

Distributed Collaborative Beamforming Design in Highly-Scattered Environments

Sim Zaidi, Bouthaina Hmidet, and Sofiène Affes
 INRS-EMT, Université du Québec, Montreal, QC, H5A 1K6, Canada,
 Email: {zaidi,hmidet,affes}@emt.inrs.ca

Abstract—In this paper, we consider a collaborative beamformer (CB) design that achieves a dual-hop communication from a source to a receiver in highly-scattered environments, through a wireless network comprised of K independent terminals. The weights of the considered CB design at these terminals, derived to maximize the received signal-to-noise ratio (SNR) subject to constraint over the terminals' total transmit power, have expressions that inevitably depend on some form of the channel state information (CSI). Only those requiring the local CSI (LCSI) available at their respective terminals lend themselves to a truly distributed implementation. The latter has the colossal advantage of significantly minimizing the huge overhead resulting otherwise from non-local CSI (NLCSI) exchange required between terminals, which becomes prohibitive for large K and/or high Doppler. We derive the closed-form expression of the SNR-optimal CB (OCB) and verify that it is a NLCSI-based design. Exploiting, however, the polychromatic (i.e., multi-ray) structure of scattered channels as a superposition of L impinging rays or chromatics, we propose a novel LCSI-based distributed CB (DCB) design that requires a minimum overhead cost and, further, performs nearly as well as its NLCSI-based OCB counterpart. Furthermore, we prove that the proposed LCSI-based DCB outperforms two other DCB benchmarks: the monochromatic (i.e., single-ray) DCB (M-DCB) whose design ignores the presence of scattering and the bichromatic (i.e., two-ray) DCB (B-DCB) which relies on an efficient polychromatic-channel approximation by two rays when the angular spread is relatively small.

Index Terms—Distributed collaborative beamforming (CB, DCB), relaying, MIMO, scattering, device/machine-2-device/machine (D2D/M2M) communications, wireless sensor networks (WSN).

I. INTRODUCTION

Due to its strong potential in increasing link reliability, transmission coverage, and wireless networks capacity, collaborative beamforming (CB) has garnered the attention of the research community [1]-[12]. The so far proposed CB designs could be broadly categorized as either the local CSI (LCSI)-based (i.e., distributed) CB namely the monochromatic DCB (M-DCB) and the bichromatic DCB (B-DCB), or the non-local CSI (NLCSI)-based (i.e., non-distributed) CB namely the optimal CB. When designing M-DCB, authors in [1]-[12] ignored scattering present in almost all real-world scenarios but very few ones with both practical and investigation values in which they have consequently assumed a simple monochromatic (i.e., single-ray) channel. In scattered

channels, however, said to be polychromatic (i.e., multi-ray) and characterized by the angular spread (AS) [13]-[17], due to channel mismatch, the performance of M-DCB slightly deteriorates in areas where the AS is small and becomes unsatisfactory when it grows large [18]-[23]. In contrast, B-DCB in [22] and [23] which accounts for scattering by an efficient two-ray approximation of the polychromatic channel at relatively low AS not only outperforms M-DCB, but also achieves the optimal performance at small to moderate AS values in lightly- to moderately-scattered environments. Nevertheless, its performance substantially deteriorates at large in highly-scattered environments [22] [23]. OCB which is able to achieve optimal performance even in highly-scattered environments is NLCSI-based and cannot be implemented in a truly distributed fashion over a network of independent wireless terminals [24]. Indeed, the latter must estimate and broadcast their own channels at the expense of an overhead that becomes prohibitive for a large number of terminals and/or high Doppler [24], [25]. The aim of this work is then to design a novel DCB technique implementation that requires a minimum overhead cost and, further, is able to achieve optimal performance for any AS values, thereby pushing farther the frontier of the DCB's real-world applicability range to include highly-scattered environments.

In this paper, we consider an OCB design whose weights are derived to maximize the received SNR subject to constraint over the terminals' total transmit power, to achieve a dual-hop communication from a source to a receiver in highly-scattered environments, through a wireless network comprised of K independent terminals. We verify that the direct implementation of the so-obtained OCB is NLCSI-based. Exploiting, the polychromatic structure of scattered channels, we propose a novel DCB LCSI-based implementation that requires a minimum overhead cost and, further, performs nearly as well as its NLCSI-based OCB counterpart. Furthermore, we prove that the proposed LCSI-based DCB always outperforms M-DCB which is designed without accounting for scattering and that it is more robust against scattering than B-DCB whose performance substantially deteriorates in highly-scattered environments.

The rest of this paper is organized as follows. The system model is described in Section II. Section III derives the power-constrained SNR-optimal CB design in closed-form and verifies that its direct implementation is NLCSI-based. Our novel DCB implementation is proposed in Section IV.

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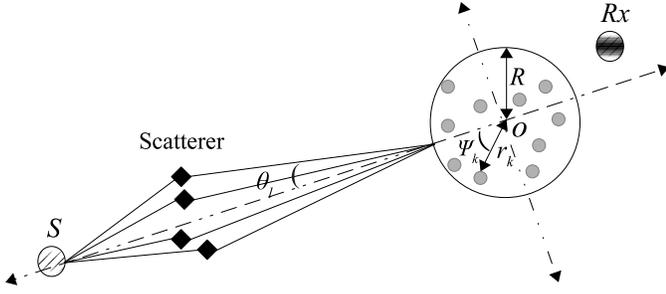


Fig. 1. System model.

Section V analyzes its performance while Section VI verifies by computer simulations the theoretical results. Concluding remarks are given in Section VII.

