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Outphasing Methods for Beyond-5G Millimeter-Wave Base Station Applications

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***Abstract*—This paper presents a review of various outphasing methods. Key performance indicators are formulated focusing on reliability, energy consumption and bandwidth and are used to compare state-of-the-art outphasing methods. Outphasing methods which show potential for beyond-5G base station applications are described and relevant advantages, disadvantages and literature gaps are pointed out. Specifically, the recent developments on using antenna elements to be co-designed with an outphasing system will be considered as a promising efficient solution. Findings in this paper show that a co-designed amplifier-antenna outphasing system achieves one of the highest peak power-added efficiencies at millimeter-wave frequencies compared to other PA topologies.**

***Index Terms*—5G mobile communication, antennas, millimeter-wave integrated circuits, power amplifier, outphasing.**

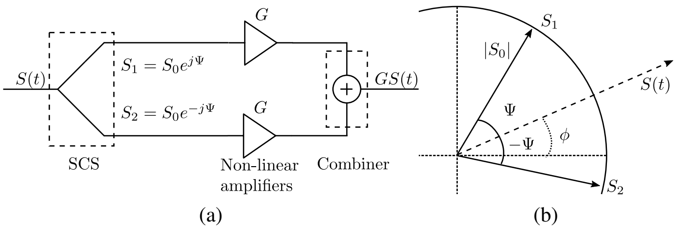

Fig. 1. General overview of outphasing. (a) Schematic with signal component separator (SCS), high efficient non-linear amplifiers and combiner. (b) Vector representation of the outphasing signals.

I. INTRODUCTION

For 5G and beyond-5G, higher data rates must be achieved up to 1000 Gbit/s to accommodate the increasing number of users and data throughput [1], [2]. These high data rates can only be realized by going to millimeter-wave (mm-Wave) frequencies because large bandwidths have been made available at these bands. Due to the short wavelengths at mm-Waves, integration of amplifiers and antennas becomes key in beyond-5G technologies.

Many strive to optimize both linearity and power efficiency in transmitter design. One well-known method for increasing the power efficiency while maintaining linearity of a power amplifier (PA) system is outphasing or linear amplification with non-linear components (LINC) [3]. This method is shown in Fig. 1. With outphasing the signal $S(t)$ is separated into constant amplitude, phase modulated signals S_1 and S_2 which are amplified and recombined. Because of the constant amplitudes, the signal can be amplified with highly efficient and non-linear amplifiers operated at their peak power. In this way, the PA always operates at maximum drain efficiency [4]. Modulating the outphasing angle Ψ between 0° and 90° achieves the desired amplitude and phase modulation of the to-be-transmitted signal. Outphasing is gaining interest in transmitter design and variations of the traditional method have been developed [5]–[7].

Insertion losses introduced by combiner circuitry components like the Wilkinson power combiner, transformers and hybrid couplers are generally 1-2 dB at mm-Wave frequencies. When employed in large antenna arrays needed for future base stations, these losses will impact the overall system power efficiency. That is why methods like LINC over the air (LINCA) and antenna combiners are under recent investigation [8], [9]. These methods make use of an antenna element to be co-designed with amplifiers leading to a compact, multidisciplinary and efficient system.

In this paper different combining methods for outphasing are reviewed with respect to their potential for future beyond-5G base station applications. In Section II key performance indicators (KPI's) are described. According to the KPI's each outphasing method is reviewed in Section III. Finally, Section IV discusses the findings and concludes the paper.

II. KEY PERFORMANCE INDICATORS

Performance of a base station can be reviewed with respect to its reliability, energy consumption and frequency band of application. Therefore, the KPI's are based on linearity, power efficiency and bandwidth performance of the outphasing methods. Base station regulations for 5G mm-Wave requires the ACPR to be at least -45 dBc [10]. EVM is expected to be in the order of 1% for fractional bandwidths up to about 10%. The KPI's are described in Table I. Power-added efficiency (PAE) results are preferred over drain efficiency because the PAE includes information on both the gain and drain efficiency of the amplifier. Some literature only report the total efficiency which takes into account supply power of driver and amplifier. Here it is chosen to determine the PAE at 6 and 12 dB relative to the peak power because future modulation formats require large peak-to-average power ratios (PAPR).

