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Near-Field Communications: A Degree-of-Freedom Perspective

Chongjun Ouyang, Yuanwei Liu, Xingqi Zhang, and Lajos Hanzo

Abstract—Multiple-antenna technologies are advancing towards large-scale aperture sizes and extremely high frequencies, leading to the emergence of near-field communications (NFC) in future wireless systems. To this context, we investigate the degree of freedom (DoF) in near-field multiple-input multipleoutput (MIMO) systems. We consider both spatially discrete (SPD) antennas and continuous aperture (CAP) antennas. Additionally, we explore three important DoF-related performance metrics and examine their relationships with the classic DoF. Numerical results demonstrate the benefits of NFC over far-field communications (FFC) in terms of providing increased spatial DoFs. We also identify promising research directions for NFC from a DoF perspective.

I. INTRODUCTION

The electromagnetic (EM) radiation field emitted by antennas is divided into two regions: the far-field and the radiation near-field. The Rayleigh distance, determined by the product of the array aperture's square and the carrier frequency, serves as the boundary between these regions [?]. In the far-field region, beyond the Rayleigh distance, EM waves exhibit different propagation characteristics compared to the near-field region within it. Planar waves effectively approximate the farfield EM field, while the near-field EM field requires precise modeling using spherical waves [?].

Limited by the size of antenna arrays and the operating frequency bands, the Rayleigh distance in current cellular systems typically spans only a few meters, making the near-field effects negligible. Thus, existing cellular communications predominantly rely on theories and techniques from far-field communications (FPC). However, with the rapid advances of wireless technology, next-generation wireless communications rely on extremely large-scale antenna arrays and higher frequencies to cater for the ever-increasing thirst for communication services [?]. In these advanced scenarios, near-field communications (NFC) can extend over longer distances, surpassing the conventional proximity range. The deployment of massive antenna arrays and the utilization of high-frequency bands allow NFC to be effective at distances of hundreds

of meters, thereby opening up novel opportunities for the development of NFC theories and techniques [?], [?].

In the realm of wireless communications, the degree of freedom (DoF) concept has emerged as a crucial framework for understanding the capabilities and potential of different communication systems [?]. Briefly, the DoF provides insights into the number of independent signal dimensions that can be exploited for conveying information in a wireless channel. While traditional FFC have been extensively studied within this context, the unique physical properties of NFC exhibit distinct characteristics that necessitate a fresh exploration of DoF.

The adoption of a DoF perspective in NFC is motivated by several factors. Firstly, NFC offers increased DoFs, which represents a significant advantage over FFC. By understanding the DoF characteristics of NFC systems, we can unveil the superior data capacity and transmission capabilities of NFC compared to FFC. Secondly, characterizing the DoF in NFC assists in optimizing the system parameters, such as the antenna configurations and transmission strategies, leading to improved overall performance. Thirdly, adopting a DoF perspective facilitates the development of communication protocols and algorithms specifically tailored for NFC environments, resulting in enhanced reliability, coverage, and throughput. Although there are some studies analyzing NFC's DoF [?], this field is still in its infancy.

Hence, we aim for the critical appraisal of NFC and its DoF. Our focus is on point-to-point multiple-input multiple-output (MIMO) channels under line-of-sight (LoS) propagation, as illustrated in Fig. ??. This emphasis arises from the anticipation that future NFC will operate at high frequencies, leading to a prevalence of LoS communication associated with limited multi-path effects. We commence by exploring the DoFs achieved in near-field MIMO by spatially discrete antennas (SPD-MIMO). Subsequently, we extend our analysis to the near-field MIMO supported by continuous aperture antennas (CAP-MIMO). Utilizing numerical simulations, we demonstrate the superiority of NFC over FFC concerning its DoF and establish connections between the DoF and effective DoF (EDoF). Finally, future research ideas are discussed.

II. DoFs Achieved in SPD-MIMO

In practical implementations of NFC, a viable approach is to equip the transceiver with an extensive antenna array comprising a large number of SPD patch antennas. In this section, we will delve into a comprehensive analysis of the achievable DoFs in near-field SPD-MIMO.

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technique of cinereasing the DoFs in NFC. By reducing the

aperture. This limitation has been theoretically demonstrated in [?], [?]. an Ten augment sour exposition; wie represent the pordered sposs itilvev sin Fullartovalueseffortinatrixt Historiogs ≥f hundred poet Millers(?) derebustrated by employing project spheroidal wave functions that of or Natial theories and determinate a likes [fall off slowlyhentialtheyf reachless critical uthiresholds, beyorld gwhielf theyddeca/Draft)dtyn This briticals threshold is cremied fas the teffection unglene taficfing dblue (EDalFI) tiede nouddpase EDalFijf Miffreover, othis uphenomenons becomes [frjor@piefmineht asDthe numbdesofistighteeiving tantennasbincréaiseslepThelenfindings thidicate othat tlathough bharnessi it gd more camternag i caforlead toomininereased enumber nothindependent distribution for both the rdominanty & DoFydiones vitain behis feetivety, this zedic for supporting reliable communications distinct characteristics thFunkerssotetefor facthree plumbernof ablehas, Miller [?] concluded a that the finne of finities of EC to Fe its No Soit in native the broducerof transmitter and receiver areas and crease inversely proportional southe diskedistance. These findings are Febrived usiderthanditterthephoricathwavetetisws modelEdeseritiethin tile Ean, uBfeil (The subWignodetaiscappoticable on the subwignodetaiscappoticable on the subwignodetaiscappoticable on field regionaliwhere the VEG mounipation distance exceeds the unittorn privileg distance Fexhibiling agriforn chantiet gains and nont-linear phase shiftsud lowever, at its important to mote that as tha tinki ationade bleedingel endimatable propedranscall occioes (iten ONF Clwidlin the phiform-power distance) ethe acturacy of the USWienodef and the HDoFoderiveto in §? Addministresh To autoriss alias, (Diagonal forroduced en vivorementeral resultates for EDoFic trasediability, sampling the orly targungling to Athe our tine from someric at wave and Swian Neel of PDF. Although fields formula may present tractability challenges, again, it reveals that the upper limit of EDDE is it is to bord out to the broduct of the stansmitter and receive our ansimum to be time to the control of the stansmitter and the stansmitte proportionalityletertink thistafice. These immissionents embande sightinglessanding agaziner in NPG tresteens Fig. ??. This entphenismaisesthe uphblusionisi drawn from fittuand NPC suill channel ricagnicity a care interestriction of the dwo obtimate affeats: Mercasing the adequire size and reducing the communication firskingel Mechanicatorija kinesiis sreare gaeteurren (SRD-tMPM66)-Substitution of the contract of the contraction of MPMDerioporanal labor tamanicae stringentonicae. CAP-MIMO). Utilizing numerical simulations, we demonstrate the superiority of NFC over FFC concerning its DoF and

