A Baseband Impedance Cancellation Technique For Wideband Multi-Transistor Amplifiers

Indy van den Heuvel, *Graduate Student Member, IEEE,* Ehsan M. Azad, *Member, IEEE,* Mark Omisakin-Edwards, Steve C. Cripps, *Life Fellow, IEEE,* Paul J. Tasker, *Fellow, IEEE,* Roberto Quaglia, *Member, IEEE*

***Abstract*—A new baseband impedance cancellation technique is presented for broadband multi transistor amplifier designs. By placing a baseband transformer in between the Doherty Main and Auxiliary amplifier, the baseband component of a 2-tone signal can be cancelled out, resulting in improved efficiency, output power and linearity over 2-tone bandwidth. A 20 W, 6dB back-off 3.5 GHz Doherty is designed and its performance measured with and without this cancellation technique. The prototype show significant improvements for all metrics for tone spacing above 130 MHz when the transformer is used, it has an efficiency enhancement up to 15% points at 300 MHz tone spacing.**

***Index Terms*—Doherty, gallium nitride, linearity, power amplifiers, wideband signals, Concurrent wideband operation**

I. Introduction

Improvements to data communication modulation protocols demand ever increasing system bandwidth. Power Amplifier (PA) design has long been a trade-off between many factors, often suffering in efficiency and linearity in order to improve its output bandwidth to meet these new standards. To reduce energy requirements, improve output power and linearity, new amplifier designs are investigated to further improve system performance and reduce environmental and economic impact.

Wideband PA intermodulation (IMD) products and efficiency have been linked to baseband (BB) signal components from as early as the 1980's [1][2]. Investigations have led to improved biasing networks [3][4], specific BB impedance matching circuits [5], and BB feedback [6][7][8] signals to reduce higher order IMD products. Efforts to model the phenomenon on transistors led to further emphasis on the BB impedance [9], active load pull was used to verify optimal BB load impedance values[10], with optimal values potentially being envelope modulated values[11]. Comprehensive models for wideband operation and its effects on nonlinearity were introduced [12][13][14]. Finally, investigations were done on the effect of BB impedance mismatch [15] and load matching first order IMD products [16].

This paper focuses on the BB impedance to improve the efficiency and linearity of a Doherty amplifier. As the signal bandwidth is becoming wider with new telecom standards, reducing the BB impedance by solely improving the biasing network might prove very difficult due to the practical limitations of real components [4]. In this paper, an alternative method of reducing the BB impedance is introduced. By connecting a transformer between the main and auxiliary outputs, the BB component of a wideband signal can be effectively cancelled out, greatly reducing the impact of the biasing network on the effective BB impedance. A demonstrator prototype Doherty amplifier using this method has been designed, built and characterised demonstrating increased efficiency and linearity under wideband excitation.

II. Wideband Amplifiers & Baseband Cancellation

In previous work, extensive effort has been spent on reducing wideband PA BB components for single transistor systems. In multi amplifier systems it is possible to use load modulation to improve performance. For example, the "Doherty action" modulates the observed load impedance at the fundamental frequency to a more desirable value by using certain matching networks to impose phase delays between the amplifiers. Recent work [17] expanded the Doherty matching network to cancel out second harmonic signals by applying a 180 degree phase delay at the second harmonic. The goal of this work is to find a matching network structure which would allow for cancellation of the BB domain signals within the Doherty structure.

When the Doherty amplifier is excited by wideband signals, the envelope of the signal will appear at the main and auxiliary inputs with approximately the same phase. As an example, drain currents in the Main and Aux transistors in the Ideal Doherty are shown for a 2-tone signal in Fig. 1. Although the drain currents of the RF components are 90° out of phase, the BB components as seen in the bottom graph are in phase. For the ideal Doherty, both BB currents will flow into the matching network, load modulating in phase, resulting in an effective higher BB impedance when assuming a negligible phase delay at BB frequency. By connecting the BB outputs of the main and auxiliary amplifiers with a 180 degree phase delay by means of a transformer (Fig. 2), the BB currents interact, cancelling the BB domain voltages, resulting in a lower effective BB impedance.