III. OUTPHASING METHODS

In the next sections, current state-of-the-art of the various outphasing methods will be described and compared to the KPI's. The state-of-the-art outphasing methods together with the KPI's are listed in Table II. In Fig. 2 the outphasing

Table I
KEY PERFORMANCE INDICATOR DESCRIPTION

Parameter	Performance indicator	Description
Adjacent channel power ratio (ACPR)	Linearity	Allowed spectral leakage to nearby channels
Error vector magnitude (EVM)	Linearity	Error of the received symbol vector in the constellation diagram
η_{avg}	Power efficiency	PAE averaged over a range of power levels
η_{peak}	Power efficiency	PAE at peak power
$\eta_{6\mathrm{dB}}$	Power efficiency	PAE 6 dB relative to peak power
$\eta_{12\mathrm{dB}}$	Power efficiency	PAE 12 dB relative to peak power
Fractional bandwidth (BW)	Bandwidth	Based on 5% reduced η_{peak}

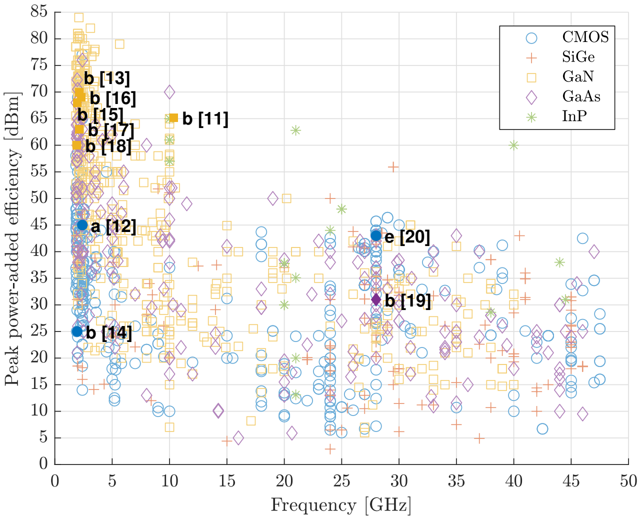

Fig. 2. Power-added efficiency peak power (η_{peak}) over frequency for different amplifier technologies between 1.8 and 50 GHz obtained from [21] compared to outphasing methods (highlighted in bold)

methods are compared to non-outphasing PA's obtained from [21]. The outphasing methods listed in Table II are highlighted in bold in Fig. 2 together with their method label letters. Also the corresponding reference is highlighted in bold and can be found in the references section. Additional literature that is not included in Fig. 2 and in Table II do not report sufficient information on the KPI's but are nevertheless mentioned because they show relevant information for future research possibilities.

A. Outphasing with isolated combiners

Fig. 3a shows the traditional isolated combiner. The combiner is mostly realised as a Wilkinson combiner or hybrid coupler [4]–[7]. It is assumed that the PA's behave like ideal voltage sources and are represented by S_1 and S_2. Constant impedance is presented at ports 1 and 2 due to the isolation or dissipation resistor R_{diss}. This means that the amplifier is always using the same amount of power for amplification, while the RF output power is varying. Low RF output power is dissipated in R_{diss}. With the use of high-order modulation formats the average efficiency of isolated combiners decreases because of larger PAPR. Indicative average efficiencies are reported in [22] and show that average efficiencies of 16QAM and 64QAM are between 19-25% where a theoretical 100% drain efficiency is assumed.

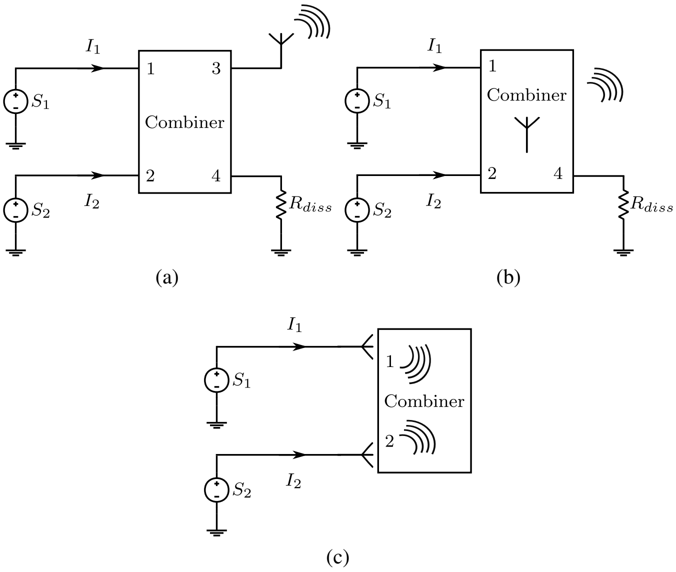

Fig. 3. Outphasing isolated combiner methods. (a) Traditional combiner (LINC) (b) Antenna combiner (c) LINCA