Notation: Uppercase and lowercase bold letters denote matrices and column vectors, respectively. $[\cdot]_{il}$ and $[\cdot]_i$ are the (i, l) -th entry of a matrix and i -th entry of a vector, respectively. \mathbf{I}_N is the N -by- N identity matrix. $(\cdot)^T$ and $(\cdot)^H$ denote the transpose and the Hermitian transpose, respectively. $\|\cdot\|$ is the 2-norm of a vector and $|\cdot|$ is the absolute value. $\mathbb{E}\{\cdot\}$ stands for the statistical expectation and $(\xrightarrow{ep1})$ denotes (element-wise) convergence with probability one. $J_1(\cdot)$ is the first-order Bessel function of the first kind, $\text{Ei}(\cdot)$ is the exponential integral function, and \odot is the element-wise vector product.

II. SYSTEM MODEL

Consider a wireless network comprised of K single-antenna terminals uniformly and independently distributed on the disc $D(O, R)$. A source S and a receiver Rx are located in the same plane containing $D(O, R)$, as illustrated in Fig. 1. Due to high pathloss attenuation, we assume that there is no direct link from S to Rx . Let (r_k, ψ_k) denote the polar coordinates of the k -th terminal and (A_s, ϕ_s) denote those of the source. The latter is assumed, without loss of generality, to be at $\phi_s = 0$ and to be located relatively far from the terminals, i.e., $A_s \gg R$.

Furthermore, the following assumptions are considered throughout the paper:

A1) The source is scattered by a given number of scatterers located in the same plane containing $D(O, R)$. The latter generate from the transmit signal L rays or "spatial chromatics" (with reference to their angular distribution) that form a polychromatic propagation channel [15]-[18]. The l -th ray or chromatic is characterized by its angle deviation θ_l from the source direction ϕ_s and its complex amplitude $\alpha_l = \rho_l e^{j\varphi_l}$ where the amplitudes ρ_l , $l = 1, \dots, L$ and the phases φ_l , $l = 1, \dots, L$ are independent and identically distributed (i.i.d.) random variables, and each phase is uniformly distributed over $[-\pi, \pi]$. The θ_l , $l = 1, \dots, L$ are i.i.d. zero-mean random variables with a symmetric probability density function (pdf) $p(\theta)$ and variance σ_θ^2 [13], [15], [16]. All θ_l s, φ_l s, and ρ_l s are mutually independent. All rays have equal power $1/L$ (i.e., $\mathbb{E}\{|\alpha_l|^2\} = 1/L$). Note that the standard

deviation σ_θ is commonly known as the angular spread (AS) while $p(\theta)$ is called the scattering or angular distribution. We are particularly interested here in addressing highly-scattered environments.

A2) The terminals' forward channels to the receiver $[\mathbf{f}]_k$, $k = 1, \dots, K$ are zero-mean unit-variance circular Gaussian random variables [9], [11].

A3) The source signal s is narrow-band with unit power while noises at the terminals and the receiver are zero-mean Gaussian random variables with variances σ_v^2 and σ_n^2 , respectively. The source signal, noises, and the terminals' forward channels are mutually independent [9], [11], [12], [26].

A4) The k -th terminal is aware of its own coordinates (r_k, ψ_k) , its forward channel $[\mathbf{f}]_k$, its backward channel $[\mathbf{g}]_k$, and the wavelength λ while being oblivious to the locations and the forward channels of *all* other terminals in the network [1]-[5], [11], [12].

Due to A1 and the fact that $A_s \gg R$, it can be shown that the backward channel gain from the source to the k -th terminal can be represented as

$$[\mathbf{g}]_k = \sum_{l=1}^L \alpha_l e^{-j \frac{2\pi}{\lambda} r_k \cos(\theta_l - \psi_k)}. \quad (1)$$

Obviously, in the conventional scenario where the scattering effect is neglected (i.e., $\sigma_\theta \rightarrow 0$) to assume a monochromatic plane-wave propagation channel, we have $\theta_l = 0$ and, hence, $[\mathbf{g}]_k$ can be reduced to $[\mathbf{g}_1]_k = e^{-j(2\pi/\lambda)r_k \cos(\psi_k)}$, the well-known steering vector in the array-processing literature [1]-[12], [19]-[25].

As can be observed from (1), the summation of L chromatics causes a variation, with a particular channel realization, of the received power at the k -th terminal. The channel is then said to experience a form of fading. When L is large, according to the Central Limit Theorem, the distribution of the channel gain $[\mathbf{g}]_k$ approaches a Gaussian. Since, according to A1, $\mathbb{E}\{\alpha_l\} = 0$ for $l = 1, \dots, L$, then $[\mathbf{g}]_k$ is a zero-mean Gaussian random variable and, hence, its magnitude is Rayleigh distributed. Therefore, when L is large enough (practically in the range of 10), the channel from the source to the k -th terminal is nothing but a Rayleigh channel. It can also be observed from (1) that we did not take into account any line-of-sight (LOS) component in our channel model. If this were the case, $[\mathbf{g}]_k$'s distribution would approach a non-zero mean Gaussian distribution and the channel would become Rician.

