Applicability of Space-Time Block Codes for Distributed Cooperative Broadcasting in MANETs with High Node Mobility

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***Abstract*—Mobile Ad-Hoc Networks (MANETs) are often characterized by high node mobility and rapid topology changes which in turn can cause high packet loss rates. In order to cope with this, MANETs typically rely on routing algorithms that try to efficiently distribute messages in the entire network. Such routing schemes introduce an overhead that limits the scalability of MANETs with respect to the number of nodes and/or mobility. Cooperative communication techniques have the potential to improve the efficiency of distributing messages and thus to increase the MANET scalability. In this paper, we propose an efficient cooperative broadcasting scheme based on distributed transmit diversity. To this end, we adapt Space-Time Block-Codes (STBCs), that were initially designed for a co-located setup in quasi-static environments, to a distributed setup with time-variant channels. We perform a comprehensive analysis based on bit error simulations to compare different STBC candidates and identify Linear-Scalable Dispersion Codes (LSDCs) to be a valuable option. For those, we propose an improvement of the inner-code for different channel models without the need for channel state information at the transmitter (CSIT). Besides, we validate the performance advantage of cooperative broadcasting by outage simulations in typical MANET scenarios.**

***Index Terms*—MANET Scalability, Distributed Cooperative Communication (Broadcasting), Space-Time Block Codes (STBC)**

I. Introduction

Mobile Ad-Hoc Networks (MANETs) are infrastructure-less and typically consist of lightweight, low-power, low-cost nodes [1], [2]. Nowadays, two subclasses of MANETs, Vehicular (VANETs) and Flying Ad-Hoc Networks (FANETs) gain an increasing popularity [3]–[5]. Both introduce new challenges and constraints. The mobility of nodes (vehicles in VANETs, unmanned aerial vehicles (UAV) in FANETs) is massively increased leading to rapidly changing topologies and frequent disconnections [3]–[5]. To manage these, common routing protocols distribute topology control messages within the entire network. However, the necessary overhead limits the scalability with respect to the number of nodes N_{TX} [1], [6], [7]. A more efficient distribution of such messages has therefore the potential to immediately improve the routing and hence the overall scalability of MANETs. Besides, it is advantageous for sending the same information to a large amount of nodes as it is often required within a VANET or FANET, e. g. safety-critical warnings. Within this paper, we

- propose an efficient cooperative broadcasting scheme,
- perform a comprehensive analysis which linear STBCs are basically suitable for this scheme,
- investigate the performance of those for varying channel realizations,
- identify Linear-Scalable Dispersion-Codes (LSDCs) to be the most favourable option and
- propose an improvement for LSDCs (new inner-code design) for different channel models without the need for channel state information at the transmitter (CSIT).

II. Motivation for Cooperative Broadcasting

For broadcasting the available resources are often assigned according to a multiple-access scheme. So, only a very limited subset of nodes is active at the same time and interference on the physical layer can be avoided. If $\mathbf{u} \in \mathbb{C}^{L,1}$ denotes the transmit signal with $\mathbb{E}\{|\mathbf{u}|^2\} = E_\text{s}$ and L being the total number of necessary time-slots ν, the received power P_rx for one active node can be calculated by

$$P_\text{rx} = E_\text{s} \cdot |h|^2 \cdot d^{-\eta}, \tag{1}$$

where $h \in \mathbb{C}^{1,1}$ refers to the channel coefficient between the transmitter (TX) and receiver (RX), d to the distance between TX and RX and η to the path-loss exponent. However, the routing overhead (number of control packets, retransmissions, etc.) increases significantly for large-scale networks, wherefore this type of broadcasting a message is inefficient and costly. To overcome this scalability limitation, all nodes can be allowed to send simultaneously. In a *concurrent* broadcasting scenario, all nodes send the same information and same transmit signal ($\mathbf{u}_1 = \mathbf{u}_2 = \ldots = \mathbf{u}_{N_\text{TX}}$), where $\mathbf{u}_\text{i} \in \mathbb{C}^{L,1}$ is the i-th TX transmit signal with $\mathbb{E}\{|\mathbf{u}_\text{i}|^2\} = E_\text{s}$. Hence, according to

