of the signal as $A_n = G_n/L_n$. Additionally, the two outphased signals may be also affected by an arbitrary phase delay (θ_n) introduced by either the system or the channel. In general terms, any element in both transmission and reception chains can induce a modification in either amplitude or phase of the outphased signal. It is to be expected that each path of the T-LINC system does not present identical gain, loss or phase delay. Since the outphasing amplification process relies on vector cancellation, the key factor is not the absolute level of amplitude or phase, but the difference in either amplitude or phase between both outphased signals. The amplitude and phase mismatch between the T-LINC paths are defined as

$$\Delta A = A_2 - A_1 \tag{7}$$

and

$$\Delta\theta = \theta_2 - \theta_1\,, \tag{8}$$

A mismatch in either amplitude or phase between both outphased signals leads to an incorrect vector cancellation causing distortion in the final reconstructed signal. It is desired to keep (7) and (8) as small as possible.

The delayed and amplified quadrature-modulated outphased signals once at the receiver are described as

$$S_{RX1}(t) = \Re\left\{[I_1(t) + i\,Q_1(t)]A_1\,e^{i(\omega_c t - \theta_1)}\right\} \tag{9}$$

$$S_{RX2}(t) = \Re\left\{[I_2(t) + i\,Q_2(t)](A_1 + \Delta A)\,e^{i(\omega_c t - (\theta_1 + \Delta\theta))}\right\}\,. \tag{10}$$

C. Combination and mismatch correction at the receiver

After demodulation, the in-phase and the quadrature components of the outphased signals (I_{RXn} and Q_{RXn}) can be combined to generate the received version of the transmitted baseband signal as follows

$$\begin{aligned} I_{RX}(t) &= I_{RX1}(t) + I_{RX2}(t) \\ &= A_1 I_1(t)\, e^{-i\theta_1} + (A_1 + \Delta A) I_2(t)\, e^{-i(\theta_1 + \Delta\theta)} \end{aligned} \tag{11}$$

$$\begin{aligned} Q_{RX}(t) &= Q_{RX1}(t) + Q_{RX2}(t) \\ &= A_1 Q_1(t)\, e^{-i\theta_1} + (A_1 + \Delta A) Q_2(t)\, e^{-i(\theta_1 + \Delta\theta)}\,. \end{aligned} \tag{12}$$

It is possible to expand (11) and (12) and regroup the terms by substituting the outphased baseband in-phase and quadrature components by their corresponding input baseband components

$$\begin{aligned} I_{RX}(t) = A_1\, e^{-i\theta_1} \Bigg[& I(t) \left(1 + e^{-i\Delta\theta} + \frac{\Delta A}{A_1} e^{-i\Delta\theta}\right) \\ & + Q(t) \left(e^{-i\Delta\theta} + \frac{\Delta A}{A_1} e^{-i\Delta\theta} - 1\right) \\ & \times \sqrt{\frac{I_{max}^2 + Q_{max}^2}{I(t)^2 + Q(t)^2} - 1}\,\Bigg] \end{aligned} \tag{13}$$

$$\begin{aligned} Q_{RX}(t) = A_1\, e^{-i\theta_1} \Bigg[& Q(t) \left(1 + e^{-i\Delta\theta} + \frac{\Delta A}{A_1} e^{-i\Delta\theta}\right) \\ & - I(t) \left(e^{-i\Delta\theta} + \frac{\Delta A}{A_1} e^{-i\Delta\theta} - 1\right) \\ & \times \sqrt{\frac{I_{max}^2 + Q_{max}^2}{I(t)^2 + Q(t)^2} - 1}\,\Bigg]\,. \end{aligned} \tag{14}$$

By analyzing (13) and (14), the common term defined as mismatching coefficient (ΔM) can be defined as

$$\Delta M = e^{-i\Delta\theta} + \frac{\Delta A}{A_1} e^{-i\Delta\theta} - 1\,. \tag{15}$$

Equation (15) provides the information of the level of mismatching between the two T-LINC paths. A value $\Delta M = 0\angle 0$ means both paths are equally matched and no distortion is introduced in the reconstructed signal, whilst any other value occurs when the outphased signals are not balanced in the system. For any arbitrary ΔM it is possible to find a Matching Correction (MC) parameter that satisfies the next condition

$$MC = \frac{1}{\Delta M + 1}\,. \tag{16}$$

The MC parameter rectifies any amplitude and phase mismatch of one outphased signal regarding its outphased pair, causing $\Delta M = 0$. In order to calculate the MC parameter an arbitrary calibration signal, $c(t)$, must be transmitted simultaneously through both T-LINC paths and the two received signals compared as follows

$$MC = \frac{c(t) A_1\, e^{-i\theta_1}}{c(t)(A_1 + \Delta A)\, e^{-i(\theta_1 + \Delta\theta)}} = \frac{A_1}{A_1 + \Delta A} e^{i\Delta\theta}\,. \tag{17}$$