A dual-hop communication is established from the source S to the receiver Rx . In the first time slot, S sends its signal s to the terminals while, in the second time slot, each terminal multiplies its received signal by a properly selected beamforming weight and forwards the resulting signal Rx . The received signal at the latter is given by

$$r = \mathbf{s} \mathbf{w}^H \mathbf{h} + \mathbf{w}^H (\mathbf{f} \odot \mathbf{v}) + n, \quad (2)$$

where $\mathbf{w} \triangleq [w_1 \dots w_K]$ is the beamforming vector with w_k being the k -th terminal's beamforming weight, $\mathbf{h} \triangleq \mathbf{f} \odot \mathbf{g}$

with $\mathbf{f} \triangleq [[\mathbf{f}]_1 \dots [\mathbf{f}]_K]^T$ and $\mathbf{g} \triangleq [[\mathbf{g}]_1 \dots [\mathbf{g}]_K]^T$, and \mathbf{v} and n are the terminals' noise vector and the receiver noise, respectively. Several CB designs exist in the literature but we are only concerned herein by the one which maximizes the received signal-to-noise ratio (SNR) subject to constraint over the terminals' total transmit power [26].

III. POWER-CONSTRAINED SNR-OPTIMAL CB

Let \mathbf{w}_O denote the power-constrained SNR-optimal CB, or simply OCB, which satisfies the following optimization problem:

$$\mathbf{w}_O = \arg \max \xi_{\mathbf{w}} \quad \text{s.t.} \quad P_T \leq P_{\max}, \quad (3)$$

where $\xi_{\mathbf{w}}$ is the achieved SNR using \mathbf{w} and $P_T = (1 + \sigma_v^2) \|\mathbf{w}\|^2$ is the terminals' total transmit power. From (2), $\xi_{\mathbf{w}}$ is given by

$$\xi_{\mathbf{w}} = \frac{P_{\mathbf{w},s}}{P_{\mathbf{w},n}}, \quad (4)$$

where $P_{\mathbf{w},s} = |\mathbf{w}^H \mathbf{h}|^2$ and $P_{\mathbf{w},n} = \sigma_v^2 \mathbf{w}^H \mathbf{\Lambda} \mathbf{w} + \sigma_n^2$ are, respectively, the desired and noise powers with $\mathbf{\Lambda} \triangleq \text{diag}\{|\mathbf{f}_1|^2 \dots |\mathbf{f}_K|^2\}$. Note that \mathbf{w}_O should satisfy the constraint in (3) with equality. Otherwise, one could find $\epsilon > 1$ such that $\mathbf{w}_\epsilon = \epsilon \mathbf{w}_O$ verifies $(1 + \sigma_v^2) \|\mathbf{w}_\epsilon\|^2 = P_{\max}$. In such a case, since $d\xi_{\mathbf{w}_\epsilon}/d\epsilon > 0$ for any $\epsilon > 0$, the SNR achieved by \mathbf{w}_ϵ would be higher than that achieved by \mathbf{w}_O contradicting thereby the optimality of the latter. As such, (3) could be rewritten as

$$\mathbf{w}_O = \arg \max \frac{\mathbf{w}^H \mathbf{h} \mathbf{h}^H \mathbf{w}}{\sigma_v^2 \mathbf{w}^H \tilde{\mathbf{\Lambda}} \mathbf{w}} \quad \text{s.t.} \quad (1 + \sigma_v^2) \|\mathbf{w}\|^2 = P_{\max}, \quad (5)$$

where $\tilde{\mathbf{\Lambda}} = \mathbf{\Lambda} + \beta \mathbf{I}$ and $\beta = \sigma_n^2(1 + \sigma_v^2)/(P_{\max})$. It is straightforward to show that the OCB solution of (5) is

$$\mathbf{w}_O = \left(\frac{P_{\max}}{K(1 + \sigma_v^2)\eta} \right)^{\frac{1}{2}} \tilde{\mathbf{\Lambda}}^{-1} \mathbf{h}, \quad (6)$$

where $\eta = (\mathbf{h}^H \tilde{\mathbf{\Lambda}}^{-2} \mathbf{h})/K$. Nevertheless, according to (6), OCB is a NLCSI-based design since the computation of its beamforming weight $[\mathbf{w}_O]_k$ at the k -th terminal depends on information unavailable locally, namely $[\mathbf{g}]_k$, $k = 1, \dots, K$ and $[\mathbf{f}]_k$, $k = 1, \dots, K$ as well as P_{\max}/K and σ_n^2/P_{\max} . In order to implement \mathbf{w}_O in the considered network, each terminal should then estimate its backward channel and broadcast it over the network along with its forward channel. This process results in an undesired overhead which becomes prohibitive especially for large K and/or high backward channel's Doppler, resulting thereby in substantial throughput losses [24]. Therefore, OCB is unsuitable for implementation in the network of interest, unless relatively exhaustive overhead exchange over the air were acceptable or if \mathbf{w}_O were to be implemented in conventional beamforming, i.e., over a unique physical terminal that connects to a K -dimensional distributed antenna system (DAS).