$$P_\text{rx} = E_\text{s} \cdot \left| \sum_{i=1}^{N_\text{TX}} h_\text{i} \cdot d_\text{i}^{-\eta/2} \right|^2, \tag{2}$$

destructive interference can occur, where $h_\text{i} \in \mathbb{C}^{1,1}$ denotes the channel coefficient for the path between the i-th TX to the RX and d_i the distance between the i-th TX to the RX. Depending on the node density and network topology, the interference can cause a severely degraded performance. In contrast, in a *cooperative* broadcasting scenario, all nodes jointly transmit a common information but a different signal ($\mathbf{u}_1 \neq \mathbf{u}_2 \neq \ldots \neq \mathbf{u}_{N_{TX}}$). Transmit-diversity schemes enable that the signals add up in power and not in amplitude, so that the interference is always constructive:

$$P_{rx} = E_s \cdot \sum_{i=1}^{N_{TX}} |h_i|^2 \cdot d_i^{-\eta}. \quad (3)$$

Both, concurrent and cooperative broadcasting, can be combined with a *multistage* procedure. One node sends a message to its neighbours, who join transmission after decoding. As more and more nodes contribute their TX power to the transmission, the range steadily increases, typically reducing the number of necessary hops to reach all nodes, particularly if some are located aside. Nodes that cannot be reached are considered to be isolated from communication and not able to participate in the network. The outage rate, i. e. the probability that a node cannot be reached, is higher in a concurrent than in a cooperative broadcasting scenario due to the destructive interference that can occur in the former (2) and that is avoided in the latter (3). An efficient *multistage cooperative broadcasting* has thus the potential to significantly boost the performance of distributing messages to a large number of nodes, e.g. routing massages or other urgent (safety related) messages. A more efficient distribution of routing topology control messages as well as the possibility of efficiently distributing the same information to a large subset of nodes can enable an improved MANET scalability.

In order to minimize the overhead and bearing the practical feasibility, it is of crucial importance that the cooperation can be organized without much coordination effort, CSIT and phase synchronization. STBCs that were in the focus of research especially in the years around 2000 basically fulfill these requirements, but were designed for co-located antennas at one node and quasi-static environments. We study whether they are applicable to establish (multistage) cooperative broadcasting for distributed nodes to improve the scalability of MANETs with high node mobility.

III. System Model

We assume a network of homogeneous one-antenna nodes. Many of those are aggregated to transmit, while each RX performs decoding on its own, wherefore the overall communication can be classified as a *Distributed* or *Virtual Multiple-Input Single-Output (MISO)* system. A virtual Multiple-Input Multiple-Output (MIMO) system can increase the throughput, but assorting a group of RX nodes arises the question how to exchange the received information among all RX. It is obvious that the overall communication overhead has to be increased to achieve such an exchange, which we want to avoid, wherefore a virtual MIMO system built with one-antenna nodes is currently not behold a feasible approach for practical low-complexity systems.

The nodes are randomly distributed in space and the channels between each TX and RX are considered to be uncorrelated. For the remainder of the paper, narrow-band one-tap channels in a single-carrier setup are assumed. The extension to multi-carrier systems such as OFDM is straightforward.

The encoding process of each STBC can be expressed by a matrix $\mathbf{X}_{STBC} \in \mathbb{C}^{L,N_{TX}}$ that describes the necessary processing of the input symbol vector $\boldsymbol{\alpha} \in \mathbb{C}^{N_I,1}$. While each row of the matrices or respectively vectors represents a time-slot ν and the totality of time-slots the block-length L to transmit all N_I elements (payload symbols), the columns of $\mathbf{X}_{STBC}$ can be assigned to the individual antennas. Thus, the transmit signal for the i-th antenna ($\mathbf{u}_i$) corresponds to the i-th column of $\mathbf{X}_{STBC}$. In order to use STBCs (initially designed for co-located antennas) for distributed nodes, each node has to employ the same encoding matrix $\mathbf{X}_{STBC}$. Hence, all nodes have to agree on the number of columns and available time-slots. Moreover, if various ancillary matrices are used to generate the overall encoding matrix, these have to be the same, too. Thereby, the chosen number of columns does not necessarily have to match the actual number of available nodes N_{TX}. If the number of columns is smaller than N_{TX}, the remaining nodes will be used for replicating selected columns. If the number of columns is larger than N_{TX}, some generated transmit signals will not be sent which physically corresponds to channels in a deep fade. For our simulations, we assume that the number of columns exactly matches N_{TX}. With this we avoid that some columns are sent multiple times while others are not sent at all. The received symbol vector $\mathbf{y} \in \mathbb{C}^{L,1}$ results from the multiplication with the channel vector $\mathbf{h} \in \mathbb{C}^{N_{TX},1}$ [8], such that