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(EDoFull vFinitibe, that increased DoFs on BiboFs (ressEDoF1) offered by near-field SPD-MIMO, it is crucial to apply SVD to

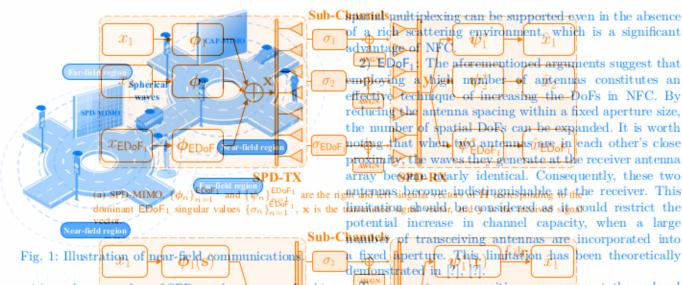
the channel matrix Ff. This allows for the identification of the

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Consequently, these two antennas become indistinguishable at

restrict the potential increase in channel capacity, when a large number of transceiving antennas are incorporated into a fixed



comprising a large number of SPD patch antennas. In section, we will delve into a configuration as the section of the achievable DoFs in near-field SPD-MIMO.

A. Calculation of the Dol

1) DoF: In the context of SPD-MIMO, the channel response can be represented as a match HINVing dimensions of N₁(b) N₁(b) N₁(d) receive antennas and Donagues and the human albert an anamate (of Diese for diagram in the formation of the antennas. By applying the singularical distributed apparent of the property of the second of the pendent antennas. (SVD) to this channel matrix, the steefield point within the C Fig. 2: Communication architecture based on orthogonal parcan be effectively decomposed interpultiple independent are the transmitted symbols. are the received symbols, T. are the received symbols, and the received symbols that channel channel matrix or Green's function, and AWGI erate in parallel without mutual interference. Ma concludes that the upper limit of EDoF₁ is proportional

matically, the number of positive singular values channel capacity, the water-filling algorithm can be rank of the correlation matrix HIT corresponds for judiciously sharing the power among the LOOF, number of sub-channels having a non-zero signal-t sub-channels. Fig. ?? illustrates the detailed architect channels Fig. ?? Illustrates the detailed architecture that of SNR). Each of these sub-channels accommodates me exploitation of Dof m NFC relying on SPD independent communication mode within the MIMO channel. The total number of communication modes is referred to as the spatial DoF of the channel, denoted S Discussion and Quileak hand, for a MIMO Gaussian chain millimide NEar Sa Changa bw The a DoF of a Million Stehalos Date is light to the light of t Inraerichs stattering-Senvirohopenty thex/MiMO rehatipelexcan gehieve full wanto for both the meal field and far-field regions duG to the randome phase ishif M, inthoduced ibly Deafterers. As heresuffy the itelievable DoFst inxMEMOh LoSighannels value approach the minimizer halve betwield the himbers of receive andytransingleantenhast. When is largitablembere of transediving autoribals plane a employed of the a tauth of source (Renand the) chave demonstrateds by fleveraging systripging, theory, than the upper limited EDdFy isoliteasly, problemional to the defective apenture of the iteans ceivers exhibit different phase-shifts and power levEds SPD-MIMOk.thEbixadtvvalues bfaDoFoandbEDoF_r.cab ber obtained Mcombiner SVD and the achannels enate in 1H af dri bloth Doß and Nicos channels. However, sobtaining Nactably, closede SOMD expressions afor these stwo performance chetrical remains 6haltèngingarF6 elddresEMf0s, [pnSviolus istudiess have jnvestig atbd then uppen limite of two Eq. widen war Yous Tehannet reford i tions

To attement our exposition, we represent the ordered positive singular $uh(\mathbf{e})$ of matrix M as $\sigma_1 \geq \ldots \geq \sigma_{DoF}$. Miller demonstrated by employing prolate spheroidal wave functions that for small values of n, the σ_n values fall off stowly until they reach a critical threshold, beyond which they dear papielly Phis critical threshold is termed as the "effective degree of freedom (EDoF)", denoted as EDOF₁. Modern this phenomenon becomes more promi-

then the smumb nincolnt or creativing contennas increases. surface of the receiver, the dominant EDOE, ones candered to superchannels for MIMO NFC. In this figure, $\{x_n\}_{n=1}^{\infty}$ for supporting reliable communication, for are the dominant singular values of the MIMO NFC additive white Gaussian noise.