IV. PROPOSED DCB IMPLEMENTATION

In order to reduce the excessively large implementation overhead incurred by the NLCSI-based OCB, we resort to substitute η with a quantity that could be locally computed by all terminals at a negligible overhead cost. This quantity must also well-approximate η to preserve the optimality of the solution in (6). In this paper, we propose to use $\eta_D = \lim_{K \rightarrow \infty} \eta$ in lieu of η . First, we show that

$$\eta = \frac{1}{K} \sum_{k=1}^K \frac{|\mathbf{f}_k|^2}{(|\mathbf{f}_k|^2 + \beta)^2} \sum_{l=1}^L \sum_{m=1}^L \alpha_l \alpha_m^* e^{j4\pi \sin(\frac{\theta_l - \theta_m}{2}) z_k}, \quad (7)$$

where $z_k = (r_k/\lambda) \sin((\theta_l + \theta_m)/2 - \psi_k)$. Using the strong law of large numbers and the fact that r_k , ψ_k and $[\mathbf{f}]_k$ are all mutually statistically independent, we have

$$\eta_D = \lim_{K \rightarrow \infty} \eta \xrightarrow{p1} \rho_1 \sum_{l=1}^L \sum_{m=1}^L \alpha_l \alpha_m^* \Delta(\theta_l - \theta_m), \quad (8)$$

where $\rho_1 = \mathbb{E} \left\{ \frac{|\mathbf{f}_k|^2}{(|\mathbf{f}_k|^2 + \beta)^2} \right\} = -(1 + \beta)e^{\beta} \text{Ei}(-\beta) - 1$ and $\Delta(\phi) = \mathbb{E} \left\{ e^{j4\pi \sin(\phi/2) z_k} \right\}$. Note that to derive the closed-form expression of $\Delta(\phi)$, the z_k 's pdf $f_{z_k}(z)$ which is closely related to the terminals' spatial distribution is required. In this paper, we are only concerned by the main distributions frequently used in the context of collaborative beamforming that are: Uniform distribution and Gaussian distribution. It can be shown that [1], [2]

$$f_{z_k} = \begin{cases} \frac{2\lambda}{R\pi} \sqrt{1 - \left(\frac{\lambda}{R} z\right)^2}, & -\frac{R}{\lambda} \leq z \leq \frac{R}{\lambda} & \text{Uniform} \\ \frac{\lambda}{\sqrt{2\pi}\sigma} e^{-\frac{(\lambda z)^2}{2\sigma^2}}, & -\infty \leq z \leq \infty & \text{Gaussian} \end{cases}, \quad (9)$$

where σ^2 is the variance of the Gaussian random variables corresponding to the terminals' cartesian coordinates. Using (9) we obtain

$$\Delta(\phi) = \begin{cases} 2 \frac{J_1(4\pi \frac{R}{\lambda} \sin(\phi/2))}{4\pi \frac{R}{\lambda} \sin(\phi/2)}, & \phi \neq 0 & \text{Uniform} \\ 1, & \phi = 0 & \\ e^{-8(\pi \frac{\sigma}{\lambda} \sin(\phi/2))^2}, & & \text{Gaussian} \end{cases}. \quad (10)$$

Substituting η with η_D in (6), we introduce

$$\mathbf{w}_P = \left(\frac{P_{\max}}{K(1 + \sigma_v^2)\eta_D} \right)^{\frac{1}{2}} \tilde{\mathbf{\Lambda}}^{-1} \mathbf{h}, \quad (11)$$

the beamforming vector of our proposed DCB. From (11), in contrast with $[\mathbf{w}_O]_k$, the k -th terminal's beamforming weight $[\mathbf{w}_P]_k$ solely depends on the forward and backward channels $[\mathbf{f}]_k$ and $[\mathbf{g}]_k$, respectively, which can be locally estimated. Therefore, according to (11), the proposed beamformer is a LCS-based design that requires only a negligible overhead that does not grow neither with K nor with the Doppler, namely P_{\max}/K , σ_n^2/P_{\max} , and R or σ depending on the terminals' spatial distribution. Consequently, the proposed LCS-based DCB is much more suitable for a distributed implementation over the considered network than its NLCSI-based OCB counterpart. Furthermore, we will prove in the

sequel that it performs nearly as well as the latter even for a relatively small number of terminals. We will also compare it with two other LCS-based DCB benchmarks, namely M-DCB and the recently developed B-DCB. The former's design ignores scattering and assumes a monochromatic channel and, hence, its CB solution reduces from (11) to

$$\mathbf{w}_M = \left(\frac{P_{\max}}{K(1+\sigma_v^2)\rho_1} \right)^{\frac{1}{2}} \tilde{\mathbf{\Lambda}}^{-1} \mathbf{a}(0), \quad (12)$$

where $\mathbf{a}(\phi) \triangleq [[\mathbf{a}(\theta)]_1 \dots [\mathbf{a}(\theta)]_K]^T$ with $[\mathbf{a}(\theta)]_k = [\mathbf{f}]_k e^{-j(2\pi/\lambda)r_k \cos(\theta-\psi_k)}$. In turn, the B-DCB design whose CB solution is given by

$$\mathbf{w}_{BD} = \left(\frac{P_{\max}}{K(1+\sigma_v^2)\rho_1} \right)^{\frac{1}{2}} \frac{\tilde{\mathbf{\Lambda}}^{-1} (\mathbf{a}(\sigma_\theta) + \mathbf{a}(-\sigma_\theta))}{(1 + \Delta(2\sigma_\theta))}, \quad (13)$$

relies on a polychromatic channel's approximation by two chromatics at $\pm\sigma_\theta$ when the latter is relatively small. Note that from (12) and (13) both \mathbf{w}_M and \mathbf{w}_{BD} depends on the information commonly available at each terminal and, hence, are also suitable for a distributed implementation.