An ideal Doherty design to test the impact of the transformer on wideband signals has been created in Keysight ADS, with S2P blocks used to simulate ideal filters. The transistors are implemented using the "N-Model" [18], which is an idealized model that includes the knee effects hence allowing for voltage swings to affect drain current and capture an approximation of

I. van den Heuvel, Steve C. Cripps, Paul J. Tasker and Roberto Quaglia are with Centre for High Frequency Engineering, Cardiff University, Cardiff CF24 3AA, U.K. (e-mail: vandenheuveli@cardiff.ac.uk)

Ehsan M. Azad and Mark Omisakin-Edwards are with CSA Catapult, IMPERIAL PARK Innovation Centre, Celtic Way, Newport, NP10 8BE U.K.

This article was presented at the IEEE MTT-S International Microwave Symposium (IMS 2024), Washington, DC, USA, June 16–21, 2024.

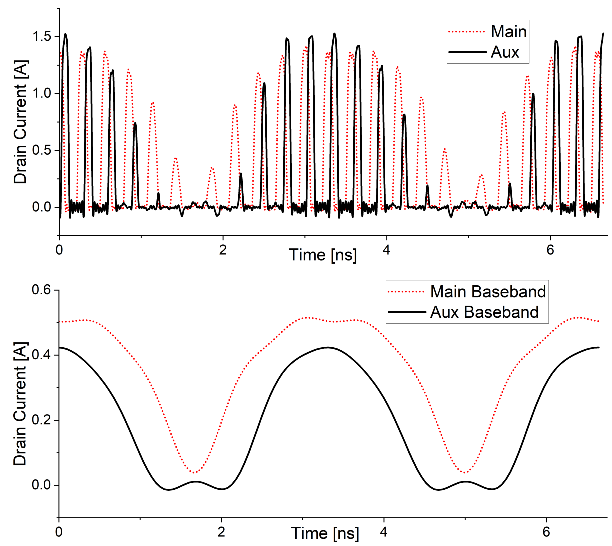

Fig. 1: Ideal Doherty transistor drain current vs. time for 2-tone excitation. Full signal (top) and baseband component (bottom).

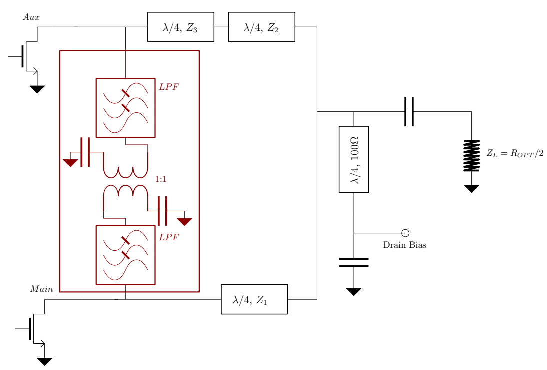

Fig. 2: Doherty with Transformer Cancellation network (Red)

current clipping and its effect on the baseband signal. Fig. 3 shows the key result of simulating this simplified circuit by comparing the drain efficiency, output power, and Carrier to third order intermodulation ratio (CIMR3) at full drive, with and without transformer, over swept 2-tone bandwidth. The performance at peak output power no longer sharply drops over increasing 2-tone bandwidth when using the transformer for BB cancellation, indicating an improvement in all metrics and a more uniform response to wideband signals.

III. Doherty Design

A proof-of-concept Doherty prototype has been designed to validate the BB cancellation method. The design consists of a 6 dB Doherty using the Wolfspeed CG2H40010F device for both main and auxiliary, for the 3.5 GHz frequency band. The design equations introduced in [19] have been used to dimension the output Doherty combiner, resulting in design equations that depend on the tunable design variables a and b, and the optimal device load R_{OPT}. The variables are used to calculate equivalent transmission line impedances Z_1, Z_2 and

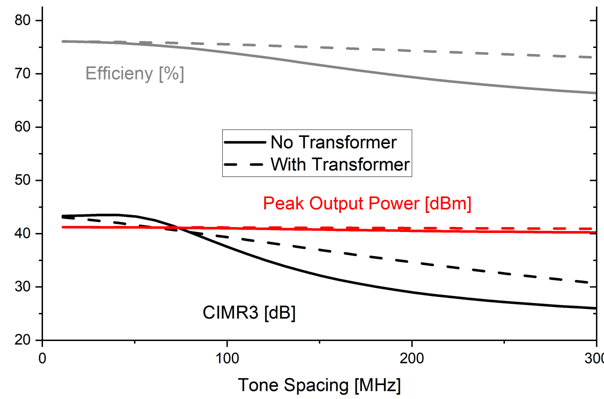

Fig. 3: Simulated 2-tone performance of the ideal Doherty, comparing the cases with (solid line) and without (dashed line) transformer. Output power (red), efficiency (grey) and CIMR3 (black) are shown for swept bandwidth at peak output power.