the product of transmitter and receiver areas and it considering the asymptotic scenario of a large number of a large numbers of the link distance. These finding transceiving antennas [7], the large derived using the uniform spherical wave (USW) mode pressions are derived using Green's function model, which is appear impervious to newcomers, who are experts the near-field region, where the computations of the near-field region. field region, where the leads to an imp un2forED plowe Recently; e)orderesearchers diave in 1530 une den alternative Drefrieleti asslessi NFGliperfoshiance palsoltermedias Than deffective of degreed of freedom (EDoF) for which is reignory (trs/HIHCh)/214 Hallip)mand blengted as through file file for the readdyncasoulated for any arbitrary channel matrix, regardless ofiisvfietherlahensysteresoperatestäbilitär-clorlfangieldagegionis, andealideh AtoSher (NIDeS) bropagati bibo As ianpenampliculet us considerathetLoS (duarturel). Im fate field dloS: dMIMO a the schadulet itiatsixirhas selyanjo offort and thence he Diffly biscomes. 1. Tilene wersely, eforenear-field LoS (MIMO): ED off infalls between Nand Do Ferand it is also proportional to the number of transceiving antennasn(?)) aif he the per tirbits of n EDb Ewis obtained for dea? sield dsoStMIMO by riettiberthe fruinbeinen antennas approach infidity, alethoristrating dispinivessecaproportionality and the link distancy. iThe nesults reas[Ng ithlicate that the reardical offect the enhance fill offen Selietalisted i Behaveled lyned lywith out any gistificationsyithat (El@oFourepresents) the equivalent mymber for

TABLE I: Summary of DoF-related metrics for MIMO NFC supported by SPD antennas.

	$\overline{}$	\			
Metric	Degree of Freedom: DoF				Effective Degree of Freedom: EDoF
	#1 P 691		EDoF: Q	_	ψ_1 EDoP ₂ x_1 EDoF ₃
Definition		/ \	?		[?]
Values Range	€ Z ⁺ , [1, N _{min}]	\	€, Z ⁺ , [1, N _{min}] , WGN	_	$\in \mathbb{R}^{+}, [1, N_{\min}]$ $\in \mathbb{R}^{+}, (0, N_{\min}]$
SNR Ranges	High-SNR region	Low	Medium SNR region		Low-SNR region All SNR ranges
Relation with	Number of sun-changely	NAX.	Number of Φ	_	J/No dire exception with X2 Number of
Sub-Channels	with a non-zero SNR	/ *() *	omisant sub-channels	\rightarrow	the number of sub-channels equivalent sub-channels
SPD-MIMO LoS	1	<i>*</i>	AWGN		1 ≤1
Fae-Field NLo	Rank of HH^H , ≥ 1	Obtained	from SVD of H, ≥ 1	(tri	$ HH^H / HH^H _F ^2$ [?], $\geq 1 \left[\frac{d}{d\delta}C(SNR/2^{\delta})\right]_{\delta=0}$ [?], $\leq N_{min}$
(Calculation) Palaci	Upper bound: N _{min}		Upper bound: N _{min}		Upper bound: N_{min} Upper bound: N_{min}
SPD-MIMO LoS Near-Field	Rank of $\mathbf{H}\mathbf{H}^{H}_{J}$, ≥ 1	Obtained	from SVD of H, ≥ 1 (tr(H		$\ \mathbf{H}^{H}\ _{F}^{2}$, [?, Eqn. (8)], ≥ 1 $\Big _{s} \frac{d}{da}C(SNR \cdot 2^{a}) _{s=0}$, $\leq N_{min}$
	"EDolpper to the PEDoFU	pper limit: ∝.	A.A., A PEDBE ?	Upper	limit (* Banc(58)); and WEDOF1 Upper bound: Namin
(Calculation) NLos	Rank of HH ⁿ , > 1	Obtained	rom SMD of H, ≥		$\operatorname{tr}(\mathbf{H}\mathbf{H}^{n})/\ \mathbf{H}\mathbf{H}^{n}\ _{F}^{1}$, ≥ 1 $\frac{\alpha}{4\delta}C(\mathbf{S})\mathbb{R} \cdot 2^{\delta}) _{\delta=0}$, $\leq N_{\min}$
74130	Upper bound: N _{min}	- Upper li	$mit \propto A_t A_r$, [?], [?]	CDI	Upper bound: N _{min} Upper bound: N _{min}

sub-channels, as depicted in Fig. ??, and can be employed for In a SISO channel, a G fold increase in transmit power evaluating the NFC performance MISHowever, it is rucial1 statements lack mathematical rigor and to note that these may lead to misinterpretations of the actual meaning and $\phi_2(s)$ **(**) implications of EDoF₂.

The concept of EDoF₂ was originally introduced Muharemovic et al. [?], who built upon Verdú's previous work [?] to approximate the MIMO channel capacity as EDO [$\log_2(\frac{E_b}{N_0}) - \log_2(\frac{E_b}{N_0})$] in the low-SNR regime. Here, represents the bit energy over noise power spectral density, and $\frac{E_h}{N_0}$ is the minimum value required for reliable communications. Additionally, $\frac{E_h}{E_h}$ is determined by the production of the cations. Additionally, $\frac{E_h}{E_h}$ is determined by the dominant elocities. that EDeE, possessing of the receiver in the property of 1, leading to EDeE, being no larger than 1. Conversely for compared to EDeE, and Does Generally the value of EDeE, and Does Generally the value of EDeE, and Does Generally the value of EDeE, and the figure of EDeE, and Does Generally the value of EDeE, and Does Generally the value of EDeE, and the received symbols of the is not directly associated with the number of dominant sub-lifting this comparison that the near-field elect can improve channels depicted in Fig. ??. However, an exception occurs the insights gleaned from the receiver of the receiver of the receiver of the receiver of the parameter of t when the dominant sub-channels have nearly identical channel supporting NFC, emphasizing the superior spatial EDOF