V. PERFORMANCE ANALYSIS OF THE PROPOSED DCB

Let $\tilde{\xi}_{\mathbf{w}} = \mathbb{E}\{P_{\mathbf{w},s}/P_{\mathbf{w},n}\}$ be the achieved average SNR (ASNR) using the CB vector \mathbf{w} . Note that the expectation is taken with respect to r_k , ψ_k and $[\mathbf{f}]_k$ for $k = 1, \dots, K$ and α_l and θ_l for $l = 1, \dots, L$. Since to the best of our knowledge, $\tilde{\xi}_{\mathbf{w}}$ for $\mathbf{w} \in \{\mathbf{w}_P, \mathbf{w}_O, \mathbf{w}_M\}$ is untractable in closed-form thereby hampering a its study rigorously, we propose to adopt the average-signal-to-average-noise ratio (ASANR) $\tilde{\xi}_{\mathbf{w}} = \mathbb{E}\{P_{\mathbf{w},s}\}/\mathbb{E}\{P_{\mathbf{w},n}\}$ as a performance measure instead to gauge the proposed DCB against its benchmarks.

A. Proposed DCB vs M-DCB

Following derivation steps similar to those in [22, Appendix A] and exploiting the fact that, according to A1, we have

$$\mathbb{E}\{\alpha_l^* \alpha_m\} = \begin{cases} 0 & l \neq m \\ \frac{1}{L} & l = m \end{cases}, \quad (14)$$

we obtain $\mathbb{E}\{P_{\mathbf{w}_P,s}\} = \frac{P_{\max}}{(1+\sigma_v^2)\rho_1} (\rho_2 + (K-1)\rho_3^2)$ where $\rho_2 = \mathbb{E}\{|\mathbf{f}|_k|^4 / (|\mathbf{f}|_k|^2 + \beta)^2\} = 1 + \beta + \beta(2 + \beta)e^\beta \text{Ei}(-\beta)$ and $\rho_3 = \mathbb{E}\{|\mathbf{f}|_k|^2 / (|\mathbf{f}|_k|^2 + \beta)\} = 1 + \beta e^\beta \text{Ei}(-\beta)$. Furthermore, to derive $\mathbb{E}\{P_{\mathbf{w}_P,n}\}$, one must first take the expectation only over the r_k s, ψ_k s and $[\mathbf{f}]_k$ s yielding to

$$\begin{aligned} \mathbb{E}\{P_{\mathbf{w}_P,n}\} &= \mathbb{E}_{\alpha_l, \theta_l} \left\{ \frac{\sigma_v^2 P_{\max} \rho_2 \sum_{l,m=1}^L \alpha_l \alpha_m^* \Delta(\theta_l - \theta_m)}{(1 + \sigma_v^2) \eta_D} \right\} + \sigma_n^2 \\ &= \sigma_v^2 \frac{P_{\max} \rho_2}{(1 + \sigma_v^2) \rho_1} + \sigma_n^2. \end{aligned} \quad (15)$$

It directly follows from the latter results that the achieved ASANR using the proposed DCB is

$$\tilde{\xi}_{\mathbf{w}_P} = \frac{\rho_2 + (K-1)\rho_3^2}{\sigma_v^2 (\rho_2 + \beta\rho_1)}. \quad (16)$$

As can be observed from (16), $\tilde{\xi}_{\mathbf{w}_P}$ linearly increases with the number of terminals K . More importantly, from the latter

result, $\tilde{\xi}_{\mathbf{w}_P}$ does not depend on the AS σ_θ meaning that the proposed DCB's performance is not affected by the scattering phenomenon even in highly-scattered environments where σ_θ is large.

Now, let us focus on the achieved ASANR $\tilde{\xi}_{\mathbf{w}_M}$ using M-DCB. Following the same approach above, one can prove that

$$\tilde{\xi}_{\mathbf{w}_M} = \frac{\rho_2 + (K-1)\rho_3^2 \int_{\Theta} p(\theta) \Delta^2(\theta) d\theta}{\sigma_v^2 (\rho_2 + \beta\rho_1)}, \quad (17)$$

where Θ is the span of the pdf $p(\theta)$ over which the integral is calculated¹. Since $\Delta(0) = 1$ regardless of the terminals spatial distribution, it follows from (16) and (17) that when there is no scattering (i.e., $\sigma_\theta = 0$), $\tilde{\xi}_{\mathbf{w}_M} = \tilde{\xi}_{\mathbf{w}_P}$. In such a case, indeed, $\mathbf{w}_P = \mathbf{w}_M \sum_{l=1} \alpha_l / \sqrt{\sum_{l=1} \alpha_l \sum_{m=1} \alpha_m^*}$ and, hence, $P_{\mathbf{w}_P,s} = P_{\mathbf{w}_M,s} \sum_{l=1} \alpha_l \sum_{m=1} \alpha_m^*$. Since according to (14) $\mathbb{E}\{\sum_{l=1} \alpha_l \sum_{m=1} \alpha_m^*\} = 1$, we have $\mathbb{E}\{P_{\mathbf{w}_P,s}\} = \mathbb{E}\{P_{\mathbf{w}_M,s}\}$. Furthermore, it is straightforward to show that $P_{\mathbf{w}_P,n} = P_{\mathbf{w}_M,n}$ when $\sigma_\theta = 0$ and, therefore, M-DCB achieves the same ASANR as the proposed DCB when there is no scattering. This is in fact expected since the assumption of monochromatic channel made when designing the monochromatic solution is valid in such a case. Nevertheless, assuming that the terminals's spatial distribution and the scattering distribution $p(\theta)$ are both Uniform, it can be shown for relatively small AS that [27]

$$\tilde{\xi}_{\mathbf{w}_M} \simeq \frac{\rho_2 + (K-1)\rho_3^2 {}_3F_4\left(\frac{1}{2}, 2, \frac{3}{2}; \frac{3}{2}, 2, 2, 3, -12\pi^2 \left(\frac{R}{\lambda}\right)^2 \sigma_\theta^2\right)}{\sigma_v^2 (\rho_2 + \beta\rho_1)}, \quad (18)$$