Z_3 located as seen in Fig. 2:

$$\begin{cases} Z_1 = a^{-1} R_{OPT} \\ Z_2 = a^{-\frac{3}{2}} b^{-1} R_{OPT} \\ Z_3 = a Z_2 \\ Z_L = \frac{1}{2} a^{-2} R_{OPT} \end{cases} \tag{1}$$

The design equations are combined with a transistor parasitic cancellation technique [20], where the transmission lines ideally connected at the output of the main and auxiliary devices are synthesized by a semi-lumped equivalent network that includes the device equivalent output capacitance and inductance (values imposed by the transistor choice), and a piece of transmission line and an open stub (whose characteristics can be adjusted to match delay and impedance of the line), as illustrated in Fig. 4. The

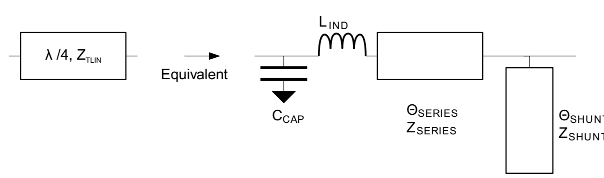

Fig. 4: Transmission line equivalent parasitic network

circuit was synthesized by varying the design variables until performance was optimized when using realistic transmission line impedance values. The second harmonic was controlled to avoid impedance regions with minimum efficiency. The full schematic of the realized Doherty prototype is shown in Fig. 5.

In order to magnify the effect of an unfavourable BB termination, the bias has been provided through a quarter-wave stub with a relatively high impedance of 100Ω connected at the common-node point of the Doherty combiner. The transformer has been connected between the drain contacts of the main and auxiliary devices through 90° transmission lines. By placing fundamental and second harmonic 90° stubs in parallel to the transformer contact, an RF short is created at the fundamental and all of its harmonics, eliminating the effect of the transformer pads on the RF impedance. This method allows

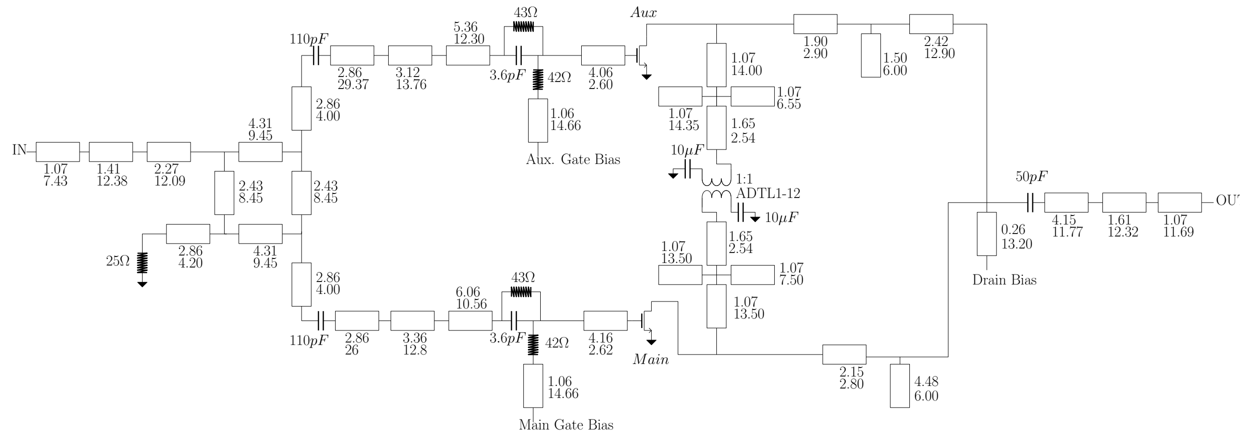

Fig. 5: Schematic diagram of the Doherty prototype with BB cancellation.

for operating the circuit with and without the transformer with negligible effect on the RF matching, allowing for verification of its effects on wideband performance. The adtl1-12 core & wire transformer was chosen for its wide bandwidth and low losses below 1 GHz. The effect of introducing the transformer was verified in terms of effective BB impedance seen by the devices in the two-tone simulation of the Doherty, using the EM simulated results for the microstrip layout. The resulting BB impedance for both main and auxiliary amplifiers at peak output power is shown in Fig. 6, showing how the introduction of the transformer leads to reduced impedance magnitude and a shift to higher frequency of the resonance.