$$\mathbf{y} = \mathbf{X}_{STBC}(\boldsymbol{\alpha}) \cdot \mathbf{h} + \mathbf{n}, \quad (4)$$

where $\mathbf{n} \in \mathcal{CN}\left(0, \sigma_n^2 \mathbf{I}\right)$ denotes the complex-valued additive white Gaussian noise (AWGN). $\mathbf{h}$ can be different for each time-slot ν (time-variant channel). Each STBC differs in the construction of $\mathbf{X}_{STBC}$, whereas for every STBC that has all its transmit symbols in the form of $\pm\alpha_n$ or $\pm\alpha_n^*$, an equivalent channel matrix $\mathcal{H}$ can be found as [8]

$$\mathbf{y} = \mathcal{H} \cdot \boldsymbol{\alpha} + \mathbf{n}. \quad (5)$$

IV. Preselection of STBC Code Families

Fundamentally, STBCs can be subdivided into linear and non-linear, e. g. Trellis-based, STBCs. Since we want to investigate the applicability of STBCs for practical low-complexity MANETs, we do not consider the computationally more demanding non-linear codes, but prefer linear codes. Linear STBCs themselves can be further split into a vast variety of coding families which are all designed with a slightly different focus. One prominent class consists of *Orthogonal STBCs (OSTBCs)* which are known to be computationally very efficient and to achieve full transmit-diversity. Nonetheless, OSTBCs are only able to achieve a code-rate of $R_c = \frac{1}{2}$ for $N_{TX} > 4$ [9]. For OSTBCs, an ML-Decoding is possible by simply multiplying the received symbol vector $\mathbf{y}_{rx}$ with the adjoint (complex transpose) equivalent channel matrix $\mathcal{H}^H$.

However, the decoding advantage is gone, once the orthogonality is lost which is the case in a time-variant environment ($h_{1t_1} \neq h_{1t_2}$ and $h_{2t_1} \neq h_{2t_2}$, where the second index refers to the time-slot t_ν) or in presence of carrier frequency offset (CFO). E. g. for the famous Alamouti code [10] it follows that

$$\mathcal{H}^H \cdot \mathcal{H} = \begin{bmatrix} h^*_{1t_1} & h_{2t_2} \\ h^*_{2t_1} & -h_{1t_2} \end{bmatrix} \cdot \begin{bmatrix} h_{1t_1} & h_{2t_1} \\ h^*_{2t_2} & -h^*_{1t_2} \end{bmatrix} \neq q \cdot \mathbf{I} \quad (6)$$

and in general for OSTBCs $\mathcal{H}^H \cdot \mathcal{H} \neq q \cdot \mathbf{I}$, where for quasi-static environments the equality holds and $q = \sum_{i=1}^{N_{\text{TX}}} |h_i|^2$. Therefore, the application of linear Non-Orthogonal STBC (NOSTBC) seems more reasonable, because such can achieve an increased code-rate and full-transmit diversity at the same time. In order to select the coding scheme that is best suited, we compare the achievable performances to that obtainable with an OSTBC. However, first we conduct a pre-selection to determine a set of STBCs that are most promising on the basis of theoretical investigations.

For that, we require that the proposed codes do not purely focus on networks with a dedicated (limited) size, do not sacrifice the achievable diversity in favour of the code-rate, do not have a significantly low code-rate and do not require a feedback-link that would be hard to realize from a practical point of view for distributed systems. Besides, it is of crucial importance that the decoding effort is manageable, i. e. that the codes perform well if a linear or suboptimal iterative receiver is applied. Basically, our main focus is on codes that achieve full transmit-diversity and at the same time a code-rate that is close to 1 with suboptimal decoders.