where ${}_3F_4\left(\frac{1}{2}, 2, \frac{3}{2}; \frac{3}{2}, 2, 2, 3, -12\pi^2 (R/\lambda)^2 x^2\right)$ is a decreasing function of x whose peak is reached at 0 known as hypergeometric function. It can be inferred from (18), that the ASANR achieved by the M-DCB decreases when the AS σ_θ and/or R/λ increases. This is in contrast with the proposed DCB whose ASANR remains constant for any σ_θ and R/λ . Therefore, the proposed DCB is more robust against scattering than M-DCB whose design ignores the presence of scattering thereby resulting in a channel mismatch that causes severe ASANR deterioration.

B. Proposed DCB vs B-DCB

It can be shown that the achieved ASANR using B-DCB is given by [22]

$$\tilde{\xi}_{\mathbf{w}_{BD}} = \frac{2\rho_2 + \frac{(K-1)\rho_3^2}{(1+\Delta(2\sigma_\theta))} \int_{\Theta} p(\theta) (\Delta(\theta+\sigma_\theta) + \Delta(\theta-\sigma_\theta))^2 d\theta}{\sigma_v^2 (\rho_2 + \beta\rho_1) (1 + \Delta(2\sigma_\theta))}. \quad (19)$$

It follows from (19) that when there is no scattering (i.e., $\sigma_\theta = 0$), $\tilde{\xi}_{\mathbf{w}_{BD}}$ boils down as expected to its maximum level $\tilde{\xi}_{\mathbf{w}_P}$, regardless the terminals spatial distribution. Since, as has been shown in [22] and [23], B-DCB is able to achieve its maximum ASANR level for small to moderate AS values such as in lightly- to moderately-scattered environments, it turns out that the proposed DCB and its B-DCB counterpart achieve

¹In the Gaussian and Uniform distribution cases, $\Theta = [-\text{inf}, +\text{inf}]$ and $\Theta = [-\sqrt{3}\sigma_\theta, +\sqrt{3}\sigma_\theta]$, respectively.

the same ASANR in such environments. However, when σ_θ is large such as in highly-scattered environments, using the fact that $\Delta(2\sigma_\theta) \simeq 0$ for large σ_θ , one can easily show that $\lim_{K \rightarrow \infty} \tilde{\xi}_{\mathbf{w}_{\text{BD}}} / \tilde{\xi}_{\mathbf{w}_{\text{P}}} = \int_{\Theta} p(\theta) (\Delta(\theta + \sigma_\theta) + \Delta(\theta - \sigma_\theta))^2 d\theta$. Since the right-hand side (RHS) of the latter equality is a decreasing function of σ_θ , the ASANR gain achieved by the proposed DCB against B-DCB increases with the latter. Consequently, in highly-scattered environments where the AS is large, the proposed DCB outperforms B-DCB whose performance deteriorates due to the channel mismatch.

C. Proposed DCB vs OCB

As $P_{\mathbf{w}_{\text{O}},s}$ and $P_{\mathbf{w}_{\text{O}},n}$ are a very complicated functions of several random variables, it turns out that it is impossible to derive the ASANR $\tilde{\xi}_{\mathbf{w}_{\text{O}}}$ in closed-form. However, a very interesting result could be obtained for large K . Indeed, one can show that

$$\begin{aligned} \lim_{K \rightarrow \infty} \frac{\tilde{\xi}_{\mathbf{w}_{\text{O}}}}{\tilde{\xi}_{\mathbf{w}_{\text{P}}}} &= \frac{(\rho_2 + \beta\rho_1) \mathbb{E} \left\{ \frac{1}{\eta_{\text{D}}} \left(\lim_{K \rightarrow \infty} \frac{\mathbf{h}^H \tilde{\Lambda}^{-1} \mathbf{h}}{K} \right)^2 \right\}}{\rho_3^2 \left(\mathbb{E} \left\{ \frac{1}{\eta_{\text{D}}} \lim_{K \rightarrow \infty} \frac{\mathbf{h}^H \tilde{\Lambda}^{-1} \tilde{\Lambda} \tilde{\Lambda}^{-1} \mathbf{h}}{K} \right\} + \beta \right)} \\ &\xrightarrow{p1} \frac{(\rho_2 + \beta\rho_1) \mathbb{E} \left\{ \left(\sum_{l,m=1}^L \alpha_l \alpha_m^* \Delta(\theta_l - \theta_m) \right) \right\}}{\frac{\rho_2}{\rho_1} + \beta} = 1, \end{aligned} \quad (20)$$

where the third line exploits (14) while the second exploits the law of large numbers by which we can prove that $\lim_{K \rightarrow \infty} \mathbf{h}^H \tilde{\Lambda}^{-1} \mathbf{h} / K = \rho_3 \sum_{l,m=1}^L \alpha_l \alpha_m^* \Delta(\theta_l - \theta_m)$ and $\lim_{K \rightarrow \infty} \mathbf{h}^H \tilde{\Lambda}^{-1} \tilde{\Lambda} \tilde{\Lambda}^{-1} \mathbf{h} / K = \rho_2 \sum_{l,m=1}^L \alpha_l \alpha_m^* \Delta(\theta_l - \theta_m)$. For large K , the latter result proves that the proposed LCSi-based DCB is able to achieve the same ASANR as the NLCSi-based OCB and, therefore, is able to reach optimality for any AS value. This further proves the efficiency of the proposed DCB.