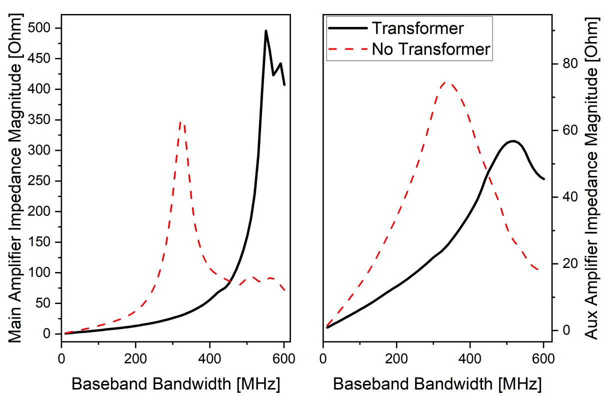

Fig. 6: BB impedance calculated from two-tone simulation vs. BB bandwidth. Main (left) and auxiliary (right) devices. Comparing simulation without (dashed line) and with (solid line) transformer .

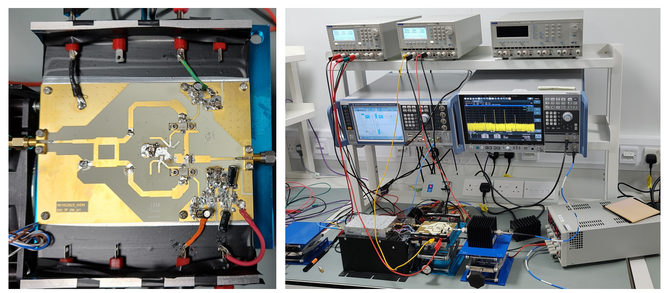

Fig. 7: Picture of the fabricated Doherty prototype (left), and of the 2-tone measurement setup (right) consisting of a signal generator, pre-amplifier, the Doherty PA, and a Spectrum Analyzer.

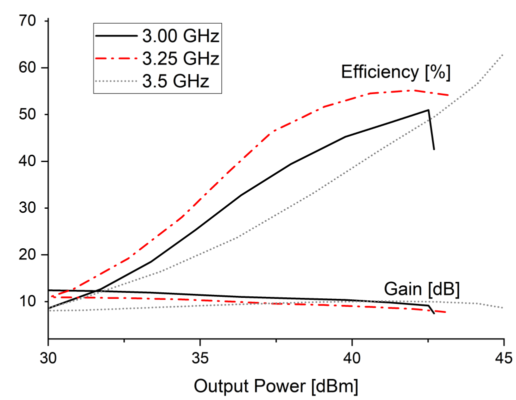

Fig. 8: Measured single-tone performance at 3 (black solid line), 3.25 (red dot-dashed), and 3.5 GHz (grey dotted). Efficiency and gain vs. output power.

IV. Characterization

The layout was finalized for a RO4350 substrate and fabricated. Fig. 7 shows a picture of the prototype.

Single tone performance was measured, showing a frequency shift towards lower frequencies, with best response at 3.25 GHz, reported in Fig. 8 alongside 3 and 3.5 GHz. The Doherty is biased at 28 V, with 25 mA for the main drain current, and -5.8 V for the auxiliary gate voltage. The successive measurements all use this centre frequency and bias configuration. The 2-tone test is measured using the setup shown in Fig. 7, where a 2-tone signal is swept for power and tone spacing. Fig. 9 shows the efficiency and CIMR3 over output power for 3 bandwidth values, while Fig. 10 shows the efficiency, output power, and CIMR3 ratio for swept 2-tone bandwidth at peak output power. The Doherty with added transformer shows significantly better performance at larger tone-spacing values, with up to 15 % more efficiency and 7 dB