As a result of the intensive literature review Toeplitz STBC [11], Overlapped Alamouti Codes (OAC) [8] and Linear-Scalable Dispersion Codes (LSDCs) [12] are identified to be the most promising candidates. Both, Toeplitz STBC and OAC can achieve full transmit-diversity with a linear receiver. At the same time, R_c can asymptotically approach 1 ($R_c \to 1$) if the block-length L and thus the number of information symbols N_I is sufficiently large. In contrast, LSDCs achieve full transmit-diversity and $R_c = 1$ simultaneously regardless of the block-length, but suggest the application of a computationally more expensive receiver architecture, e. g. a Decision-Feedback-Equalizer (DFE).

Suboptimal decoders always introduce a complexity-performance tradeoff. For our simulations we choose the MAP-MMSE-DFE [13] which is computationally tremendously more efficient than an ML-decoding and in its performance significantly better than a simple linear decoder, e. g. MMSE. The only exception is the decoding of the OSTBC in quasi-static environments, where the ML-decoding is preferred.

V. Performance Comparison

First, we compare the performance in a quasi-static Rayleigh-fading environment. I. e. block-fading is presumed, so that the channel coherence time T_c is considered to be larger than the block duration. Next, we concentrate on maximally time-variant Rayleigh-fading environments. Thereby, a different channel coefficient is assumed for each time-slot ν and TX. Thus, T_c corresponds to the sample time of the system which constitutes the extreme opposite of a quasi-static scenario ($T_c = t_s = 10\ \mu$s for a typical sampling time of $t_s = 10\ \mu$s). Last, we check the performance in an AWGN environment where the channel introduces no attenuation, but a random phase shift that is constant for the duration of a transmission, as it could correspond to e. g. a traffic jam or UAV swarm.

All simulations are performed in the equivalent baseband using a single-carrier modulation (4-QAM). It is important to denote that the encoding effort for all considered STBCs is approximately independent of the modulation order. However, increasing the modulation order will require a more complex equalizer. To investigate the pure structural performance, perfect time-alignment, the absence of any carrier frequency offset and perfect channel state information at the receiver (CSIR) is presumed. Furthermore, we assume a constant block-length of $L = 32$, wherefore the number of transmitted information symbols N_I is different for each coding scheme. E. g. the chosen OSTBC requires $L = 32$ channel uses to transmit $N_I = 16$ information symbols. To equalize any power gain resulting from this imbalance, the transmit signals are normalized with respect to the number of information bits. Table I summarizes the achievable code-rates with the different STBCs. For our bit error rate (BER) simulations, we currently concentrate on a MANET setup with $N_{\text{TX}} = 4$. To free these simulations from a specific node distribution, we neglect the distance between the TX and RX for now and do not consider a distance dependent path-loss. The latter becomes important for our MANET scenario simulations in Section VII.

TABLE I
Overview of used block lengths and code rates

	OSTBC	Toeplitz	OAC	LSDC
L	32	32	32	32
N_I	16	29	30	32
R_C	50%	≈ 90.63%	93.75%	100%

Assuming quasi-static Rayleigh fading, all selected STBCs achieve a very similar performance which is significantly better than that obtainable with concurrent broadcasting (Fig. 1), because only an SNR gain but no diversity gain is achievable with latter. However, it has to be stated that the LSDC achieves rate one ($R_c = 100\%$), while the rate is reduced for the OAC ($R_c = 93.75\%$), Toeplitz STBC ($R_c = 90.63\%$) and OSTBC ($R_c = 50\%$).

In a time-variant fading environment, LSDCs can profit from the additional fading (Fig. 2). In theory, LSDCs are able to achieve a diversity that corresponds to the channels' degrees of freedom which is 32 for this particular example. Hence, they clearly outperform OSTBCs and massively outperform Toeplitz STBCs and OACs. Thus, they seem to be the most promising STBC for the application in MANETs with high node mobility. Their only major disadvantage is the AWGN-performance as depicted in Fig. 3. However, this is not a structural problem, but reasoned in the selection of the inner-