An improvement of the traditional method can be found in power re-use methods. Instead of dissipating all of the out-of-phase power in R_{diss}, a fraction of that power is fed back to S_1 and S_2. In [11] the power is re-used with a transistor rectifier which achieves an efficiency improvement of 5.3% compared to traditional outphasing. From Fig. 2 it can be seen that η_{peak} is one of the highest PA efficiencies reported for this frequency.

Another method which tries to enhance power efficiency for isolated combiners make use of supply modulation with multi-level outphasing (ML-LINC) and asymmetric multi-level outphasing (AMO) [12]. With this method the constant-amplitude signals S_1 and S_2 have varying levels which relaxes the power consumption of the PA for out-of-phase combining while still making use of LINC at in-phase combining.

In general, a comparison on linearity and bandwidth between [11] and [12] cannot be made because no linearity is reported in [11] and no bandwidth is reported in [12]. The AMO method shows better efficiency at $\eta_{6\mathrm{dB}}$ and $\eta_{12\mathrm{dB}}$ compared to the power re-use method.

B. Outphasing with isolated antenna combiners

In Fig. 3b outphasing with isolated antenna combining is shown. This method avoids the use of combining circuitry. Ports 1 and 2 are the two antenna feed ports whereas port 4 is used to dissipate the out-of-phase signals. In [23] a patch antenna combiner is designed, where R_{diss} is placed between

Table II
KEY PERFORMANCE INDICATORS FOR STATE-OF-THE-ART OUTPHASING METHODS

			KPI's												
Tech.	f_t \ f_{max} [GHz]	Method	ACPR [dBc]	EVM [%]	η_{avg} [%]	η_{peak}\ η_{6dB} [%]	η_{peak}\ η_{12dB} [%]	BW [%]	Mod. BW [MHz]	Mod.	P_{sat} [dBm]	PAPR [dB]	f_0 [GHz]	Year
GaN TQP15 [11]	80 / -	III-A	-	-	-	65\24*†	65\8*†	2.9*	-	-	37.8	-	10.35	2015
CMOS 65nm [12]	-	III-A	-	2.7	27.6	45\42*	45\22*	-	20	64QAM	27.7	7.5	2.4	2012
GaN [13]	-	III-D	-47§	-	50.5	70\55*	70\42*	1.4*	3.84	WCDMA	49.5	9.6	2.14	2009
CMOS 65nm [14]	-	III-D	-36	3	-	25\21*	25\3*	39.0*	20	LTE (16QAM)	29.7	6.6	1.95	2011
CMOS-GaN [15]	30&50/-	III-D	-47§	-	41.9†	68\58*†	68\29*†	18.2*	3.84	WCDMA	42.8	9.6	1.95	2011
GaN NXP 0.25um [16]	28/-	III-D	-49§	-	43.8†	69\54*†	69\37*†	11.2*	3.84	WCDMA	48.5	9.6	2.3	2013
GaN CGH40025F [17]	-	III-D	-33§	-	55.6†	70\57*† 63\52*	70\39*†	2.8*	3.84	WCDMA	50.5	9.15	2.14	2014
GaN CGH27015 [18]	-	III-D	-49§	-	-	60\39*	-	25.5*	5	LTE	43.4	10.35	1.9	2020
GaAs PIH1-10 [19]	100/-	III-D	-25	-	15.3†	30\22	30\9*	55.1*	200	LTE (64QAM)	24	7.3	28	2020
CMOS 45RFSOI [20]	305/380	III-E	-28	4.2	19.2	53\36† 43\23*	53\10*†	11.6*	2500*	64QAM	17.1	6.7*	28	2019

§ using DPD, * determined from plot, † total drain efficiency

the antenna feed ports. A similar isolated patch antenna design is shown in [24]. Further experimental investigations are needed to confirm that the isolated antenna combiner method performs similarly to isolated power combiners with respect to linearity, power efficiency and bandwidth.