The MC parameter is then applied to one of the outphased signals to obtain the final combined and corrected signal in the receiver, $I_{RX}(t)'$ and $Q_{RX}(t)'$, which are

$$I'_{RX}(t) = I_{RX1}(t) + MC \cdot I_{RX2}(t) \tag{18}$$

$$Q'_{RX}(t) = Q_{RX1}(t) + MC \cdot Q_{RX2}(t)\,. \tag{19}$$

For the ideal case where the MC parameter is perfectly calculated, the receiver baseband signals are combined and corrected without error. In this case, the perfectly combined and corrected signals in the receiver (20) and (21) are amplified, delayed, and non-distorted versions of the original transmitted baseband signals

$$I'_{RX}(t) = 2A_1\, e^{-i\theta_1}\, I(t) \tag{20}$$

$$Q'_{RX}(t) = 2A_1\, e^{-i\theta_1}\, Q(t)\,. \tag{21}$$

IV. Simulation Validation of T-LINC

A simulation has been conducted in *Keysight ADS* to validate the feasibility of the new architecture. Fig. 2 shows a simplified block diagram of the simulation setup.

A. Simulation setup

The setup runs a *Circuit Envelope simulation*. This kind of simulation allows to extract data from both the time and frequency domain of all nonlinear elements. The simulation is using a pseudo-random 16-QAM baseband signal with symbol rate of 3.84 MHz at a frequency of 3.5 GHz.

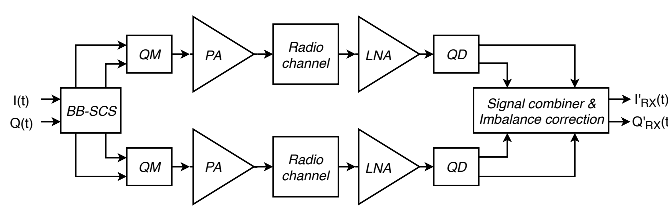
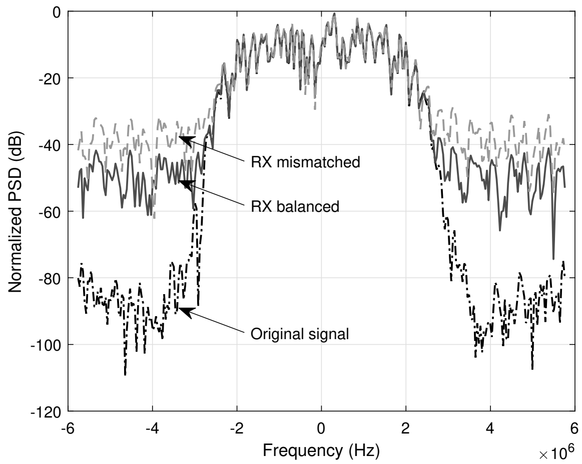
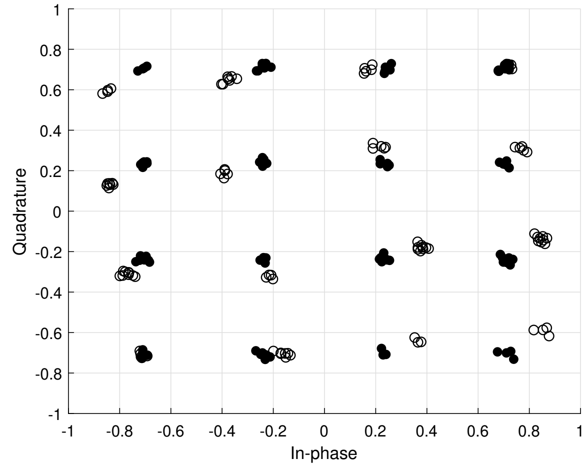


Fig. 2. Block diagram of the simulation setup.

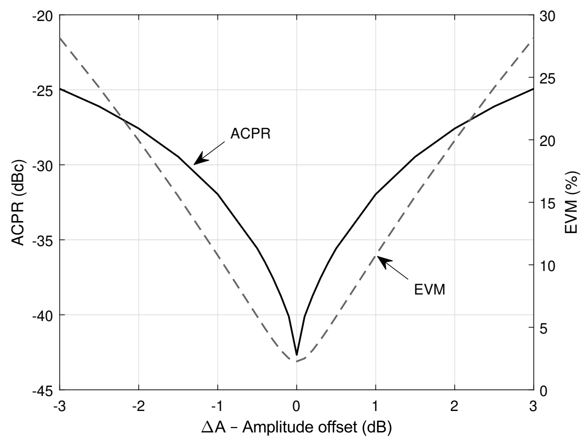
1) BB-SCS - Baseband Signal Component Separator: This block carries out the split of the baseband input signal into two outphased and constant envelope signals. Inputs are the in-phase $I(t)$, and quadrature $Q(t)$ components of the baseband signal to transmit. Outputs are the quadrature components of the two outphased signals $I_1(t)$, $Q_1(t)$, $I_2(t)$ and $Q_2(t)$.