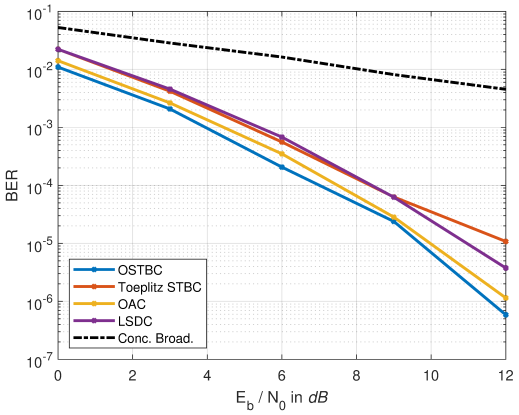

Fig. 1. Quasi-static Rayleigh fading environment

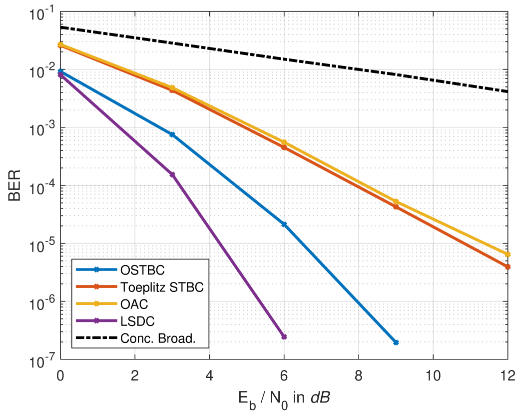

Fig. 2. Time-variant Rayleigh fading environment

code which is used for channel adaptation. The Fourier-matrix that is typically recommended for fading channels, is obviously not suited for AWGN channels. For such, the authors actually suggest to use antenna switching instead [12]. Nonetheless, this is only meaningful for co-located systems where the overall transmit power is constant. In a distributed setup this will cause a reduced transmit power compared to a simultaneous transmission with several nodes. In a distributed setup an SNR gain can occur, wherefore antenna switching is an improper inner-code, which is why we propose an adaptation that enables to achieve the AWGN lower bound for distributed nodes as well as an SNR gain.

VI. Adaptation for LSDCs

LSDCs utilize two linear but decoupled block-codes: a time-invariant outer-code $\mathbf{R} \in \mathbb{C}^{L,N_\text{I}}$ that is designed to achieve the optimal diversity performance and a time-variant (denoted by the index ν) inner-code $\mathbf{C}_\nu \in \mathbb{C}^{N_\text{TX},L}$ used for channel adaptation. For encoding, the input symbol vector is first multiplied with the outer-code. Each element of the resulting vector is then multiplied with the corresponding inner-code vector $\mathbf{c}_\nu \in \mathbb{C}^{N_\text{TX},1}$ that is the ν-th column of $\mathbf{C}_\nu$. An intermediate matched received signal $\mathbf{y}_\text{matched} \in \mathbb{C}^{N_\text{I},1}$ is introduced that allows a description with a correlation matrix $\mathbf{\Lambda}_\text{ISI} \in \mathbb{C}^{N_\text{I},N_\text{I}}$:

$$\mathbf{y}_\text{matched} = \mathbf{\Lambda}_\text{ISI} \cdot \boldsymbol{\alpha} + \mathbf{n} \quad (7)$$

$$\mathbf{\Lambda}_\text{ISI} = \mathbf{R}^H \cdot \mathbf{D} \cdot \mathbf{R} \quad (8)$$

$$\mathbf{D}(\nu,\nu) = \mathbf{c}_\nu^H \cdot \mathbf{h} \cdot \mathbf{h}^H \cdot \mathbf{c}_\nu = |\mathbf{h}^H \cdot \mathbf{c}_\nu|^2, \quad (9)$$

where $\mathbf{D} \in \mathbb{C}^{L,L}$ denotes a diagonal matrix ($D(i,j) = 0$ for $i \neq j$). The inner-code is critical if it is orthogonal to the channel, so that $\mathbf{h} \cdot \mathbf{c}_\nu = \mathbf{c}_\nu^H \mathbf{h}^H = 0$, which is the case when applying the vectors of the Fourier-matrix as inner-code for ideal AWGN transmit channels ($\mathbf{h} = \mathbf{1}_{N_\text{TX},1}$).