C. LINCA

In Fig. 3c the LINCA method is shown. LINCA is a method which feeds the outphasing signals directly to separate antenna elements without introducing combiner circuitry. Key difference between LINCA and the isolated antenna combiner is that the signals are combined in free-space in the electromagnetic domain while with isolated antenna combiners S_1 and S_2 are combined through the current distributions at the antenna structure. With LINCA, out-of-phase signals will be transmitted over the air and at least two antenna elements are needed to transmit S_1 and S_2. This can be extended to larger antenna arrays to satisfy gain requirements. The beam pattern of the array changes with outphasing angle as shown in [9]. LINCA can be classified to the isolated combiners if it is assumed that low mutual coupling between antenna elements exists. With this method, spectral mask requirements must be taken into account because the spectrum of either S_1 and S_2 is wide-band. This requires the use of band-pass filters. A minimum on the filter bandwidth for outphasing signals is reported in [25], where the filter bandwidth must be at least two times the signal IQ bandwidth in order to achieve an EVM of 1%.

The first LINCA design is reported in [26]. The PA design is realised with 65nm CMOS technology at 60 GHz. The EVM obtained with a data rate of 32 MB/s using 16QAM is 11.5%. Comparing this to developed LINCA arrays at lower frequency in [9], [27], EVM's of 1% and 5% are measured, respectively. In [28] a mm-Wave LINCA setup is realised where an EVM of 4% is measured at Ka-band. These papers do not report information on the power efficiency and bandwidth when using the LINCA method. With the current status on LINCA investigation it becomes clear that more research into spectral leakage, power efficiency and bandwidth is needed.

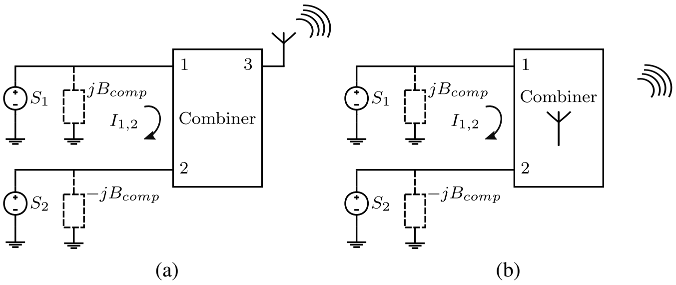

Fig. 4. Outphasing non-isolated combiner methods with Chireix combiner compensations dashed. (a) Traditional non-isolated combiner. (b) Non-isolated antenna combiner.

D. Outphasing with non-isolated combiners

In Fig. 4 the combiner maintains a shared current $I_{1,2}$ between the outphasing branches. The impedance seen from each amplifier changes with Ψ referred to as the load pull effect [4]. The load pull effect presents both a resistive and reactive load. Because of the load-pull effect the effective load impedance will become large for S_1 and S_2 out-of-phase and matched to the optimal load resistance of the amplifier for S_1 and S_2 in-phase. However, the PA will not be matched to the optimal load impedance for the other outphasing angles because of the reactive impedance, which degrades efficiency. Chireix introduced compensating reactances B_{comp}, also shown in Fig. 4, to tune out the reactive part for one particular Ψ improving efficiency over a larger range of output powers [29]. However, the Chireix combiner method introduces nonlinearity to the system because of reflections [30]. Attempts are made to make use of linearization techniques for Chireix combiners [6], [30], [31]. This, however, requires additional digital signal processing which degrades efficiency. Furthermore, the choice on compensating reactance pair B_{comp} is dependent on the modulation format used. Each modulation format has a different output power probability density function, which means that some outphasing angles Ψ have higher probability of occurring [5]. Then B_{comp} can be optimized for the highest average efficiency. Another issue which arises with non-isolated combiners is the voltage stress on high efficient switching PA's like class D or class E due to load modulation [32]. Because of this limitation less efficient class B PA's are usually chosen to be implemented in non-isolated outphasing methods.