gains, i.e. $\sigma_{\text{In}} \approx \sigma_{\text{ED}} \approx \sigma_{\text$ the value of EDoF₂. Our numerical results in Section ?? B. Exploitation of the DoF suggest that this scenario can happen in certain LoS channels. Nonetheless, utilizappheximations remains neuristic Fandi as ECONFALITY OF THE TRANSPORT OF THE PROPERTY OF to repplyment to the charmel matrix His artisellows for the rider tification not he how shared for singular arectors SATTORPANCIPPETED ash the dequivarent FRANCE singular chanliers: The starther northmer the rechievable abrened reparities of the EDGE: filling Dorg Hither, ich imborttill 76 disternindigisuslet sharing the power among the $EDoF_1$ parallel sub-channels. Fig. 22 illustrates the detailed architecture that noutlines the spanal ports offered by the exploitation of DoF in NFC relying on SPD antennas. NFC MIMO, it is desirable to operate the system in the high-SNR region. In such scenarios, the channel capacity should Exhibit roughly afficed whowth vs. the DoF or EDoF1, given a fixel/ITMGmNLp8weihaHowleveF,hachtovingf this NighNSNR chaditida imáyfluotnobylays beefgasibletii icaprakticáb settingsf Inatteognitibn afrithissfatterShiuewvirdnif2hfnttbdudelMan alternative a metric eval soulterned fas the h"effectiver-degree not freetloht (EDoE)"d which trepresents: the asmsbeft of requivalent sub-schannelss actively: participhting:life-conveying-sinforhald/dd

Imder/specific operating/conditions/nFornclarity/lwe/refereto

this metriceas EDoceive and transmit antennas. When a

leads to a capacity therease of $\log_2 \hat{G}_1$ bps/Hz at high SNRs. If a system is equivalent to EDoF₃ SISO channels in parallel, the overall system capacity should increase by $\mathsf{EDoF}_3 \cdot \log_2 G$ ps/Hz when the transmit power is multiplied by a factor of G. To formally define $EDoF_3 \cdot \log_2 G$, Shiu et al. [?] express it as $\frac{d}{d\delta}C(SNR \mid 2^{\delta})|_{\delta=0}$, where C(SNR) represents the MIMO channel capacity at a given SNR. It is important to note that C() can refer to the instantaneous capacity, outage capacity, or ergodic capacity, making the expression of EDoF₃ applicable to arbitrary channel matrices, regardless of whether the system are the right and left singular functions of Green's and under LoS or channel capacity and the SNRf [2.1Eqn. (141)], By considering ic National Propagations 1 Left us consider the continuous channel as an the insights gleaned from 17 ithid 17 Cit Pheetime soft Videnensian ample du fartfield LoS MIMO, theichancel matrix has a rank

> Essentially, EDoF₃ describes the number of equivalent SISO large number of transceiving antennas are employed, the sub-channels at a given SNR, making it a valuable perforauthors of [7] and [7] have demonstrated by leveraging mance indicator for NFC in different SNR scenarios, sampling theory that the upper limit of EDoF₁ is directly sampling theory that the upper limit of EDOF₁ is directly proportionary and enterty been primarity riscused on Ebellinging crucial destevelop propipienehulve mathematical pamework for encualing inc of himle of Epopys and appel conditions by considering the asymptotic scenario of a large number of transceiving scenarios. [?], [?], [?], These elegant expressions are derived using Green's function model, which may appear impervious to newcomers, who are experts in other fields. This leads to an important question: Can there be DoF-related metrics that evaluate NFC performance in a non-asymptotic manner in closed form? The answer is Dullizing CAP antennas presents a promising technique of affirmative, and the following parts provide the details of improving the performance of MIMO systems having limited these metrics.
>
> apertures. In contrast to SPD-MIMOs, which involve a large nuthberDuFdis tretenantensus chaving repecifibaspacing of API MIMiDeadaptseam inffriitet ourabers of Nattennas ovithainfinitelsia treah spacing high section devestigates the spa(ital DoF)s' invite ab field (CAB-MIMOIH)/||HHH|||F)2 and denoted as EDoF2.

 $A_{t/r}$ is the effective aperture size of the transmitter/receiver N_{min} is the minimum Value between Φ_0 and V_0 that V_0 are the right and left singular vectors of \mathbf{H} corresponding

d is the link distance the tween than the Boff period there and the control of a_n and a_n is the transmitted signal vector, and a_n is the transmitted signal vector. received signal vector.

A. Calculation Total Phe Pois Summary of DoF-related metrics for Mining to Truesport and synthesis and the superiority of NFC