The outer-code $\mathbf{R}$ is optimized with respect to two criteria: on the one hand, $\mathbf{R}$ is unitary to maintain the Euclidean distance in AWGN channels. On the other hand, $\mathbf{R}$ maximizes the product-distance to achieve the best performance in fading environments. Due to that, the inner-code can be optimized to either compensate the channel and retain the unitary property, so that $\mathbf{\Lambda}_\text{ISI}$ becomes a scaled identity matrix, or to maximize the interference which enables the DFE-receiver to profit most from the diversity. For former, the inner-code basically equalizes the channel at the TX-side ($\boldsymbol{c}_\nu = \mathbf{h}^H$), which in absence of CSIT is not possible. Instead, we propose to convert the AWGN channel to a fading channel by introducing ISI. The major constraint for the inner-code design to achieve the highest SNR gain is to utilize all TX nodes to the same extent at each time-slot ν. Hence, the transmit power has to retain constant, which is why the phase of the complex elements is the only parameter to be adapted. Furthermore, the inner-code has to be time-variant. If the inner-code as well as the channel is static, $\mathbf{D}$ can be expressed by a scaled identity matrix ($q \cdot \mathbf{I}$, $q \in \mathbb{R}$), so that $\mathbf{\Lambda}_\text{ISI}$ and $\mathbf{y}_\text{matched}$ become

$$\mathbf{\Lambda}_\text{ISI} = \mathbf{R}^H \cdot q \cdot \mathbf{I} \cdot \mathbf{R} = q \cdot \mathbf{R}^H \cdot \mathbf{R} = q \cdot \mathbf{I} \quad (10)$$

$$\mathbf{y}_\text{matched} = \mathbf{\Lambda}_\text{ISI} \cdot \boldsymbol{\alpha} + \mathbf{n} = q \cdot \mathbf{I} \cdot \boldsymbol{\alpha} + \mathbf{n} = q \cdot \boldsymbol{\alpha} + \mathbf{n}. \quad (11)$$

$\boldsymbol{\alpha}$ is just scaled by q, whereas in such a case $q = |\sum_{i=1}^{N_\text{TX}} h_i|^2$. Therefore, this corresponds to a concurrent broadcasting where destructive interference will very likely occur. By a time-variant inner-code, the elements of the diagonal matrix $\mathbf{D}$ always differ, wherefore $\mathbf{\Lambda}_\text{ISI} \neq q \cdot \mathbf{I}$, so that ISI is introduced. For distributed TX, it can be assumed that the phase-shift introduced by each channel follows a uniform random distribution in the interval $[0, 2\pi)$. Avoiding CSIT, a sophisticated strategy is to select random phases for the inner-code itself and to vary this random choice for each time-slot ν. So, the probability for a critical combination is minimized.

$$\mathbf{c}_\nu = \left(\mathrm{e}^{j\cdot\phi_{1,\nu}} \quad \mathrm{e}^{j\cdot\phi_{2,\nu}} \quad \ldots \quad \mathrm{e}^{j\cdot\phi_{N_\text{TX},\nu}}\right)^T, \quad (12)$$

where $\phi_{i,\nu} \in [0, 2\pi)$ denotes the random phase for the i-th TX and ν-th time-slot. Following that approach, it is best to introduce as much ISI as possible.

Aiming for a reduced overhead to establish cooperative communication by employing linear STBCs, it might appear contradictory to propose an inner code whose phase is randomly varied in each time-slot ν. Nonetheless, the random phase variations, which have to be known to the RX, do not have to be transmitted as the inner code can be estimated in compound with the channel vector, so that the complexity for channel estimation which has to be performed for all investigated STBCs remains the same.

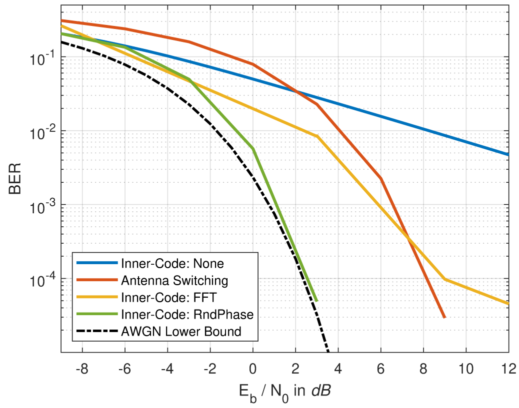

Fig. 3. AWGN-like environment (no Attenuation, random phase shift)