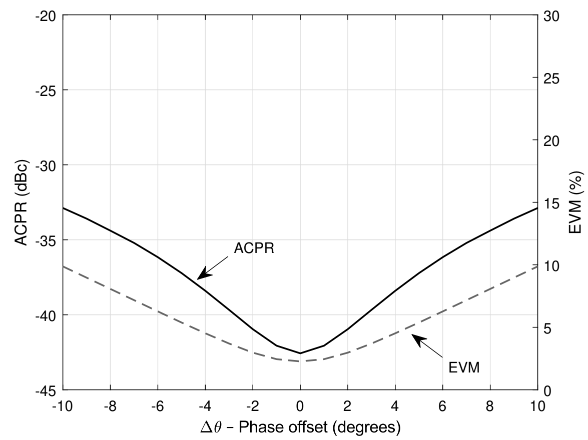
(a) Normalized PSD of original signal (black dot-dashed) and received signal for balanced (dark gray) and 1 dB and 5° mismatched (light gray dashed) T-LINC system.



(b) Received 16-QAM constellation for balanced (full), and 1 dB and 5° mismatched (empty) T-LINC system.



(c) ACPR and EVM vs. amplitude offset (zero phase offset).



(d) ACPR and EVM vs. phase offset (zero amplitude offset).

Fig. 3. T-LINC system simulation results.

2) QM/QD - Quadrature Modulator and Demodulator: The ideal Quadrature Modulator block has as input the baseband in-phase and quadrature components of the outphased signals. It generates the quadrature-modulated RF signals (5) and (6). Likewise, the ideal Quadrature Demodulator block is placed in the receiver and it performs the demodulation of the transmitted RF quadrature-modulated signals (9) and (10), generating at the output the in-phase and quadrature components of the received baseband signals $I_{RX1}(t)$, $Q_{RX1}(t)$, $I_{RX2}(t)$ and $Q_{RX2}(t)$.

3) PA, LNA - Power Amplifier and Low Noise Amplifier: Power amplifiers are modeled by CREE CGH40006P transistors. Both PAs are configured to operate close to the 1 dB compression point. The transistor model is able to offer $P_{out} = 39\ dBm$ with drain efficiency of 60 % for an operation frequency of 3.5 GHz. LNAs are *amplifier2* blocks configured as $G = 30$ dB, and $NF = 3$ dB.

4) Radio channel: The radio channel is assumed to be a simple line-of-sight channel. Both transmitted signals are isolated. If needed, the channel may also include any other physical element placed between the PAs and LNAs, such as antennas and cables or connectors.

5) Signal combiner & Imbalance correction: This block performs the imbalance correction and the signal combination of the outphased signals described by (18) and (19). This is the last block and it provides the output signals of the system.

B. Simulation Results

Fig. 3(a) shows the Normalized Power Spectral Density (PSD) of a transmitted and received signals by the proposed T-LINC system. The figure shows the performance of the system for both an ideal balanced system (dark gray), and a mismatched system (dashed light gray) for a case of 1 dB amplitude and 5 degrees phase offset between outphasing paths. The black dot-dashed line represents the original baseband signal. When the system is balanced, a received signal with approximately -42 dBc of Adjacent Channel Power Ratio (ACPR) may be obtained. Whilst for the 1 dB amplitude and 5 degrees phase offset mismatched system, the achieved ACPR is -32 dBc. As evaluated in Section III, the T-LINC system relies on vector cancellation and it is sensitive to amplitude and phase offset between the outphasing paths.

For illustration, the constellation of received 16-QAM signals for a balanced (full circle) and a mismatched (empty circle) system are shown in Fig. 3(b). For a balanced T-LINC system the Error Vector Magnitude (EVM) is below 2.5 %, since the received constellation has small distortion. On the other hand, for a mismatched system—1 dB amplitude and 5 degrees phase offset—the received signal shows an EVM of 14 %. The constellation distortion is easily seen in this case. Nevertheless, distortion caused by the non-balanced system of this example, and any distortion caused by either amplitude or phase offset, can be digitally corrected at the receiver as explained in Subsection III-C. The mismatch correction in the receiver is one of the biggest advantages of this proposed architecture.