Weregonsider a scenario where hoth the transmitter and to the MIMO setup for SPD antennas. Ho SPD antehna array that delivers finite-dimensional signal unber of an electric radiation field)alithefraceiver H. aperture. FThe two points on the transceiving surfaces is described by Green functions which connects the transmitter's current distribution and the receiver speterer is field where spatial integral. Green's function accurately models the EM characteristics in free space and effectively represents the channel response between the EDUCCIVARS Jakin atti the channel matrix for a SED MAMOS and malthipoFeeaBased, on whe tabove considerations, then spatial GARTMIMOrechannels can the decomposed onto the series of parallel SISO subjehannels by dinding the sequivalent "SVD" af Green's Mungion (Re Egam(27)) a The resultant equivalent "aleft singular perfors" and "right singular vectors" form flyo complete wats Epfoprthagonal thasis, functions on anterithe transmitter/staperture and the other for the receiver/scaperture. The resultant, equivalent f"singular; values incorrespond, to the channel rains of the decomposed sub-channels alternatively. these; "singular, yalues" can be obtained through the eigenvalue degomposition phothes. Hermitian ikernet of h Green's not unstion (analogous to the correlation matrix, HHH for SPD antennas); see [2] Eqn_a(42) |send-12 ioSectional I-€D for more details. The number of non-zero "singular values" of Green's function. or equivalently, the non-zero eigenvalues of its kernel-is defined as the Does, denoted an Dofot The Does also trignifies take numbernati SIS Og subtahannels let da teon izerog SNR a casik of which supports an independent communication mode within the rentire of EDoF₂ was originally introduced by Mannoted in [2], the far-field Los CAP-MIMO can support Munaremovin [2], and far-field Los CAP-MIMO can support when the control of th a maximum of one communication modera Consequently, the Description of the case of near-field LoS MIMO, the DoF has the potential the case of near-field LoS MIMO, the DoF has the potential the case of near-field LoS MIMO, the DoF has the potential the case of near-field LoS MIMO, the DoF has the potential the potential the potential the potential that the potential the potential that the potential the potential that the potent tral density and Therefore, we may conclude that the near nelia blreconsuminicationen handlisi que spatiat de reterminand product of the channel capacity and the SNR [?, Equ. EDOF, Bythousidering the Air-inflytoglessiesh from the rendarkabite abititive to violoport linti file of anany communication nhorais;altinterpretation cylicial compareshize Ellia Frontyl (1985) fronteral having explainment Edwinets ground dean the sense cityets utilizeth consumber infrolomation to The relian member pict of eige Effective Homovonicanios constites as known has the Election and EDoFharSeverahamethods/havelebeenabroposed/togaletermine Or approximate the value of be EDoF ; such as analyzing the eigenvalues for the kernet pur Green's hincipus (24) tempto ving salusting Ethe Ezy P. proprint a trips at the etion theoretical that whis ingenantae and hope 4? in certain LoS channels. Nonethelesearchis has reterioristicated unains or meatine to Life CAPIMIM Or the wather of EDOFTEST directly proportional to the Production the, transmittenand reserves igreas: with bedong inverselyaptroportional Control inkvdistance (2) pr[?];e[2]. On the btheir hapid, for day-field LoS (GAP-MHMO), the wallbe of dE DoB_T

Regin Exploitation of the DoFR region All SNR ranges Number of behannels of fully exploite the since with Number of behannels of the DoFR region All SNR ranges Number of behannels of the property of the property of the property of the left of the property of the left of

 EDoF₃: To fully harness the spatial DoFs offered by VFDishishion itnik Outlookle to operate the system in the high-SAMMOCRIEDS Tensucher constitution the character areaty Mand have also roughly linear tear on the context of NLOS ED9E_ateixen_a fixed_traps;nitheowernoFoweyereachiexing Eastering SN Roccinedition durantized salvanting before interior practical eptimer heir mongrition at that teory of NLSs CAPIMIMO IS Angaelfernative in restrictue la caterina da ana tale fieffective ode grotore by tree down deliboration and high represents the pumber of equivalent sub-channels actively particinating in conveying information under specific operating conditions. For clarity, we refer to this metric as EDoF. The concept of EDoF. has been extended to CAPSMIMO enames Supold repracing the tenames many bea Green's manemonty in Eggs 989f. Cased-form Hometakish EDBs, Have veta ucin vegri ver hear the la PCAP - MEMOC hap 1795. isbacentalint, the overall-systember-parityanbould increase that \mathbb{E}_{P} \mathbb{E}_{S} \mathbb{E}_{P} \mathbb{E}_{S} \mathbb{E}_{P} \mathbb{E}_{S} \mathbb{E}_{S} \mathbb{E}_{S} \mathbb{E}_{P} \mathbb{E}_{S} \mathbb{E}_{S} Prieds by a factorious Guarante Printer and a factorious of the fa Sheerstore the advantage of NFC the tends of EDOFD. Those EVSNR) is existent to each the leading of the contract of the SNBtudies i proving than the chaiffeit babacity of coareful Mo the sectors are our capacity, putage capacity the long of the ramacity A making 1the Darpression of a high stappoinable for CAP-WIMO, TAURING PARECISES PHYSICAL PROFERRIDGES, PURTHER restaren apareetren in estabrisha moreargiorbus and practical Understanding of PEDSF PIN PINS STOREXT LIFT CAP-PAINS OF the Los, change capancaxample, Infar-field LoS MIMQuetha chappoinmotrix haseoidankundi lebarlingita FD9Foid Ping enalmere eathor exceenverselvine for openearied of 95.84 EAP. MANTO, COURT SECTION HIGHER CHART YELFOWEVER IN 18 HAPPOTRANT that the near field he fack or closed from Expressions for the charmentiable in FOAP MIMO, that cutating the force is black SPED of before the careming becomes intractabled to Theferoren runnel cutvestigations in cliffoured StoPaddress into aspectSandingain andeepentlanderstandingabledEDoFapinishe context Of Geneficies, CARDMIMQnd EDoF3 is summarized in 4)Essimmäry and Outlandet lAndettillede comparison of Dorl Endoffes Edofess aliffeEdofphissiurhmarized in aliablec&beThe agsplitsapirese meds inh Tabley 32 ophimlaridy promain tedy pointsted point CARIMIMO to hannels: However life Wigating the spatial