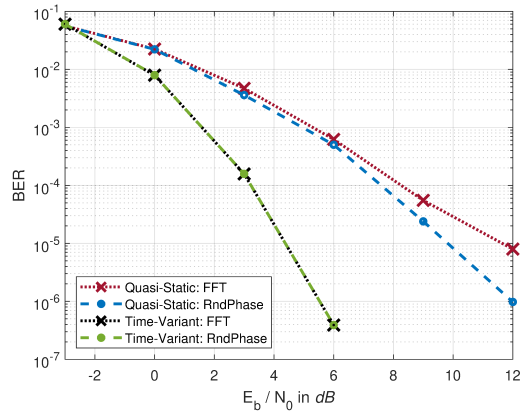

Fig. 4. Quasi-static and time-variant Rayleigh fading; varying inner-code

Simulation results verify that the AWGN performance can be significantly improved with the new inner-code (Fig. 4), whereas the visualized lower-bound is obtained by the complementary Gaussian error function

$$\mathrm{BER}\left(\frac{E_b}{N_0}\right) = \frac{1}{2} \cdot \mathrm{erfc}\left(\sqrt{N_{\mathrm{TX}}} \cdot \sqrt{\frac{E_b}{N_0}}\right). \quad (13)$$

Besides, it is important, that the obtainable performance in a fading scenario can be maintained, which we also verified by simulations. Fig. 4 depicts that there is no performance degradation neither in a quasi-static nor in a time-variant Rayleigh-Fading environment compared to the Fourier-matrix. To conclude, our proposed solution appears to be a well-suited approach for varying channel models, not only because it slightly performs better than the Fourier matrix inner code in a quasi-static environment, but because it allows to achieve the AWGN lower bound while the performance in the remaining scenarios can be maintained. Besides, no CSIT is needed and no additional overhead is introduced.

VII. MANET Scenario Evaluation

Hitherto, a snapshot in the propagation of a message in a MANET has been considered where a stage with $N_{\mathrm{TX}} = 4$ TX was active. Within this section, we increase the number of nodes and investigate the propagation of a message within a MANET if LSDCs are used to employ cooperative broadcasting. For the presented simulations, we presume an area of fixed size (10m x 10m). A certain number of nodes (population) is randomly distributed, so that a random topology is generated. The broadcasting is organized in stages. For each stage, we consider several channel realizations and calculate the mean BER for each receiving node (RX). If the mean BER is below 10^{-2}, we consider the packet to be successfully decoded, so that the RX becomes a TX for the next stage. The algorithm is visualized in Fig. 5. Within this context, we chose this threshold with respect to common forward error correction (FEC) schemes, which typically allow to correct all remaining errors once the BER is below 10^{-2}. For our BER simulations, we do not consider FEC, as it is reasonable to assume that such a coding will be advantageous for all STBCs to the same extent. For cooperative broadcasting, one node starts to transmit a message. Surrounding nodes, that were able to successfully decode, join the transmission and assist to distribute the information. An exemplary simulation result is shown in Fig. 6, which depicts the propagation for the first 3 stages. The transmission between all active TX and each RX can be modelled as a virtual distributed MISO setup, whereas we presume a different quasi-static Rayleigh-fading channel between each node, which varies from stage to stage. Besides, we consider a path-loss as denoted in (3) with $\eta = 4$. We expect all nodes to transmit with $E_{\mathrm{b}} = 1$, while we consider a noise variance of $\sigma_n^2 = 10^{-4}$. For our simulations, we evaluate various random topologies and compare the obtainable result for cooperative broadcasting with a classical multi-hop communication. For latter, we choose classical non-cooperative flooding as a robust representative.