In [13], a mixed-mode outphasing PA with digital predistortion (DPD) is presented. Mixed-mode outphasing takes advantage of both non-isolating combiners with Chireix compensation and ML-LINC as described in Section III-A. The disadvantage of a non-isolated Chireix combiner is that for Ψ close to out-of-phase combining the efficiency curve is very steep. Allowing amplitude control of S_1 and S_2 for the close to out-of-phase recombination Ψ flattens the efficiency curve from this point, hence, improving average efficiency. The method requires the use of a class B amplifier, which is a drawback compared to the other methods. Compared to the other non-isolated methods the highest η_{peak} and $\eta_{12\mathrm{dB}}$ are achieved because of the two method ML-LINC and non-isolated combining. This design shows that even with linearization by DPD we can still achieve high efficiencies for non-isolated Chireix combiners. On the other hand, bandwidth should be considered in future work because in this design the lowest bandwidth is achieved compared to the other methods.

In [14], a non-isolated combiner without reactive compensation is co-designed with a switching class D amplifier. In order to address the voltage stress issue, four amplifiers are used and S_1 and S_2 are combined differentially. The design also avoids the use of impedance transformations showing a high bandwidth. This design achieves the highest ACPR without DPD because no reactive compensation is used.

In [15] and [16], a non-isolated Chireix combiner with DPD is co-designed with switching class E amplifiers. The highest $\eta_{6\mathrm{dB}}$ efficiency is achieved with [15] which results from optimal co-design of amplifier and Chireix combiner. The class E designs slightly trade reduced η_{avg} for increased bandwidth compared to [13].

In [17], a four-way combination method is reported. The combiner makes use of at least four class F PA's and reduces the reactive load impedance seen from each PA so that it sees mainly a resistive impedance, increasing efficiency. The combiner consists only of radial stubs and microstrip lines which is disadvantageous with respect to bandwidth considerations. The efficiency values are comparable to [15], [16].

Re-configurable Chireix reactive compensations are achieved at L-band and Ka-band in [18], [19]. These re-configurable compensations are used to switch between frequency bands and achieve high bandwidth compared to the other methods. In [19], high bandwidth is obtained due to the use of coupled line structures instead of quarter-wave sections for combining.

E. Outphasing with non-isolated antenna combiners

Fig. 4b shows the non-isolated antenna combiner. S_1 and S_2 are fed to the antenna ports at port 1 and 2. With this method coupling exists between ports 1 and 2 so that a shared current $I_{1,2}$ is maintained. In [8] it is demonstrated that such a method is feasible and behaves similar to traditional non-isolated combiners. Seen from [8], an advantage of this method can be found looking at the radiation pattern, where both the main beam and side-lobes decrease with increasing outphasing angle. This favors the non-isolated antenna combiner with respect to bandwidth and spectral masks requirements compared to LINCA, where only the main lobe and *not* the sidelobes decrease when Ψ is out-of-phase. In [8] an EVM lower than 4% within the 3 dB beam-width is obtained. Unfortunately, the power efficiency and fractional bandwidth of such a structure is not experimentally validated.

A more recent mm-Wave non-isolated Chireix compensated antenna combiner design is presented in [20]. In this design a dual-feed loop antenna is used as non-isolated antenna combiner. From Fig. 2 it can be seen that η_{peak} is one of the highest in current PA designs favoring the use of this method for mm-Wave applications.

IV. DISCUSSION AND CONCLUSION

Comparing the methods in Section III it becomes clear that it is challenging to overcome the trade-off in linearity and power efficiency. Pre-distortion techniques bring non-isolated combiners one step forward to being a good solution for beyond-5G base station applications because of high η_{avg} and sufficient bandwidth compared to other PA architectures. But voltage stress on the device must be taken into account in future designs to increase reliability of the PA's over a longer time span.

Traditional isolated combiners should be accompanied with integration methods in order to be a good solution for beyond-5G base station applications because of efficiency considerations. The recent improvements on the power efficiency of isolated power combiners with ML-LINC and AMO in Section III-A show that together with LINCA or integrated antenna combiners this method can be promising. Moreover, mixed-mode outphasing shows the highest $\eta_{12\mathrm{dB}}$ compared to only the use of either isolated or non-isolated combiners.

In general, many outphasing methods are developed at lower frequencies and only a few at mm-Wave frequencies which indicates the need for more outphasing designs at mm-Wave for better comparison. Specifically, the non-isolated antenna combiner competes well with other PA solutions at 28 GHz with respect to η_{peak}. Because of this, outphasing can be considered as one of the promising amplifier topologies for mm-Waves, especially when co-designed with the antenna.

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