Using the same method as in (20), one can easily show that $\lim_{K \rightarrow \infty} \tilde{\xi}_{\mathbf{w}} / \bar{\xi}_{\mathbf{w}} \xrightarrow{p1} 1$ for $\mathbf{w} \in \{\mathbf{w}_{\text{P}}, \mathbf{w}_{\text{O}}, \mathbf{w}_{\text{M}}\}$. Therefore, all the above results hold also for the ASANR as K grows large.

VI. SIMULATION RESULTS

All the empirical average quantities, in this section, are obtained by averaging over 10^6 random realizations of all random variables. In all simulations, the number of rays or chromatics is $L = 10$ and the noises' powers σ_n^2 and σ_v^2 are 10 dB below the source transmit power $p_s = 1$ power unit on a relative scale. We also assume that the scattering distribution is uniform (i.e., $p(\theta) = 1/(2\sqrt{3}\sigma_\theta)$) and that α_l s are circular Gaussian random variables. For fair comparisons between the Uniform and Gaussian spatial distributions, we choose $\sigma = R/3$ to guarantee in the Gaussian distribution case that more than 99% of terminals are located in $D(O, R)$.

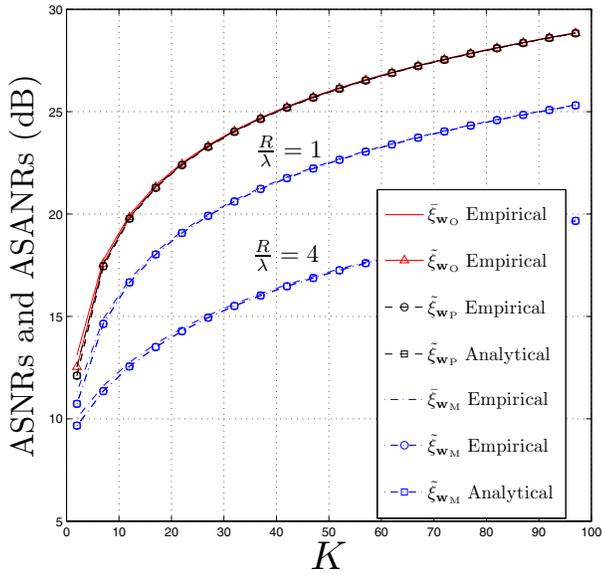
Fig. 2 plots the empirical ASNRs and ASANRs achieved by $\mathbf{w} \in \{\mathbf{w}_{\text{O}}, \mathbf{w}_{\text{P}}, \mathbf{w}_{\text{M}}\}$ as well as the analytical ASANRs achieved by \mathbf{w}_{P} and \mathbf{w}_{M} versus K for $\sigma_\theta = 20$ (deg) and $R/\lambda = 1, 4$. The terminals' spatial distribution is assumed to be Uniform in Fig. 2(a) and Gaussian in Fig. 2(b). From these

figures, we confirm that the analytical $\tilde{\xi}_{\mathbf{w}_{\text{P}}}$ and $\tilde{\xi}_{\mathbf{w}_{\text{M}}}$ match perfectly their empirical counterparts. As can be observed from these figures, the proposed DCB outperforms M-DCB in terms of achieved ASANR. Furthermore, the ASANR gain achieved using the proposed DCB instead of the latter substantially increases when R/λ grows large. Moreover, from Figs. 2(a) and 2(b), the achieved ASANR using the proposed LCSi-based DCB fits perfectly with that achieved using NLCSi-based OCB, which is unsuitable for a distributed implementation, when K is in the range of 20 while it loses only a fraction of a dB when K is in the range of 5. This proves that the proposed DCB is able to reach optimality when K is large enough. It can be also verified from these figures that $\tilde{\xi}_{\mathbf{w}_{\text{P}}}$ and $\tilde{\xi}_{\mathbf{w}_{\text{B}}}$ perfectly match $\bar{\xi}_{\mathbf{w}_{\text{P}}}$ and $\bar{\xi}_{\mathbf{w}_{\text{M}}}$, respectively, for $K = 20$. All these observations corroborate the theoretical results obtained in Section V.