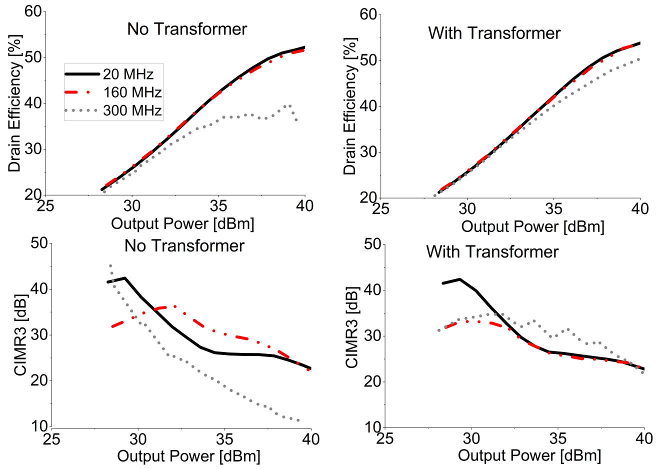

Fig. 9: Measured 2-tone Doherty performance comparing the device with (right) and without (left) transformer. Efficiency and CIMR3 are shown at 3.25 GHz excitation vs. output power for different tone spacing values.

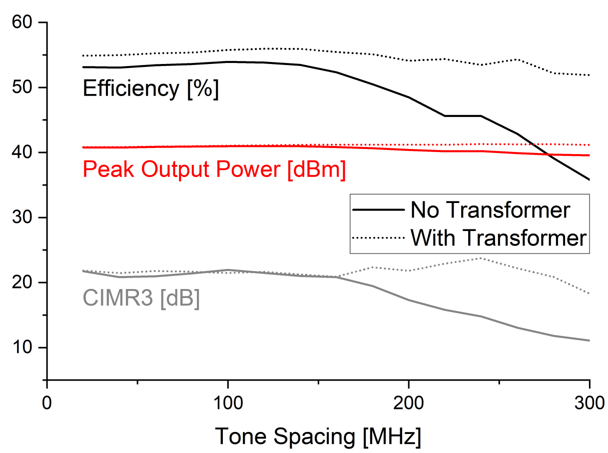

Fig. 10: Measured 2-tone Doherty performance comparing the device with (solid line) and without (dashed line) transformer. Output power (red), efficiency (black) and CIMR3 (grey) are shown vs. tone spacing at peak output power.

better CIMR3 at 300 MHz 2-tone bandwidth.

Conclusion

A new multi amplifier BB impedance cancellation technique was introduced. By placing a 180° phase delay in between the main and auxiliary transistors of a Doherty amplifier the effective BB impedance observed by each transistor was reduced under wideband signal excitation, leading to substantial performance improvement. The performance improvement was simulated with simplified transistor models, and then verified in measurements with a Doherty prototype at 3.25 GHz. This new technique has great potential for engineering in multi-transistor power amplifiers that need to amplify very wideband signals with high linearity.

References

[1] Y. Hu, J. C. Mollier, and J. Obregon, "A new method of third-order intermodulation reduction in nonlinear microwave systems," *IEEE Trans. Microw. Theory Tech.*, vol. 34, no. 2, pp. 245–250, Feb. 1986.

[2] W. Bosch and G. Gatti, "Measurement and simulation of memory effects in predistortion linearizers," *IEEE Trans. Microw. Theory Tech.*, vol. 37, no. 12, pp. 1885–1890, 1989.

[3] M. Franco, A. Guida, A. Katz, and P. Herczfeld, "Minimization of bias-induced memory effects in UHF radio frequency high power amplifiers with broadband signals," in *2007 IEEE Radio and Wireless Symposium*. IEEE, 2007.

[4] H. H. Ladhani, J. K. Jones, and G. Bouisse, "Improvements in the instantaneous-bandwidth capability of RF power transistors using in-package high-k capacitors," in *2011 IEEE MTT-S International Microwave Symposium*. IEEE, Jun. 2011.

[5] X. Chen, W. Chen, G. Su, F. M. Ghannouchi, and Z. Feng, "A concurrent dual-band 1.9–2.6-GHz Doherty power amplifier with intermodulation impedance tuning," in *2014 IEEE MTT-S International Microwave Symposium (IMS2014)*. IEEE, Jun. 2014.

[6] Y.-P. Kwon, Y.-C. Jeong, Y. Kim, and C.-D. Kim, "A design of predistortion linearizer using 2nd order low frequency intermodulation signal injection," in *33rd European Microwave Conference, 2003*. IEEE, Oct. 2003.