results have been TABLETI; Summary of POF; this cretics for MIMO NEC supported by VAP aptennas [?]. Therefore, conclude the trethe prease field of the significantly to develop a comprehensive mathematical frame enhanges the spatial Defs, for CAP-MINO. calculating the upper limits of EDoF₂ and EDoF₃ under both LoS and and LoS escenarios. This avenue represents 2 LEDoF₁: The near field CAP-MIM. O. system has the potential direction for future research romar kable ability, to support infinitely all and communisektionels nordes and Holyely depends is quive testab-chonnels og nize that chievedsina GAR-MAMA only, those modes having significant channel gains can Be effectively utilized to convey information. The total Utilizing CAP antennas presents a promising technique ntmiber of these effective communication of mades is known of improving the merformance is the province of improving the province of improvince of improvin 4as, the EDoF, The exce EDOS on Several new book have been limited apertures. In contrastictous Polation, which proposed to determine or approximate the value of $EDoF_1$, involve, as libe geffective laper to feel is enough the anatem inter/reactive of periodicing such as analyzing the eigenvalues of the kernel of Green's spacing, CAP-MIMO adopts an infinite number of antenfunction [?], employing sampling theory [?], [?], [?], utiliznas with infinitesimal spacing. This section investigate ing diffraction theory ?, or leveraging Landau's theorem the spatial DoFs to near field CAP-MIMO as d = 20 mPriorpresearch has demonstrated that for near-field LoS A Calculation of the DoF EDoF (Limit CAP-MIMO where value of Elog is directly proportional $\lambda/2$ spacing We consider a scenario where both the transmitter to the product of the transmitter and receiver areas while and receiver are equipped with CAP antennas, which is being inversely proportional to the link distance [?], [?], 7 On the other hand, for far-field LoS CAP-MEMO, the analogous to the MIMO setup for SPD antennas. However, in contrast to the SPI autenna array that delivers finitevalue of EDoF₁ is limited to 1. These findings highlight dimensional signal vectors, the CAP surface supports the superiority of NFC in terms of enhancing the spatial 120 oFs200 a continuous distribution of source currents within the SNR [dB] transmitting aperture, giving rise to the generation of an EDoF₂ (c) EDoF₃. electric radiation fielders the receiper apporture. The spatial where Both citatismitter and Deceiver are equipped with uniform them alivered aspense containing we awennes intended the system top quales at a drequency of 28 GHD (with accordance transceigh of syrfaces in the cube as have an entire size of 4.37 m ATho conter of the transmittern is located at the origin which comments the drame; while the centerist that to eavel is per (0, de 0); grith, de ganoting albadink distance. The allies face the receiver's electric field vine a spatial integral. Green's their associated singular values. This task involves solving function accurately models the EM characteristics in the eigenvalue problem for the Hermitian kernel [?]. A ison spano and officially arministration channel response that a shorter link distance results in a bigher frDoF till? ktsbowt MIMO sethe horas scire the akin apathe practical significance. casing the superiority of NFC in terms of DoF enhancement. AS breviously mentioned, the practical implementation of near-Howard ipresents of the office of the Foundation of the French of the House of the Control of the House of the Control of the field CAF: Mixed on the above gonsiderations the spatial the inear-field Net-observe athat astithe pumber of jointennas GARDANG 16hannole carache af anaryearable teenniques i or increases. EDoffepof, SRID-MIMQ converges to its. limit, which efaparalleloSISO sub-channels by finding the equivalent is requiral and the Convergence SVD" of Green's function [?, Eqn. (27)]. The resultant pecurs? more; rapidly for higher link distances. (Remarkably, equivalent "left singular vectors" resultight singular vecas depicted in the graph, SPD-MIMO having half-wavelength tors" form two complete sets of orthogonal basis functions. In this section, we explore the enhanced DoFs and EDoFs one for the transmitter is aperture and the other for the offered by MIMO NFC through computer simulations, in LoS receiver's aperture. The resultant equivalent "singular channel secretarios." antenna spacing can achieve nearly the same EDoF2 as CAP-MIMO. The results in Fig. 22 indicate that the singular values Discussion and Outlook our system satisfy $\sigma_1 \approx \ldots \approx \sigma_{\mathsf{EDoF}_1} \gg \sigma_{\mathsf{EDoF}_1}$ 1) MIMO NLoS Channel. The Dol's of near field $\sigma_1 \approx \sigma_{\mathsf{DoF}_1} \approx \sigma_{\mathsf{DoF}_1}$ channel scenarios, values correspond to the channel gains of the decomposed sub-channels. Alternatively, these "singular values" can APEDOP That subservation at igns with the montest not in Fig. the SPD amed through the eigenvalue decomposition of propagation. In [?] and [?], the authors explored various th Fig1e?? hitlastrates who f DGFs eard fED of Snin (aSRD) MIMO; scattering prvironment bod utilized sampling theory showcasing the increased HBoFs oprospaded about the shear-field onalyze that Epolicing heir finding stayealed that Epolicing Effect. (Specifically,?in Segtion, WeCpresentatures ingulars valles NLOS CAP MIMO is higher than I in hoth the near-field of the MIMO channel snatrika for a different. Gukedistancest and and far-field cregionad Moranyer with fixed unan strated that numbers of early notably, the DoFadfiNF6fists ignificantly Some asing the offective aperture esothe arangoivers ran sad to further improvements of EDOF and sub-channels Higher than the DaFue lackiewed showers DaFCC Is urbasking the exiffele can asposoppThe comacre tooh Enone ahons, em extendines DoFnthresholdf SASChown cthen singulars values confibites slow déclihéchntil (they tse ach iaidritieall threshold), aftera tiblich (they P-MIMO channels upon replacing the channel matrix detheasthrapidlyce Thetenumber of dominant singular values by Green's function [?, Eqn. (8)]. Closed-form formulas of defines notice EDoF[2] From Fig-fi2?d weoSarCihFerMhatOas othe EDoF₂ have been derived for near-field CAP-MIMO [?], By Specifically for the LoS channel. The analysis reveals support of anterinas ninereases, the singularivalues odered thus the ghathel (gairs) of the ideelind of sub-channels experienced th Figw 1717e presents can Finaliss is not ether above Do Fe Do Fe AP AMINIO slight improvements, with carolof converging tapfelly 11 of 0s systemsly Due to this computationally displexity Tassociafed livids

caldelatingethth charlnean tagacity on ECAPHM HM On {?} hf wieDo Eus

tippeDidrith(as calculated iti [2]).oAdditionally, it fis it of the worthy

TABLE II: Summary of DoF-related metrics for MIMO NFC supported by CAP antennas.