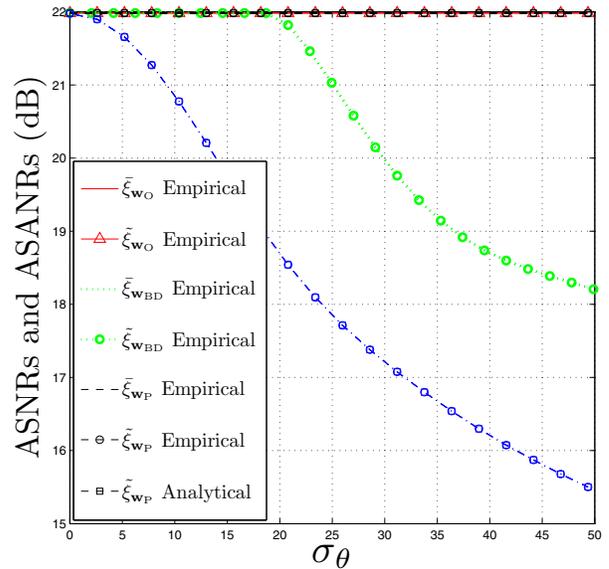
Fig. 3 displays the empirical ASNRs and ASANRs achieved by $\mathbf{w} \in \{\mathbf{w}_{\text{O}}, \mathbf{w}_{\text{BD}}, \mathbf{w}_{\text{P}}, \mathbf{w}_{\text{M}}\}$ as well as the analytical ASANRs achieved by \mathbf{w}_{P} and \mathbf{w}_{M} versus the AS for $K = 20$ and $R/\lambda = 1$. It can be observed from this figure that the ASANR achieved by M-DCB decreases with the AS while that achieved by the proposed beamformer remains constant. This corroborates again the theoretical results obtained in Section V. Furthermore, we observe from Fig. 3 that B-DCB achieves the same ASNR as the proposed DCB when the AS is relatively small such as in lightly- to moderately-scattered environments. Nevertheless, in highly-scattered environments where the AS is large (i.e., $\sigma_\theta \geq 20$ deg), the proposed DCB outperforms B-DCB whose performance further deteriorates as σ_θ grows large. This is expected since the two-ray channel approximation made when designing B-DCB is only valid for small σ_θ . Moreover, it can be noticed from Figs. 3(a) and 3(b), that the ASNR gain achieved using the proposed DCB instead of M-DCB and B-DCB can reach until about 6.5 (dB) and 4 (dB), respectively. From these figures, we also observe that the curves of $\tilde{\xi}_{\mathbf{w}_{\text{P}}}$ and $\tilde{\xi}_{\mathbf{w}_{\text{O}}}$ are indistinguishable. As pointed out above, this is due to the fact that both OCB and the proposed DCB constantly reach optimality.

VII. CONCLUSION

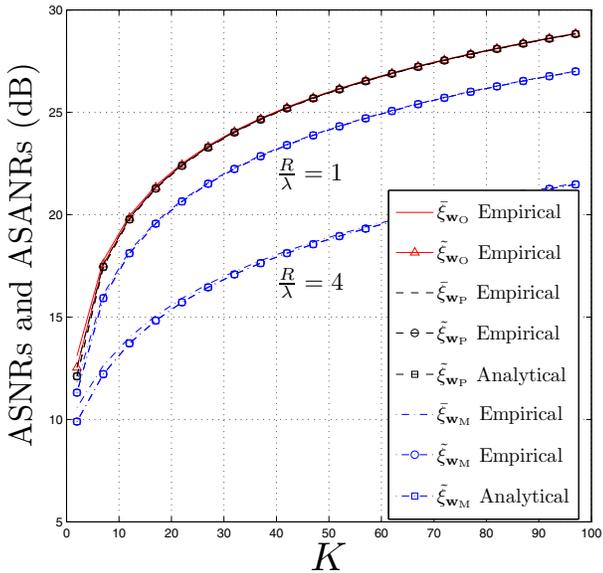
In this paper, we considered a power-constrained SNR-optimal CB design that achieves a dual-hop communication from a source to a receiver, through a wireless network comprised of K independent terminals. We verified that the direct implementation of this CB design is NLCSi-based. Exploiting the polychromatic structure of scattered channels, we proposed a novel LCSi-based DCB implementation that requires a minimum overhead cost and, further, performs nearly as well as its NLCSi-based OCB counterpart. Furthermore, we proved that the proposed DCB implementation always outperforms M-DCB which is designed without accounting for scattering and that it is more robust to scattering than B-DCB whose performance substantially deteriorates in highly-scattered environments.



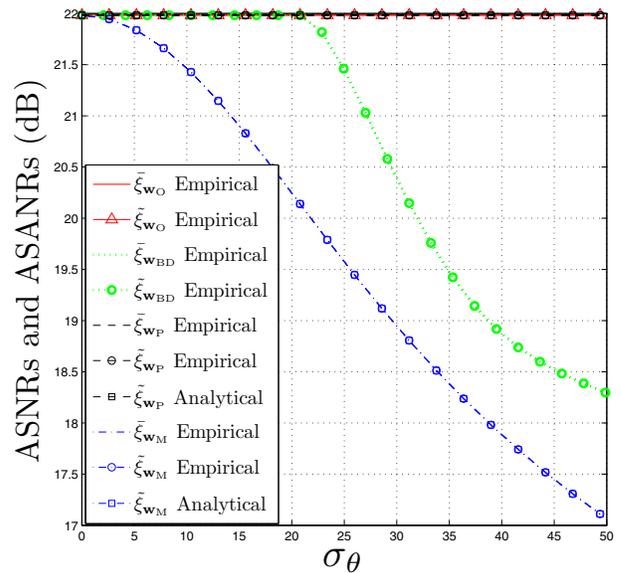
(a) Uniform distribution



(a) Uniform distribution



(b) Gaussian distribution



(b) Gaussian distribution

Fig. 2. The empirical ASNRs and ASANRs achieved by $\mathbf{w} \in \{\mathbf{w}_O, \mathbf{w}_P, \mathbf{w}_M\}$ as well as the analytical ASANRs achieved by \mathbf{w}_P and \mathbf{w}_M versus K for $\sigma_\theta = 20$ (deg) and $R/\lambda = 1, 4$ when the terminals' spatial distribution is (a): Uniform and (b): Gaussian.

Fig. 3. The empirical ASNRs and ASANRs achieved by $\mathbf{w} \in \{\mathbf{w}_O, \mathbf{w}_{BD}, \mathbf{w}_P, \mathbf{w}_M\}$ as well as the analytical ASANRs achieved by \mathbf{w}_P and \mathbf{w}_M versus σ_θ for $K = 20$ and $R/\lambda = 1$ when the terminals' spatial distribution is (a): Uniform and (b): Gaussian.

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