on condition of CSIR and no adaptation, similarly as in [10]. We define a class of alphabets avoiding all catastrophic parameters and reaching its upper-bound on minimal distance for all parameter values (denoted Uniformly Most Powerful (UMP)). The papers [11], [12] are also related, restricting, however, on non-coherent (no CSIR) complex-orthogonal Frequency Shift Keying (FSK) modulations.

The following contributions are provided:

1) EXclusive Code (XC) must fulfill certain conditions not to imply catastrophic parameters. Particularly, the XC matrix must be symmetric and the same symbols must lie on its main diagonal. Bit-wise XOR operation obeys these conditions and it is the only solution for binary and even quaternary alphabet. Hence, it is convenient to assume fixed XOR XC.

2) All non-binary linear modulations with one complex dimension (e.g. PSK, QAM) have inevitably catastrophic parameters and binary modulations not, even fulfilling the UMP condition. It is shown that non-binary UMP alphabets require more than a single complex dimension.

3) Non-binary complex orthogonal and non-binary complex bi-orthogonal modulations with XOR are UMP.

4) Non-linear frequency modulations FSK and full-response Continuous Phase Modulation (CPM) naturally comprise multiple complex dimensions needed to obey UMP condition. We optimize a scalar parameters of FSK (modulation index) and full-response CPM (frequency pulse shape) to yield UMP alphabets. We find that a lower modulation index (proportional to bandwidth) than that leading to complex orthogonal alphabet fulfills UMP condition. Numerical simulations conclude that the considered frequency modulations do not have catastrophic parameters and perform close to the utmost UMP alphabets which however require more bandwidth.

II. SYSTEM MODEL

A. Constellation Space Model and Used Notation

Let both terminals A and B in 2-WRC use the same modulation alphabet $\alpha$ with cardinality $|\alpha| = M_c$ to be strictly a power of two. We suppose that the alphabet is formed by complex arbitrary-dimensional baseband signals in the constellation space $\mathcal{A} = \{c_T | c_T | h \in \mathbb{C}^{N_t}, \text{where symbol} c_T \in \mathbb{Z}_{M_c} = \{0, 1, \ldots, M_c - 1\} \text{denotes a data symbol transmitted by terminal} T \in \{A, B\} \text{and} N_t \text{denotes the signal dimensionality. Linear modulations (e.g. PSK, QAM) have single complex dimension, i.e.} N_t = 1 \text{and their constellation vectors are complex scalars} s_c \in \mathbb{C}. \text{Later in this paper, we will use non-linear frequency modulations FSK and full-response CPM which are multidimensional and their dimensionality is} N_t = M_c; \text{the constellation space vectors are consequently} \mathbf{s}_c \in \mathbb{C}^{N_t}. \text{Without loss of generality, we assume memoryless constellation mapper} \mathcal{M} \text{such that it directly corresponds to the signal indexation,} \mathbf{s}_c = \mathcal{M}(c_T)$.

B. Model Assumptions

We assume a time-synchronized scenario with full CSIR which is obtained e.g. by preceding tracking of pilot signals.

The synchronization issues are beyond the scope of this paper and interested reader may see e.g. [13], [14] for further details. We restrict ourselves that adaptive techniques are not available either due to the missing feedback channel, increased system complexity, or unfeasible channel dynamics.

We consider per-symbol relaying (avoiding delay induced at the relay) and no channel coding which however can be additionally concatenated with our scheme [15].

C. Hierarchical-Decode-and-Forward Strategy

HDF strategy in 2-WRC consists of two stages, see Fig. 2. In the first MAC stage, both terminals A and B transmit simultaneously to the relay in the interfering manner, see Fig 3. The received composite (interfering) signal is

$$x = h_A s_A + h_B s_B + w,$$

where $w$ is complex AWGN with variance $2\sigma_0$ per complex dimension, and the channel parameters $h_A$ and $h_B$ are frequency-flat complex Gaussian random variables with unit variance and Rayleigh/Rician distributed envelope. The Rician factor $K$ is defined as a power ratio between stationary and scattered components. We assume that the channel parameters $h_A, h_B$ are known to $R$.

Subsequently, the relay decodes exclusively coded data symbol $c_{AB} = c_A \oplus c_B$ from interfering signal (1). Operation $\oplus$ is a network coding-like exclusive (invertible) operation which incorporates data from multiple sources via a principle of exclusivity, see Sec. II-D for more details. We assume a minimal cardinality exclusive operation, i.e. cardinality of $c_{AB}$ alphabet is $M_c$ [7]. We suppose an approximated nearest neighbor two-step decoding [16]: estimate of exclusively coded data symbol $c_{AB}$ is obtained by joint maximum likelihood decoding

$$[\hat{c}_A, \hat{c}_B] = \arg \min_{c_A, c_B} ||x - h_A c_A - h_B c_B||^2$$

followed by exclusive encoding $\hat{c}_{AB} = \hat{c}_A \oplus \hat{c}_B$; by $||*||^2$ we denote the squared vector norm.