The sensitivity of the system to amplitude and phase mismatch has been studied as well. Figures 3(c), 3(d) show the sensitivity of the system performance to amplitude and phase imbalance, respectively. System performance is measured in terms of ACPR and EVM. Results show that ACPR and EVM values for the combined signal are maintained better than -27 dBc and 20 %, respectively, when the amplitude imbalance is within 2 dB. The case of phase imbalance shows similar behaviour. The ACPR and EVM of the combined signal are maintained better than -30 dBc and 10 %, respectively, when subjecting to a phase imbalance of 10 degrees. Biggest sensitivity to amplitude offset than compared to phase offset is expected to happen [5], [12]. It should be noted that keeping an amplitude imbalance and a phase imbalance below 2 dB and 10 degrees, respectively are not considered as stringent requirements [4], [13], [14], indicating the promising potential of the proposed approach.

V. Conclusion

In this paper the novel Transmission LINC (T-LINC) is introduced. This architecture allows to perform RF linear amplification with nonlinear power amplifiers, and carry out a digital signal combination and imbalance correction of the baseband signal in the receiver. Fundamentals of the system are evaluated and a procedure to perform the imbalance correction in the receiver is provided. Isolated channels and no crosstalk between outphased signal is assumed in this work. Simulation results show that it is possible to get a received signal with ACPR of -42 dBc and EVM below 2.5 % when the system is balanced, whilst the amplitude or phase offset can be corrected in the receiver. Finally, this architecture allows to correct in the receiver the amplitude and phase imbalance that may occur in the system, which further simplifies the complexity of the transmitter. The proposed architecture can benefit communication systems based on simple line-of-sight transmission, or those that might need simple but still power-efficient transmitters such as nano-satellites.

References

[1] H. Chireix, "High power outphasing modulation," *Proceedings of the Institute of Radio Engineers*, vol. 23, no. 11, pp. 1370–1392, 1935.

[2] D. Cox, "Linear amplification with nonlinear components," *IEEE Trans. Commun.*, vol. 22, no. 12, pp. 1942–1945, 1974.

[3] A. Birafane, M. El-Asmar, A. B. Kouki, M. Helaoui, and F. M. Ghannouchi, "Analyzing linc systems," *IEEE microwave magazine*, vol. 11, no. 5, pp. 59–71, 2010.

[4] X. Zhang, L. E. Larson, P. M. Asbeck, and P. Nanawa, "Gain/phase imbalance-minimization techniques for linc transmitters," *IEEE Transactions on Microwave Theory and Techniques*, vol. 49, no. 12, pp. 2507–2516, 2001.

[5] P. Garcia, J. de Mingo, A. Valdovinos, and A. Ortega, "Adaptive digital correction of gain and phase imbalances in linc transmitters," in *2004 IEEE 59th Vehicular Technology Conference. VTC 2004-Spring (IEEE Cat. No. 04CH37514)*, IEEE, vol. 3, 2004, pp. 1237–1241.

[6] Y. Zhou and M. Y.-W. Chia, "A novel alternating and outphasing modulator for wireless transmitter," *IEEE Transactions on Microwave Theory and Techniques*, vol. 58, no. 2, pp. 324–330, 2010.

[7] I. Hakala, D. K. Choi, L. Gharavi, N. Kajakine, J. Koskela, and R. Kaunisto, "A 2.14-GHz Chireix outphasing transmitter," *IEEE Trans. Microwave Theory Tech.*, vol. 53, no. 6, pp. 2129–2138, 2005.

[8] D. J. Perreault, "A new power combining and outphasing modulation system for high-efficiency power amplification," *IEEE Trans. Circuits Syst.*, vol. 58, no. 8, pp. 1713–1726, 2011.

[9] M. El-Asmar, A. Birafane, M. Helaoui, A. B. Kouki, and F. M. Ghannouchi, "Analytical design methodology of outphasing amplification systems using a new simplified Chireix combiner model," *IEEE Trans. Microwave Theory Tech.*, vol. 60, no. 6, pp. 1886–1895, 2012.

[10] T. W. Barton and D. J. Perreault, "Theory and implementation of RF-input outphasing power amplification," *IEEE Trans. Microwave Theory Tech.*, vol. 63, no. 12, pp. 4273–4283, 2015.

[11] C. Liang and B. Razavi, "Transmitter linearization by beamforming," *IEEE Journal of Solid-State Circuits*, vol. 46, no. 9, pp. 1956–1969, 2011.

[12] Y. Zhou, M. Y.-W. Chia, X. Qing, and J. Yuan, "Rf spatial modulation using antenna arrays," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 10, pp. 5229–5236, 2013.

[13] V. Karunanithi, C. C. Verhoeven, and W. Lubbers, "LINC transmitter architecture for nano-satellite applications," in *2015 IEEE Aerospace Conference*, IEEE, 2015, pp. 1–9.

[14] D. Tresnawan, P. Smulders, B. van Ark, and A. Smolders, "Linear LINC transmitters using dual-polarized power-combining antennas," 2018.