[7] A. Doric, A. Atanaskovic, B. Alorda, and N. Males-Ilic, "Linearization of Doherty amplifier by injection of digitally processed baseband signals at the output of the main and auxiliary cell," in *2019 14th International Conference on Advanced Technologies, Systems and Services in Telecommunications (TELSIKS)*. IEEE, Oct. 2019.

[8] W. Sear, D. T. Donahue, M. Pirrone, and T. W. Barton, "Bias and bias line effects on wideband RF power amplifier performance," in *2022 IEEE 22nd Annual Wireless and Microwave Technology Conference (WAMICON)*. IEEE, Apr. 2022.

[9] J. Brinkhoff and A. E. Parker, "Effect of baseband impedance on FET intermodulation," *IEEE Trans. Microw. Theory Tech.*, vol. 51, no. 3, pp. 1045–1051, Mar. 2003.

[10] D. J. Williams, J. Leckey, and P. J. Tasker, "Envelope domain analysis of measured time domain voltage and current waveforms provide for improved understanding of factors effecting linearity," in *IEEE MTT-S International Microwave Symposium Digest, 2003*. IEEE, 2003.

[11] M. Akmal, J. Lees, S. Bensmida, S. Woodington, V. Carrubba, C. S, B. J, M. K, B. M, M. J, and T. P. J, "The effect of baseband impedance termination on the linearity of GaN HEMTs," *The 40th European Microwave Conference*, pp. 1046–1049, 2010.

[12] N. Borges de Carvalho and J. C. Pedro, "A comprehensive explanation of distortion sideband asymmetries," *IEEE Trans. Microw. Theory Tech.*, vol. 50, no. 9, pp. 2090–2101, Sep. 2002.

[13] X. Chen, W. Chen, F. M. Ghannouchi, Z. Feng, and Y. Liu, "Enhanced analysis and design method of concurrent dual-band power amplifiers with intermodulation impedance tuning," *IEEE Trans. Microw. Theory Tech.*, vol. 61, no. 12, pp. 4544–4558, Dec. 2013.

[14] T. Qi, S. He, B. Hu, C. Liu, X. Du, Y. Zhao, M. Helaoui, W. Chen, and F. M. Ghannouchi, "Efficiency analysis of concurrently driven power amplifiers," *IEEE Access*, vol. 8, pp. 91 379–91 393, 2020.

[15] L. C. Nunes, D. R. Barros, P. M. Cabral, and J. C. Pedro, "Efficiency degradation in wideband power amplifiers," in *2018 IEEE/MTT-S International Microwave Symposium - IMS*. IEEE, Jun. 2018.

[16] F. M. Barradas, L. C. Nunes, J. Louro, D. R. Barros, P. M. Cabral, and J. C. Pedro, "The effect of IMD drain impedances in RF PA concurrent dual-band operation," *IEEE Trans. Microw. Theory Tech.*, vol. 71, no. 7, pp. 2920–2933, Jul. 2023.

[17] X. Y. Zhou, S. Y. Zheng, W. S. Chan, S. Chen, and D. Ho, "Broadband efficiency-enhanced mutually coupled harmonic postmatching Doherty power amplifier," *IEEE Trans. Circuits Syst. I Regul. Pap.*, vol. 64, no. 7, pp. 1758–1771, Jul. 2017.

[18] R. Quaglia, D. J. Shepphard, and S. Cripps, "A reappraisal of optimum output matching conditions in microwave power transistors," *IEEE Trans. Microw. Theory Tech.*, vol. 65, no. 3, pp. 838–845, Mar. 2017.

[19] A. Barakat, M. Thian, V. Fusco, S. Bulja, and L. Guan, "Toward a more generalized Doherty power amplifier design for broadband operation," *IEEE Trans. Microw. Theory Tech.*, vol. 65, no. 3, pp. 846–859, Mar. 2017.

[20] J. J. Moreno Rubio, V. Camarchia, M. Pirola, and R. Quaglia, "Design of an 87% fractional bandwidth Doherty power amplifier supported by a simplified bandwidth estimation method," *IEEE Trans. Microw. Theory Tech.*, vol. 66, no. 3, pp. 1319–1327, Mar. 2018.