		4 1001	1 ! ! .	! !!	4 1001	4
Metric	1.1	Degree of Freedom: DoF			$A = 100\lambda$ Effective L	Degree of Freedom: EDoF
	2011	4 - 251 DoF	2019	bF ₁	$A = 25\lambda$ EDoF ₂	EDoF ₃
Definition		n = Bandaish Distance		[7]	n = Paulai sh Distance	[2]
Values Range	- 11	Rayleign Unsched	$\in \mathbb{Z}^+, [1]$	∞)	Kayki Elizakik (L. do)	$\in \mathbb{R}^+, (0, \infty)$
SNR Ranges	15	High-SNR region	Low&Med jum-SNR5 tel	ion	Unknown	All SNR ranges
Relation with	- 11:	Number of sub-channels	Sumbe		No direct relation with	Number of
Sub-Channels	1 1	with a non-zero SNR	dominant suff-chan	iels the	number of sub-channels	equivalent sub-channels
CAP-MIMO	Ins -	1	10	1	1	≤ 1
Far-Field	NLoS	Obtained from solving the	Obtained from solving	the	The exact expression	$\frac{d}{dt}C(SNR \cdot 2^{\delta}) _{\delta=0}$
(Calculation)	141600	eigenvalue problem, ≥ 1	eigenvalue problem	21	is unknown, ≥ 1	a C (3MK-2 //a=0
CAP-MIMO Near-Field (Calculation)	Los	Obtained from solving the	$\propto A_1A_r$, $\propto d^{-2}$, ≥ 1 , ?	12	$\propto d^{-1}$, ≥ 1 , [?], [?]	$\frac{d}{dt}C(SNR \cdot 2^{\delta}) _{\delta=0}$
		<u>leigenvalue</u> problem, ≥ 1	Same 1 ≤ 1, 1)	(1.)	A 1 2 1 (1) (1)	
	NJ os .	Obtained from solving the	× A₁A₂01	171	The exact expression	$C(SNR \cdot 2^{\delta}) _{\delta=0}$
		eigenvalue problem > 1	200 250 0	50	100 s unkipawn, ≥ 1	0 250

** $A_{t/r}$ is the effective aperture size of the this term in $A_{t/r}$ is the link distant and $A_{t/r}$ between the transmitter and receiver

(a) EDoF₁ (b) EDoF2.

Fig. 4: Illustration of EDoFs in CAP-MIMO LoS channels, where the transmitter and receiver are equipped with continuous Howeverrays of the sentina perture size of dend that system operates but a frequency but 28 Citiz (without deresponding the verticing the oux entlycm). The dienter of the transmitter is to ented an the thrigin of a tikede three his is har fune, while the yealer of the repobler if at AC AMMinistration of the like distince. The Unicar array Three would other advance puralish go the values defines the in the low-SNR regime. As a result, EDoF₂ remains a bouthtistrating ED6F, CAR-MED4P, lincking pregise platsidal interpretations for the office are different eded to establish a mone Frigory and Frig. proceed however at ED bing and ED big in functions of the Mildace, respectively. To differentiate before Palie: near field and faf feld regions lowe amaikathe Raylelell-distance if the bistheyidents. The trigues demonstrate that both EDuFrehigh EDuF example enhanced for either-findreakins the Paperture sizes of the transberiers thraceducing when think itisiumeertahtesto sustresilestatiun toithecombonfulcombilored regimispies ster supporting NPC at thout ble Bold Polition strom their gridparison to falling. of ?EahoFFigur ??e is -fhalt the Adur Vels 160 EDOF refollows similar trends worthose of EDoF i every booking the findings drow Figdres this aspect and gain a deeper unthestoanierical febris, presenteantexFigf nearfieldFigAP? dellectively underscore the substantial impact of near-field effectSummagmentingOtheloDloFsAindMaMid systems.isThese Dodings Dontri have Valuable in Sights ito sther understanding and designhof wiff Otsechnotogies, in Table ?? primarily pertain to point-to-point CAP-MIMO channels. However, investi-MATIGONGA USBON AND PROMOSING RESEAR CHAD WALCHENS in in this littlere. See Raw Eddauster Pan Indeed to the stream to tino the pernotical common NAC montion but pentioned. we practical implementation of a particle health which METELPSPED INTENTO INTERCEPTION IN THE PROPERTY IN THE PROPERT ear lose expisition for the male high the himmer of apachy. MNext wer langifyzed and compared three DoF-related performance metrics, namely EDoF1, EDoF2, and EDoF3, to their farfield counterparts for demonstrating Pheusuperiority of NFC in terms of spatial multiplexing and channel capacity. To further explore the potential of MIMO NFC, we extended these results of softered by MIMO NFC through computer simulations to CAP-MIMO to determine the upper limit of performance. We have deepened the understanding of the augmented spatial DoFs offered by the near-field effect, with the hope of inspiring further in the still numerous open resparch problems in this Darra, avhich Darr summarized from three aspects the increased DoFs provided by the near-field effec DoSpBas@dallnformalfog-Theoretic phimitst. The Dolgustan valuesignificant inflormationstheoreticameasure difficulyntelated distatecehandl papabitys Exploring the DoFaldychthaeterize of NIEC fundamentals the foliable of the fundamentals of the fundamental of the fundament by FinCluding desiving the sachley abbF DoF relgible, can phowide