Fig. 7 depicts the outage rate. An outage is detected if not all nodes of the topology can be reached. It becomes obvious, that cooperative communication enables a much more stable transmission. The outage rate is tremendously lower.
Evaluating the average number of necessary stages for all successful transmissions (see Fig. 8) a further advantage of

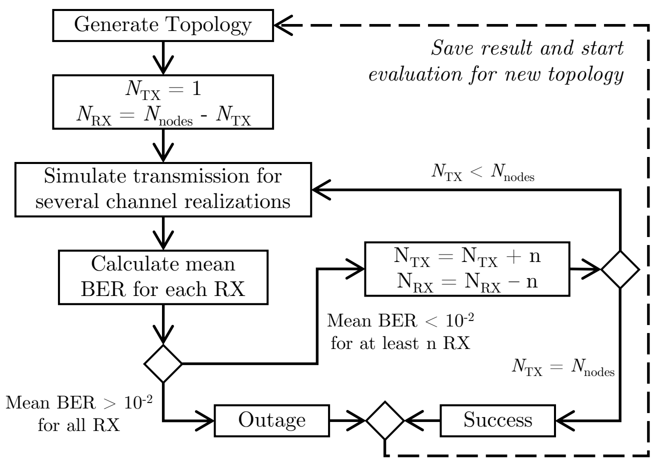

Fig. 5. MANET simulation: algorithm to detect outage / success

cooperative broadcasting is revealed. The message can be distributed to all nodes with significantly less hops. The necessary number of hops becomes even regressive for large population sizes due to the increased range once several nodes joined the transmission. The effectiveness is not only increased due to the reduced amount of hops, but also because one hop itself requires less time. All nodes transmit simultaneously instead of one after the other like it is the case for non-cooperative multi-hop communication. Cooperative communication typically comes at the downside of an increased overall transmit power, since in our simulations in total more TX are active more often.

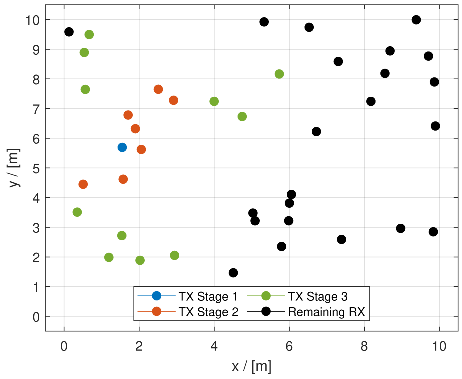

Fig. 6. Example: message propagation

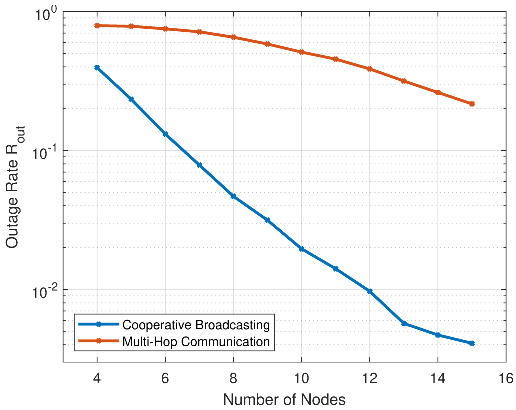

Fig. 7. Outage rate vs. population size

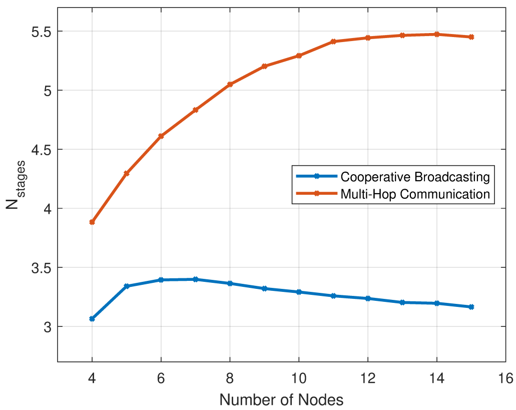

Fig. 8. Number of necessary stages vs. population size considering only successful broadcasts (no outage)

VIII. Conclusion

Multistage cooperative communication has the potential to improve the efficiency of distributing the same message within the entire network. On the one hand, this is advantageous for common routing protocols, particularly to deal with an increased mobility. On the other hand, depending on the size of the network, this can be used to share common, e. g. safety-relevant, messages resource-efficient without any routing. Our analysis shows, that STBCs are well-suited for cooperative broadcasting. We suggest to use LSDCs, which are, considering our proposed improvement, ideal for both, high-mobility time-variant fading environments and static AWGN-like channels. In our future research, we will address the impact of imperfections (multiple timing and carrier frequency offset) and methods to mitigate these.

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