EDoF₁. From Fig. ??, we can infer that as the number of autsennial incremes, for existent designue Additionality, the changel-seitne fof capacity capproaching by transmission xpetiences slightoinne or from the Dotth of Dective or considers a residuable its uppleadinit (as calculated in [?]). Additionally, it is note Dort Braske Persberitere li Andissas Armsulte our ahabbas EDolhas Concentrated and boint notion in MINO (NFC) extends DoFiguhoucementigations to multiuser scenarios holds the

Figorentialesontoffeling logical participation of the Figure 1 the iDaFsinkhale comptex contraintention is been specificated as increasoron For a vehue Plot MIMO research good ditionally white whicheuristic inature of EDDF 2 and the Computational thats converges inocatest aringe EDpFly6p CAPIMINO decessing Remarkablyress alenierred in the derive her SPiDe MAMCahawing half-prevalenst land presence as positions around these positives and presence as positions around the second contractions. saureDot Prispired Bearforming Design: Effective bearingorm? indicate designs are singular for dutty harmousing the incretised σ₁ ≈DoFs offerend by NFC7Hhowever>the computational hand. EDofhargwake compressmessed-particular rolum of EDofatexThis obse CAPOMINIO implementation i pase frigmificient challenges.

In Thisrefore, Where is a pressing need to exist rescalable and Obserom phration draids at heelftelted is beaution hingerecling test furthmatvalarlateignothethischerieftis nearlighentetet DoFsirin proversement proverse ditionally, we note that in the high-SNR regime, EDoF₃ can exceed EDoF₁ and EDoF₂. This phenomenon arises because the non-dominant subchannels can also suppreferences communications, when sufficient transmit power resources are available.

Y. Liu et al., "Near-field communications: A tutorial review," arXiv preprint arXiv:2305.17751, Accessed on 25 Jul. 2023.

B2] CMAR: uMIZM Wu, Y. Lu, X. Wei, and L. Dai, "Near-field MIMO Figure tions for 6G: Fundamentals, challenges, potentials, and future Figure tions of the College Walls was vol. of the first pp. 40-40. Jan. 2023. spatemaschue to vikeacomputational opwplexity onecosiated with Cambridge till K. them bridge blue a Brees t 2005 CAP - MIMO [?]. well for the street of the str and the representation results for a Dofa are confitted.

[5] nDF Dard 30, action biggicating with sharewinesting entropy faces a drumbor of as full limits and models little distance, respectively. To differ entiates between the mean field pand darsfield regions dars dem Trestrate that both E50 136 aft 600 can be enhanced by exhibit periodic and figure and the first state of the first state or reducing at heighath release, not. 70, hep-8935-8949; e2023 lign with

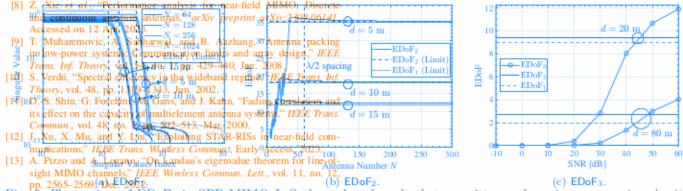


Fig. 3: Illustration of the belonging Schmid McCellos nearmels, where both transmitter and receiver are equipped with uniform in the half pressure in the ha

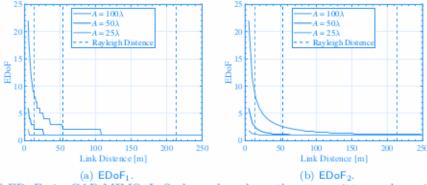


Fig. 4: Illustration of EDoFs in CAP-MIMO LoS channels, where the transmitter and receiver are equipped with continuous linear arrays of the same aperture size A, and the system operates at a frequency of 28 GHz (with a corresponding wavelength of $\lambda=1$ cm). The center of the transmitter is located at the origin of a three-dimensional plane, while the center of the receiver is at (0,d,0) with d denoting the link distance. The linear arrays face each other and are parallel to the z-axis.

commonly employed techniques for supporting NFC. A notable observation from the comparison of Fig. ?? and Fig. ?? is that the curves for EDoF₁ follow similar trends to those of EDoF₂, corroborating the findings from Fig. ??

The numerical results presented in Fig. ?? and Fig. ?? collectively underscore the substantial impact of near-field effects on augmenting the DoFs in MIMO systems. These findings contribute valuable insights to the understanding and design of NFC technologies.

V. Conclusion and Promising Research Directions

In this article, we have conducted an in-depth investigation into the performance of MIMO NFC from a DoF perspective. We began by elucidating the spatial DoFs achievable in near-field SPD-MIMO and exploring how these increased DoFs can be exploited for enhancing the channel capacity. Next, we analyzed and compared three DoF-related performance metrics, namely EDoF₁, EDoF₂, and EDoF₃, to their far-field counterparts for demonstrating the superiority of NFC in terms of spatial multiplexing and channel capacity. To further explore the potential of MIMO NFC, we extended these results to

CAP-MIMO to determine the upper limit of performance. We have deepened the understanding of the augmented spatial DoFs offered by the near-field effect, with the hope of inspiring further innovations in this field. There are still numerous open research problems in this area, which are summarized from three aspects.

- DoF-Based Information-Theoretic Limits: The DoF is a significant information-theoretic measure directly related to channel capacity. Exploring the DoF to characterize the fundamental information-theoretic limits of NFC, including deriving the achievable DoF region, can provide essential insights for system design. Additionally, the pursuit of capacityapproaching transmission schemes for NFC from a DoF perspective represents a valuable endeavor.
- DoF-Based Performance Analysis: Although our analysis has concentrated on point-to-point MIMO NFC, extending our investigations to multiuser scenarios holds the potential of offering valuable insights into the spatial DoFs in more complex communication setups, presenting a promising avenue for future research. Additionally, the heuristic nature of EDoF2